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Hydraulic Dewatered Stacking: facilitating faster and value-accretive closure of tailings facilities

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Abstract

Although there is plenty of good justification for progressive closure of tailings facilities as well as a future state desire that sees the industry designing facilities for closure (including risk reduction, financial and societal benefits), this is not necessarily going to be realised at all facilities.

Firstly, there are a myriad of reasons why a facility may not be designed for closure for example the continuous desire to develop and grow a mine's resource estimate and the requirement to meet the storage needs for this new value. Secondly, among many other reasons, not all miners have the luxury of the time and finance to engineer a structure with that end goal in sight, and of course thirdly there are many tailings dams currently in operation where formal closure planning has not been considered beyond a short, conceptualised idea.

So then, closure will likely remain a challenging prospect for a lot of tailings dams into the future.

This paper looks at the potential application and benefits of hydraulic dewatered stacking (HDS) technology in both greenfield and brownfield tailings storage facility applications to enable rapid closure, rehabilitation, and repurposing of otherwise, at best, partially closed and unrehabilitated/ sterilised areas of land.

Keywords: *Tailings, Hydraulic Dewatered Stacking, GISTM, Life Cycle, Saturation, Consolidation, Resistance to Liquefaction*

1 Introduction

Most mine operators/owners will be required to routinely assess the cost to closure for the operation as part of either an operational permit and regulatory bonding requirements, and often as part of capital investment requirements, typically in accordance with the Equator Principles. This is typically required every 3 to 5 years to demonstrate capital reserves will be sufficient to close the mine and rehabilitate it in keeping with the standards and plans agreed to as part of the environmental social impact assessment, stakeholder engagement, and permitting application.

As part of the closure plan all tailings dams will need to be closed with the eventual goal of reaching, at least a form of passive closure, and ideally where proven long-term stability has been achieved, passing on the liability to the state, municipality, or future landowner.

In the first three topics outlined in the Global Industry Standard on Tailings Management (GISTM) (ICMM et al, 2020), closure has been clearly defined as part of the life cycle of the tailings storage facility. Furthermore, the importance of designing and operating for not only closure but post-closure performance is clear.

Tailings dams can be very difficult to close, and more often than not an ongoing liability persists due to the potential consequences associated with the risk of catastrophic failures, particularly where the tailings mass is in a loose state and remains close to full saturation for a long period of time following the end of operations, meaning that the tailings are likely to have a low resistance to static liquefaction and may flow a significant distance in the event of a catastrophic failure of an impoundment wall.

Most traditional hydraulically placed slurry tailings deposits will be in this less than desirable state. Not only is the medium to long-term goal of achieving passive closure difficult to achieve, a state of active closure with the end use land value being realised can also be very difficult. Potential safe access issues can make it difficult to create the final landform, while large quantities of earth materials are often required to achieve landform and cover design requirements due to operational freeboard requirements as well as potentially large settlements occurring in the deep soft tailings mass. The deep deposits of soft tailings can also take a very long time to consolidate due to the often-low permeability of the materials.

Designing for closure would ideally mean that the final state of the tailings mass would have a high resistance to liquefaction either achieved by increasing the density of the tailings or by reducing the degree of saturation. Not only does this reduce the risk of catastrophic failure it also reduces the consequence of such a failure, with failures more akin to slumps and debris fans with greatly reduced impact zones. Prevention of ponding of water on the surface and reducing the potential for a wetting front to re-saturate tailings is critical in achieving this in perpetuity.

1.1 Hydraulic Dewatered Stacking (HDS)

HDS is a patented tailings storage system that utilises engineered co-disposal of a fines-free sand (FFS) and conventional tailings (Newman et al, 2022). The FFS is deposited in contiguous layers and channels and exploits the higher horizontal permeability present in tailings facilities (Naeini et al, 2018). The resulting saturation of the main body of the tailings will fall well below 100%, subject to the mass balance of FFS and tailings; which inherently delivers 3 main sources of value for operations:

- Safety: a desaturated stack reduces the likelihood of a liquefaction failure (Halabi et al, 2022) and also reduces the consequence of any such failure, should it occur.
- Water: proof of concept testing and the full-scale demonstration at El Soldado has delivered very good water recovery, much faster than conventional water recovery
- Legacy: perhaps one of the greatest sources of stakeholder value for HDS is the ability to re-purpose the tailings facility within weeks / months of the last tonne of tailings being deposited.

The idea was developed because of work completed by Anglo American on coarse particle recovery (CPR) which involved a series of pilot trials from 2015 on both copper and platinum tailings. This work culminated in the successful commissioning and operation of the largest CPR unit in the base metals industry at Anglo Americans El Soldado Mine in Chile (Arburo et al, 2022).

