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Hydraulic Dewatered Stacking Demonstration – Approaching Operational Completion

Phil Newman, Anglo American, UK
Mark Bruton, WSP, UK
James Purrington, WSP, UK
Alireza Nickman, WSP, UK
Andrea Lopez, Anglo American, Chile

Abstract

Hydraulic Dewatered Stacking (HDS) is an engineered co-disposal approach that uses a fines-free sand, derived from the tailings themselves, to deliver robust and effective omnipresent drainage channels throughout the tailings facility, accelerating consolidation and dewatering.

Since its inception in 2019, Anglo American have rapidly developed the science behind the new tailings system and designed, built, and commissioned a bespoke 150,000 m^3 capacity greenfield tailings facility at the El Soldado Mine in Chile.

This paper presents the results to date of the trial encompassing two of the planned three stages of tailings and sand drainage layer deposition and the construction of drainage channels. A review of the efficacy of the technology will be presented and a comparison between two different methods of co-disposal and placement of sands will be considered.

Key parameters associated with the desaturation and resaturation of the facility will be presented based on the review of in situ data collected from an extensive array of instrumentation and where available, follow-on intrusive investigations and laboratory testing.

The industry appears ready to embrace the benefits of the technology:

- Enhanced water recovery delivering real value and increasing the resilience of operations in water-scarce regions;

- Limited capital expenditure while delivering much of the performance benefits of filtered tailings stacking;
- A final tailings facility footprint suitable for re-purposing, reducing long term liabilities; and
- An instrumentation solution that can deliver on enhanced transparency for stakeholders helping owners to move towards GISTM compliance.

Introduction

Hydraulic Dewatered Stacking (HDS) is a novel tailings management approach developed by Anglo American that utilises fines free, rapidly draining sand to create a 3-dimensional drainage structure to deliver a predominantly desaturated tailings storage facility (TSF).

The sand is derived from the tailings themselves, which in most cases, assures compatibility as a robust and long-lasting filter medium (Terzaghi and Peck, 1948). Suction pressures are developed rapidly in the tailings, which drain both vertically and horizontally thanks to spigotted tailings possessing a K_h that is 10x K_v. This anisotropy in permeability is exploited well by the engineering design of HDS and although results remain preliminary, the data generated from the 150,000 m^3 demonstration facility at the El Soldado Mine in Chile supports the initial hypothesis. The dewatering and consolidation performance measured to date has been excellent and an extensive site investigation planned for Q4 2024 will provide the final calibration of the data collected to date.

The trial was constructed in 2021 after initial laboratory testing (Newman et al, 2022) indicated that a desaturated stack was feasible. As with all pilots, operational learnings and data generated has led to design changes during the trial. Significant data has been generated, and lessons learned regarding in-situ instrumentation to monitor tailings facilities. Data is presented below, with interpretation and reference to the ongoing concurrent modelling of the facility. The work completed has fed directly into studies for full-scale implementation of HDS both within and out with Anglo American's assets. Cost estimates have confirmed that HDS is more expensive to operate than conventional wet tailings disposal, but highly water generative (with associated safety, expansion optionality and closure benefits). When assessed using a Net Present Cost (NPC) approach, the results are dependent on: i) water costs / constraints; ii) time to closure; and iii) estimated closure costs. When compared to filtered tailings, both capital and operating cost savings are significant and the approach can deliver an unsaturated stack where the net present cost of implementation is between one third and one half (Newman et al, 2024).

Demonstration Design and Operation

Concurrent modelling of the proposed trial led to a variation in design with the trial facility split into two cells testing two different approaches to HDS execution, see Figure 1.

The design in Cell A was varied to exclude sand blankets and only sand channels were utilised; modelling had shown that thin layers of tailings separated by sand blankets could increase the rate of consolidation however, the development of suction pressures would be hindered such that air entry may not be achieved. Cell B was left with sand blankets so that a comparison can be made between the two approaches.