Coarse particle recovery is a technology that has been in use for some time, but its application was often limited to tailings scavenging to improve global recovery. However, through incorporating CPR into the mill circuit, there is a possibility to generate a coarse barren tailings (CPR sands) and this raises the possibility of reducing ball mill energy consumption and opening up additional capacity in the conventional flotation circuit – delivering low capex production enhancement opportunities.

The performance of the CPR at El Soldado has exceeded expectations, delivering almost double the planned production increase through the SAG mill along with a slight improvement in total plant recovery (Figure 1).

It should be noted that the CPR process can find itself inserted at various points within the flowsheet; depending on the metallurgy of the deposit, whether it is greenfield or brownfield, and the objective of the mine. However, in all positions, the product is a fines free reject sand – the difference may be the % of fines free sand delivered. In most cases, HDS or separate sand stacking of the CPR sands will deliver additional water to the operation and reduce the tailings liability.

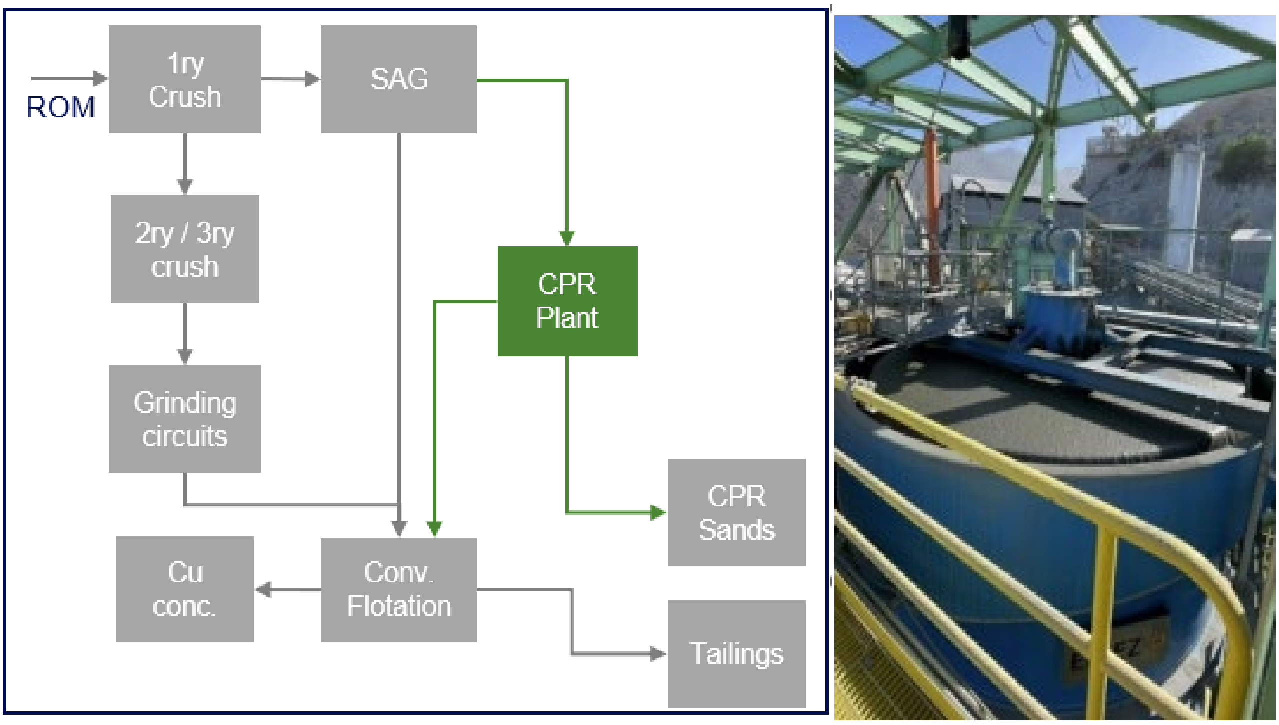

Figure 1 Simplified CPR flowsheet and Hydrofloat® CPR flotation cell

From early testing and small-scale piloting, Anglo American recognised the potential value in water recovery in the fines free reject sand – initially as a material for separate stacking (Filmer et al, 2016; Filmer et al, 2017)) and then in 2019 we hypothesised that these sands could effectively filter the tailings over time when placed into a 3-dimensional drainage matrix within the TSF (Filmer et al, 2020).