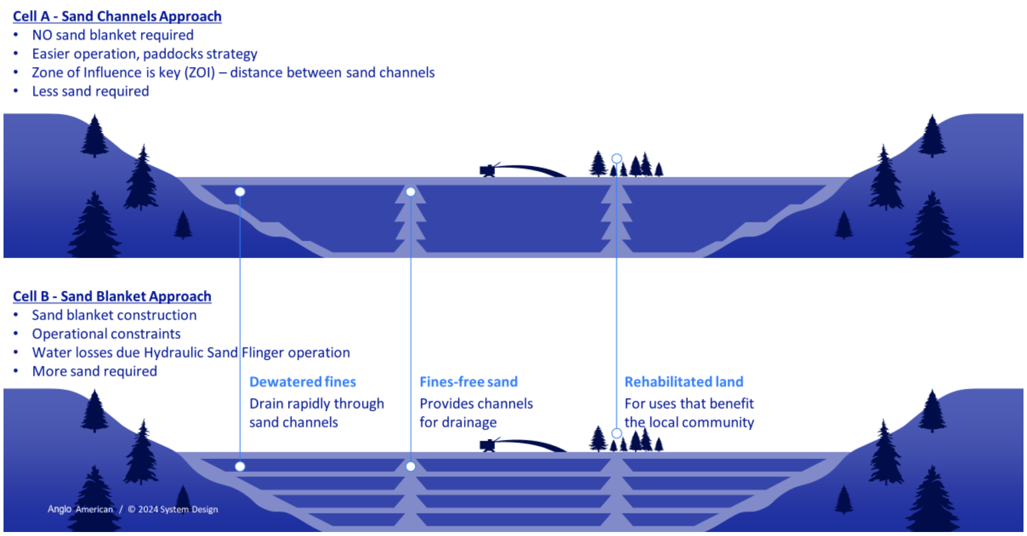

Figure 1 – Sand blankets (Cell B) vs sand channels (Cell A)

An important artefact of this change in design (of cell A) is that the sand channels are not physically continuous with the basal drain layer since a 2 m thick layer of tailings had already been placed in the cell. It was considered that this would limit the ability of the sand channel approach to drain and hence would have a conservative impact on the performance. A greenfield application of the HDS system would include such a connection – modelling of the two approaches is proposed and will be reported on in due course.

Lessons Learned and Impact on Future Commercial Applications

The change in placement approach also has operational implications; the placement of the sand blankets was considered problematic. Working with the contractor, a Hydraulic Sand Flinger (HSF) was developed to place the sand blanket; the approach worked although getting an even layer was difficult, resulting in higher consumption of sand than expected. However, at larger scale applications (wherein most of the value for HDS exists for the mining industry) the placement of these blankets would likely involve the machine moving across recently placed tailings – adding another degree of operational uncertainty. In addition, the loss of water through evaporation also reduced the attractiveness of the sand blanket approach. Alternative sand blanket options investigated included open pipe placement, creating large cones of deposited sand about 600-800 mm high and 20 m in diameter; simple and effective.

The drainage channels have been built hydraulically with an SPCU (Self Propelled Cyclone Unit) which has performed well at approximately 80-90 tph. Higher placement capacity is feasible but the demonstration was limited by the size of the fluidizer plant. The SPCU was originally developed to classify a conventional slurry and hence optimisation of the system is required when the duty is changed to dewatering a fines-free sand.

Design work is ongoing with an Original Equipment Manufacturer (OEM) looking at other sand placement techniques, with a target of achieving >250 tph sand placement. At these placement rates, larger scale operations become easier to implement with a small number of 'berm-builders'. The constraint going forward will be the pipeline management for the delivery of the sand slurry given the discharge point is continuously moving. Innovations developed on large scale conveying and stacking (i.e. the tripper conveyor) don't exist at this time for slurry transport and hence further innovation is required to fully automate the sand placement process.

Water recovery has been strong, and of good quality. Under steady state conditions, the water quality in terms of suspended solids is the same or better than conventional tailings return water. Geochemically, the water quality was similar.

Instrumentation

Designing a demonstration tailings facility provides an unparalleled opportunity to generate data on the settlement and consolidation behaviour of tailings. Lining the facility was not a permitting requirement but was a decision taken to facilitate water balance calculations and monitoring.

The HDS contains an array of geotechnical instrumentation to allow designers and operators to monitor the desaturation of the facility through operations and into closure. Vibrating Wire Piezometer's (VWP's), Moisture Content (MC) probes, Suction Transducers (ST) and Fibre Optic cabling have all been installed within the facility raises. Lidar surveys are conducted daily to monitor consolidation.

Following the development of two alternative construction approaches (Cell A and Cell B), the two approaches can be quantitatively compared. At the time of writing this paper the facility has been operated through Phase 1 and 2 of the trial. For the placement of the first 2 m layer of tailings in Phase 1 both cells were operated in the same approach, subsequent to this, two alternative approaches were implemented.

MC probes record Volumetric Water Content (Volume of water compared to volume of solid); laboratory calibration has been used to convert this to a gravimetric moisture content, but this is a function of the density of the tailings, so these values provide a relative gauge rather than absolute value. This can be seen in the data set when presenting the degree of saturation (Sr) based on a constant assumed voids ratio (Figure 2), where the consistently flat sections of the data correspond to the tailings in the location of the instrument being fully submerged by the supernatant pond.

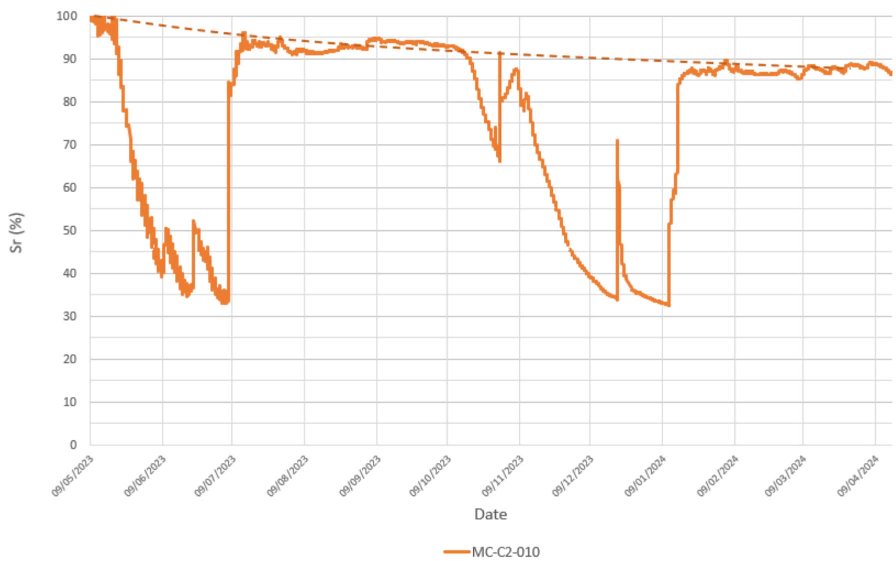

Figure 2: Change in voids ratio

The data acquisition system (DAS) at the demonstration has worked well. The permitted facility was built on top of an existing tailings facility and piezometers measure the development of excess pore pressure within the supporting tailings mass, and inclinometers in slopes that surround the facility monitor deformation that could adversely affect the safety of the staff working on the trial. The integrated satellite DAS connects directly to a user-friendly dashboard accessible globally through an internet connection. Alerts as required can be generated, resulting in direct communication with relevant personnel and linked to the Operations and Surveillance Manual (OMS) and trigger action response plan (TARP).

On-line site cameras covering the trial allows daily interaction with the facility from designers and stakeholders located thousands of miles from the site and it has provided unexpected insight. For example, a 1:10 year rain event experienced on site in June 2024 was an unscheduled (but valuable) test on the sand channels' capacity to remove excess water. Time lapse photography shows that as fast as water was entering the facility, it was being removed through the drainage system. Operational data shows that water removal through the drains rose steadily delivering clean water to the concentrator from unhindered flow through the sand channels at the demonstration site.

Lessons learned from Instrumentation Experience

The instrumentation installed in the facility has provided valuable insight into the performance of the facility. However, the discrete nature of the data points offer only part of the picture and it is evident that coupling moisture content and suction transducers at each location would offer greater insight. The attempt to create a broader spatial understanding of the facility using self-heating (active) fibre optics has proven elusive, with no significant data capture due to numerous failings in the system.

Discrete instruments have, in general, delivered a robust solution. Selecting suction transducers, not ideally suited to the intended use, has led to a few data gaps. In Phase 3 the addition of a different type of soil water potential sensor at each of the suction transducer locations has been included.

In addition to the instrumentation data the trial will be supplemented from a dense array of intrusive investigation holes, in-situ test work and laboratory testing, to increase the overall understanding of the performance of the facility.

Data and Discussion

Some insights from the data obtained during Phase 1 and 2 of the trial are presented below. It is noted that instrumentation measures performance of the facility at discrete locations and the data is indicative of trends rather than absolute values. This is particularly important where data is interpreted using assumed constants (e.g. voids ratio assumptions used to interpret gravimetric moisture content or degree of saturation). Artifacts of the trial such as the large pond size relative to the tailings storage cell volume must be carefully considered when assessing and reporting on performance of the stack.

Phase 1

Results from Phase 1 of the trial have shown that through the construction of a substantial basal drain across the facility the tailings achieved an estimated degrees of saturation (Sr) of approximately 75-80 %, Figure 3.

During Phase 1 high suction pressures were recorded in the instruments installed 1 m above the basal drain resulting in an initially low degree of saturation (Sr) from 75 to 80 %. However, with repeated wetting fronts from tailings and sand channel deposition, the tailings immediately above the basal drain became effectively fully saturated. It is likely that the initial high suction pressures were a result of desiccation at the surface of the tailings rather than downward flow into the basal drain, and as further layers of material are placed above, the influence of suction generated by desiccation, and the resultant finger flow evaporation, is lost. Figure 3 shows this general trend of reducing suction pressure development in the lower layer as more tailings are deposited. The data also indicates that air entry of the tailings occurs at around -11 kPa.

It is again noted that the apparent reduction in the degree of saturation is a function of an assumed constant voids ratio where in fact the materials have continued to consolidate. Where the suction transducer ST-C1-001 shows positive pore pressure (or even suctions less than the air entry value), it would suggest fully saturated conditions and as such Sr should be 100 %. Cell A and B showed a similar trend in the results through Phase 1. Since the instruments are in discrete locations from one another and are influenced by operational factors such as pond migration, tailings deposition and wetting fronts, correlations between suction and moisture need to be considered with a degree of judgement.

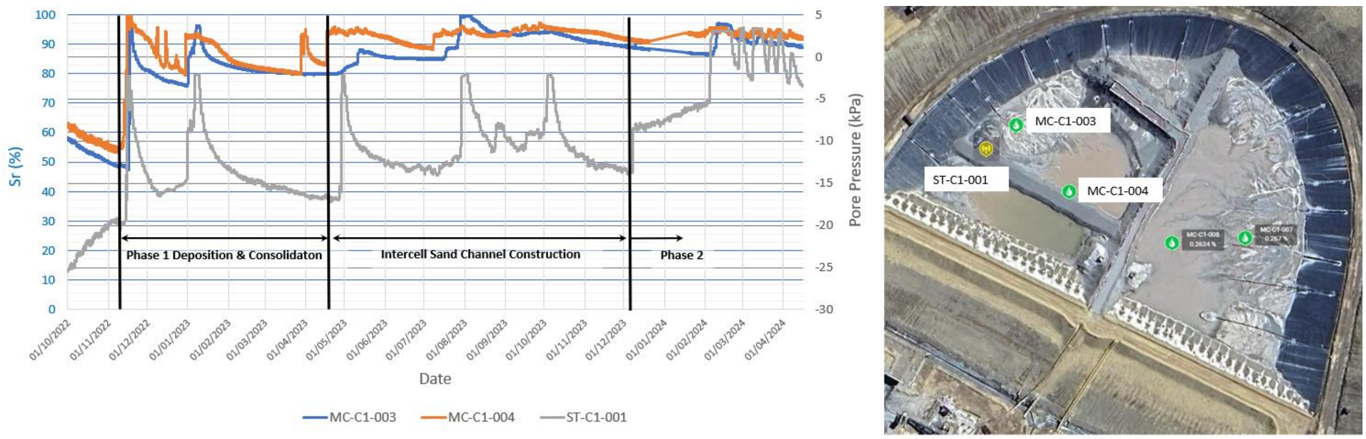

Figure 3: Phase 1 saturation of lower tailings layers (Cell A)

Phase 2

The Phase 2 tailings deposition occurs in Cell A as a continuation of tailings deposited on top of the already placed Phase 1 tailings however, the cell is now subdivided into three sections with intercell sand channels that connect directly to the central sand channel separating the two cells (Cell A and Cell B), Figure 4. Cell B had a circa. 1 m thick sand blanket layer placed on the tailings surface prior to the next 2 m layer of tailings being deposited into the cell.

In Cell A the lower instruments clearly observed wetting fronts passing through the bottom layer of tailings and into the basal drain, as observed from instruments MC-C1-003 and MC-C1-004 shown on Figure 3. Instruments MC-C2-009 and MC-C2-010 installed 1 m into the next layer of tailings, circa 3 m above the basal drain. In this layer suction pressures were maintained even with 2 m of tailings placed above the instruments, Figure 5. In this instance the data has been plotted as the raw volumetric moisture content values reported by the instrument to avoid further ambiguity relating to computed Sr values, but the trends are obvious, and clearly result in very low Sr values which are estimated in the range from about 50 % in MC-C2-009 to 80 % in MC-C2-010 at the end of the data set presented. Further desaturation is expected after deposition ceases since suction pressures were beginning to approach the apparent air entry point of around -11 kPa as the supernatant pond receded.

The results for the second layer of tailings in Cell B show similar results to the lower layer. Since the instruments are approximately 1 m above the placed sand blanket, development of suction pressure is initially high due to desiccation that occurs due to rapid drainage of supernatant water as the tailings consolidate quickly however, as seen in the lower layer, successive material deposition and wetting fronts reduce the ability for the tailings layers to generate suction in this way, thus trending towards high degrees of saturation.

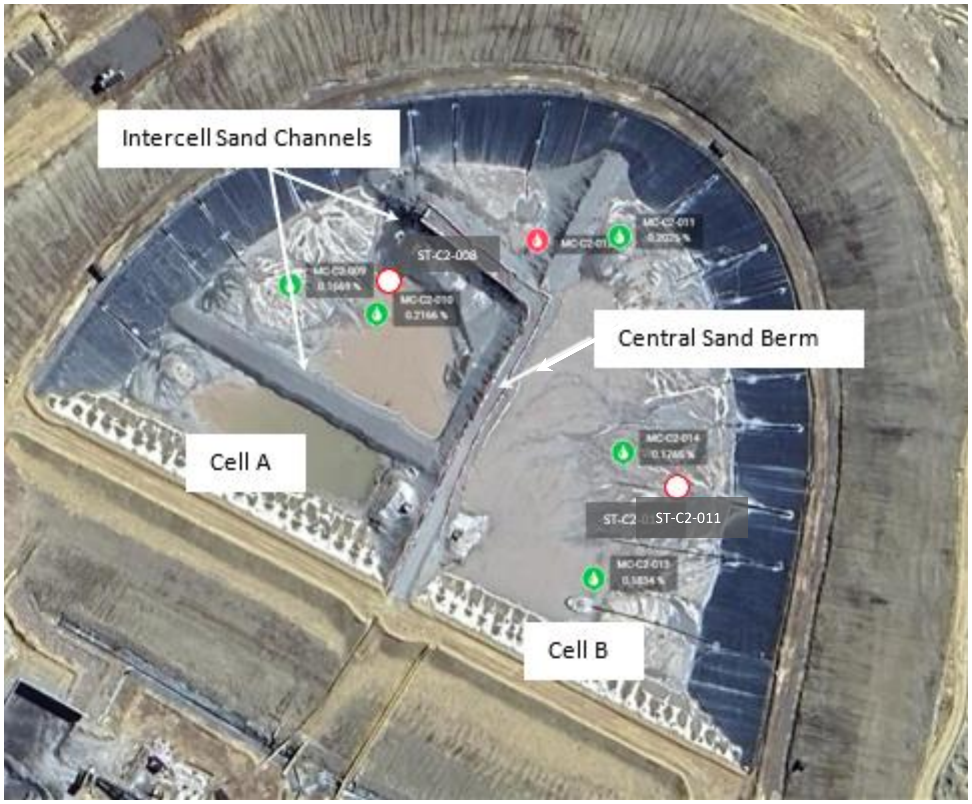

Figure 4: Phase 2 cell layout

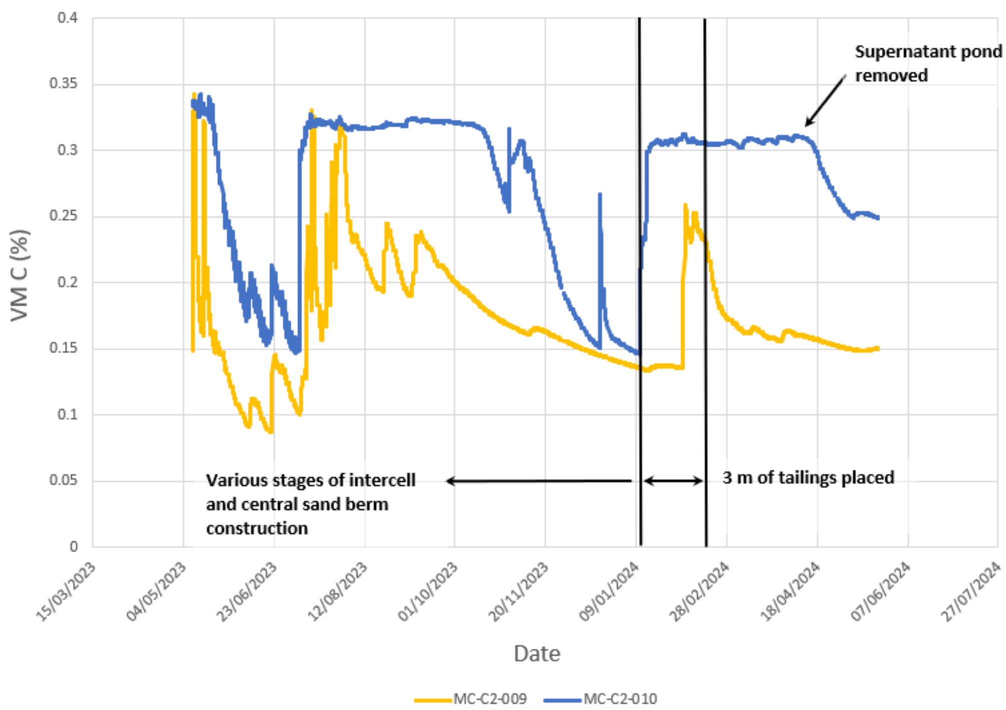

Figure 5: Moisture trends in Phase 2 tailings layers (Cell A)

Results suggest that interbedding layers of tailings with sands aids consolidation but also reduces the ability to generate ongoing gravitational desaturation (i.e. development of matric suction). This is only true where the range of suction pressures generated fall below the air entry value; hence, thicker layers of tailings between sand blankets may ultimately deliver both desaturation and accelerated consolidation. Further analyses would be required to ascertain the optimum conditions for a given tailings material and could ultimately be modelled in proprietary software.

The extent to which the sand channels are aiding the desaturation of the tailings is hard to assess based on the limited discrete instrument data points we have however, extensive geotechnical investigations are planned to take place upon completion of the trial including 42 no. CPTs, 6 boreholes, and extensive sampling for laboratory analyses.

Moving from trials to simulations

Alongside the real time data collection and in preparation for the extensive geotechnical investigation, the demonstration facility is being modelled using Seep/W. The team have conducted an initial model for Phase 1 of the trial in Cell B. This will be extended to Phase 2 and will cover both Cell A and Cell B. Furthermore, the development of a 3D model is intended.

Soil Water Content Characteristics

The soil water content parameters including the soil water content curves (SWCC) were initially established based on the results of the laboratory test results. The predicted air entry value of circa 40 kPa was not observed in the field. The approach by Fredlund-Xing (Fredlund, Xing, 1994) was adopted, which is available as a built-in function within the modelling software used (Seep/W).

The comparison between the two resultant SWCC plots are shown on Figure 6. Fredlund-Xing provides a better correlation of the air entry value to that observed in the field. The specific reasons for the variance are being explored further as part of the ongoing work to build confidence in these modelling tools.

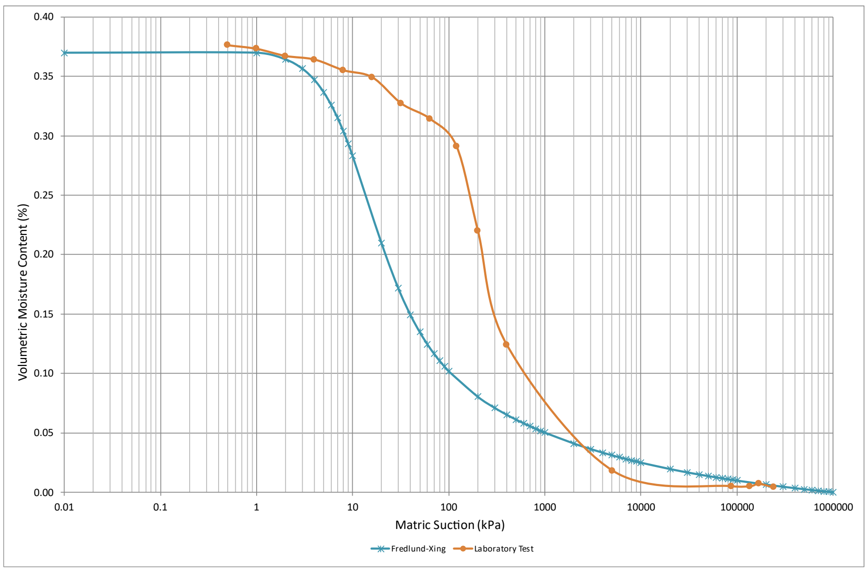

Figure 6: Comparison of matric suctions against volumetric water content for in-situ measurements (blue line) against lab measurements (orange line)

Boundary Conditions

Boundary conditions were derived from field data using real-time on-site photos. Images from the cameras indicated the periods of expansion and contraction of the temporary ponds, and site records of tailings and sand deposition were also used. These are crucial factors in numerical modelling, as they influence the available moisture in the tailings. Additionally, the rate of rise of the gradually increasing tailings levels and the thickness of each modelled layer was found to be critical in achieving comparable results between the models and the field observations. The variation in the results, and particularly the steady-state conditions, between models and field results, for varying modelled layer thickness can be seen in Figure 7. For Cell B, this is considered likely associated with the desaturation due to desiccation, and as such may be less critical to the approach being taken in Cell A. This will be explored further as modelling works continue.

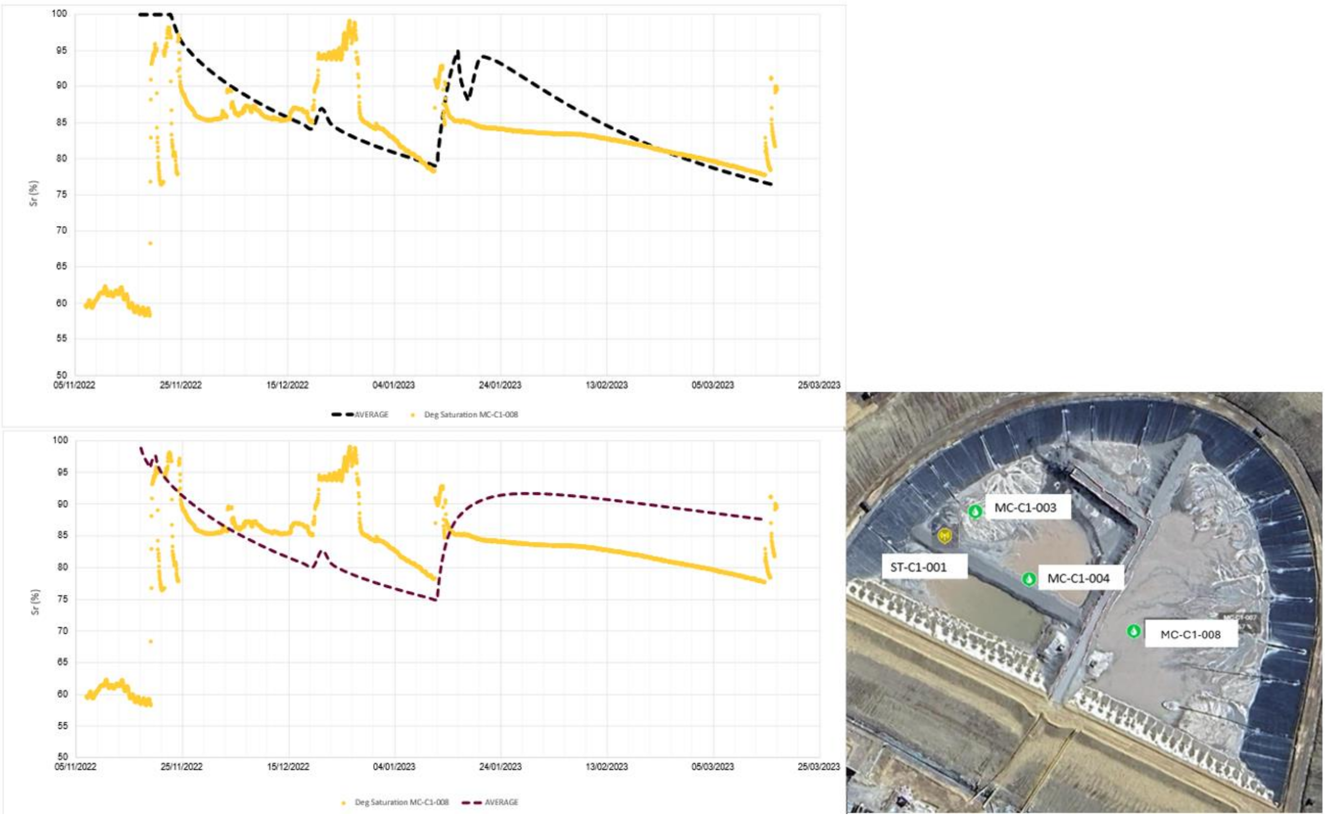

Figure 7: Variation in model calibration due to boundary conditions

Calibration Process

During the calibration process, various parameters were evaluated to identify the most relevant for optimizing the numerical model's performance. A few parameters were found to significantly impact the calibration, and they are detailed in the following sub-sections.

Saturated Hydraulic Conductivity

The saturated hydraulic conductivity of the tailings was analysed to identify the optimal performance ranges. The study considered two relevant phases of the tailings in relation to field conditions: fully saturated tailings during deposition and partially saturated tailings during consolidation. The modifications to the saturated hydraulic conductivities are detailed in the Table 1.

Table 1: Calibrated Saturated Hydraulic Conductivity Parameters

Saturated Hydraulic Conductivity	Original Values	Calibrated Values
Wet Tailings	5e-09 (m/s)	1e-08 (m/s)
Consolidated Tailings	1e-09 (m/s)	5e-08 (m/s)

Saturated Hydraulic Conductivity Anisotropy

A review of images from the field cameras revealed that dewatered tailings desiccate and form cracks. This phenomenon enhances vertical flow in the form of finger flow. Therefore, the anisotropy of saturated conductivity was adjusted to find the optimal range, and a value of 1.1 was found to work better than 1. It is noted that this phenomenon is transient and appears to be more significant than the horizontal drainage for Cell B since the drainage paths to lateral drains are much greater than the vertical drainage paths. It is anticipated that anisotropy will have a more significant impact on the calibration process for Cell A, where anisotropy may be closer to a factor of 10.

Phase 1 Cell A Seep Model Results

Simulation results were extracted, compared with the measured data, and presented in Figure 8.

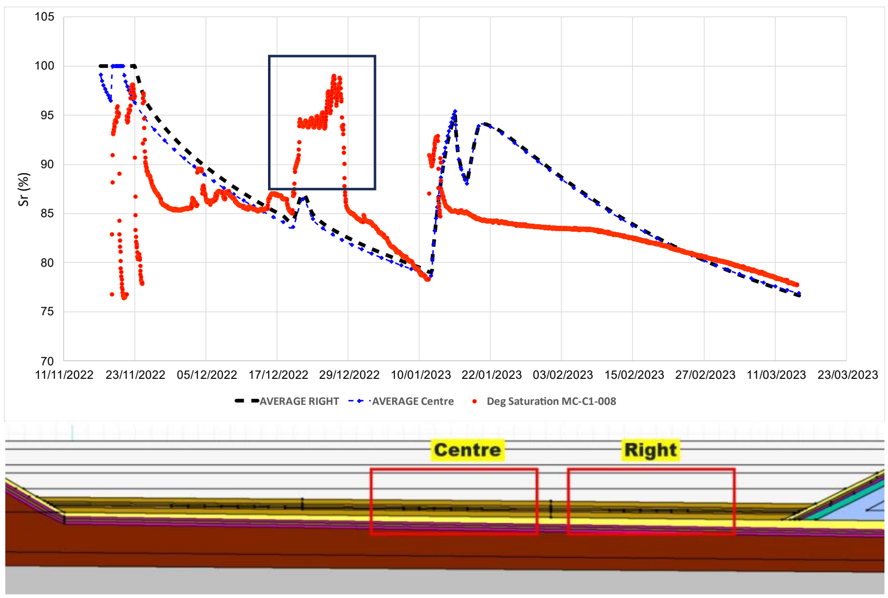

Figure 8: Phase 1 Cell B Calibration Results

The results indicate a good fit for the calibrated model, both in terms of trends and the steady-state condition of tailings during the consolidation period. During a specific period in December 2022, a high degree of saturation was observed, related to cyclone operation with the overflow creating a significant pond area on Cell B. This was ignored in the modelling. During this period there is a significant deviation between the model results and field observation and is boxed out on Figure 8. The calibrated model does not fully represent the measured data during deposition phases and wetting phases, and this discrepancy is attributed to the limitations of the numerical model in simulating finger flow due to surface desiccation and the transient nature of these characteristics. Importantly steady-state conditions show a reasonable degree of alignment.

Conclusions

The HDS trial has exceeded expectations and much of the data has supported the hypothesis that a robust basal drainage layer, coupled with horizontal drainage channels accelerates consolidation and delivers desaturated tailings.

As the demonstration extends vertically, the impacts of the horizontal drainage channels vs sand blankets are becoming more apparent. The generation of matric suction is noted and the impact of discrepancies between lab-tested SWCC parameters and field data needs to be understood further.

The prevalence of drainage paths within a tailings facility will, intuitively, reduce the saturation levels in the co-disposed tailings. Finding the optimum engineering approach is the primary goal of the HDS demonstration team going forward and modelling results show good correlation to date.

Tailings facilities are not currently designed for closure – the ability for HDS to offer a low-cost route to prevalent drainage offers a pathway to a hydraulically placed, yet rapidly desaturated tailings facility. Phase 2 and 3 modelling will allow prediction of in-situ tailings properties that can then be tested during the proposed extensive site investigation planned for Q4 2024. Water will be continually removed through operation stages of the facility. With the development of a robust cover and upon closure, drawdown to steady state seepage flows will be rapid and long-term water management will be significantly reduced. As operational experience continues to develop and additional laboratory and proof of concept testing generates more data, it is hoped that the HDS-Working Group (a community of practice for geotechnical consultants) will facilitate data sharing and accelerate the implementation opportunities for this exciting tailings storage approach.

Acknowledgements

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References

Fredlund DG, Xing A (1994) Equations for the soil-water characteristic curve. Can Geotech J 31 (4): 521-532

Newman P, Bruton M, Burgos J, and Purrington J. (2022) 'Innovations in Tailings Management – Hydraulic "Dry" Stacking', *Tailings and Mine Waste Proceedings*, 2022 Denver, USA.

Newman P, Lopez A, Bruton M, Kulmagambetova A. (2024) 'Hydraulic Dewatered Stacking – Delivering Desaturated Tailings Management without the Capital Cost of *Filtration' International Conference on Tailings Management*, Santiago, Chile.

Terzaghi K, and Peck R B, (1948) '*Soil Mechanics in engineering practice*' Wiley, New York.