The reject sands generated from CPR exhibit remarkable dewatering characteristics, literally draining in real time to a damp sand. Through engagement with WSP, a series of geotechnical tests were developed to understand the design criteria that drive the phenomenon of 'wicking' water from tailings through a compatible sand (derived from the tailings themselves). Proof of concept testing was carried out using a sample of 2-3 tonnes and in 2020, a decision was taken to build an operational-scale HDS trial at our El Soldado Mine in Chile. The subsequent learnings in HDS operation and data all relate to this demonstration, which was commissioned in Q3 2022 and will operate until early 2024.

Our demonstration work has been about understanding the engineering and operational consequences of such a design, in addition to proving the hypothesis.

2 Operation of HDS

The initial HDS concept involved a series of contiguous sand channels, with sand blankets discretely placed across the tailings cells created by these sand channels. Testing of placement methods and further modelling of the dewatering behavior of the tailings suggested that the sand blankets may not be necessary to deliver the performance improvement required to deliver a step change in performance.

Both approaches are currently being tested at the El Soldado demonstration. Figure 2 shows the current set up of the trial, clearly showing how the demonstration design has been modified to test the two approaches to accelerating consolidation/dewatering. Cell A will test the discrete sand channels approach and Cell B will continue with the sand blanket that covers the whole extent of the cell.

Operationally, the sand blanket is more complex to place and although, working with Fraser Alexander Tailings, we have adapted one of their hydraulic mining monitors to create the 'Hydraulic Sand Flinger' there are concerns that this approach, while efficient and fast, may lead to higher water losses in an arid environment. The discrete sand channels may be more operationally robust, but the economics and feasibility (from a mass balance perspective) will depend on the 'zone of influence' from these channels on 'wicking' the moisture from the tailings.

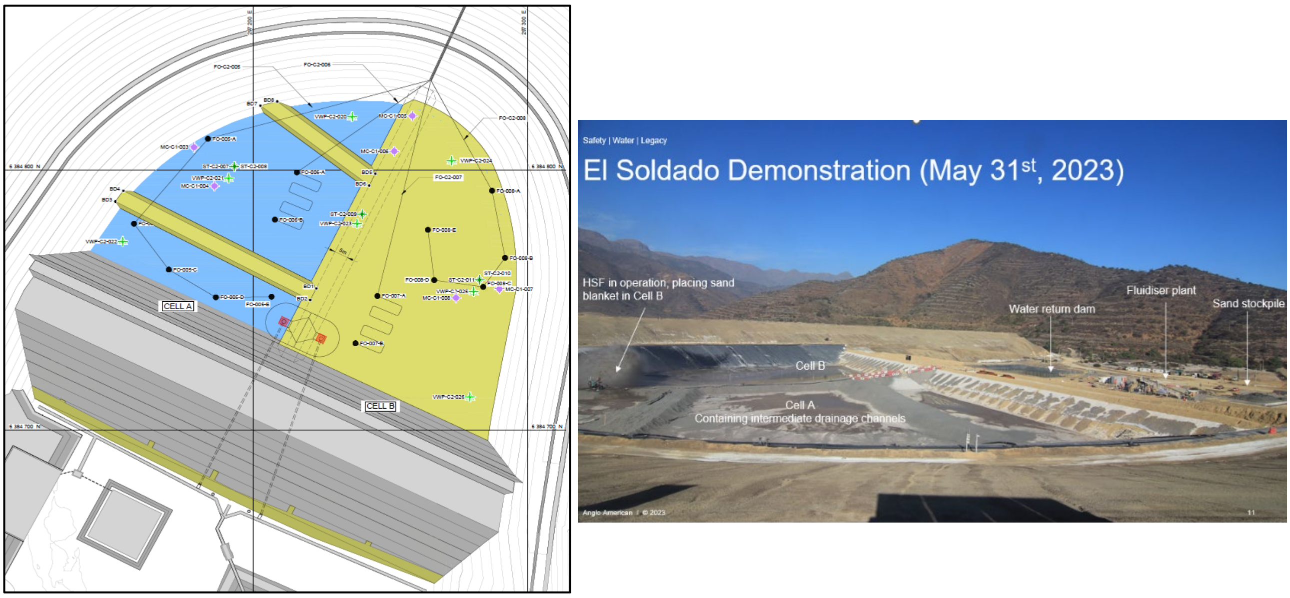

Figure 2 a) Proposed basin design for Phase 2; b) Photograph showing basin layout in May 2023

Reference above to the incredibly rapid dewatering of the sands is borne from the extremely low fines content of <5% passing 75 microns. Figure 3 shows the particle size distribution (PSD) of the El Soldado tailings and CPR sands; and also shown here (blue dashed lines on Figure 3) are the Terzaghi limits of compatibility for the sand (as a filter to the tailings). It is hypothesised that the derivation of the sand from the tailings themselves results in excellent compatibility.

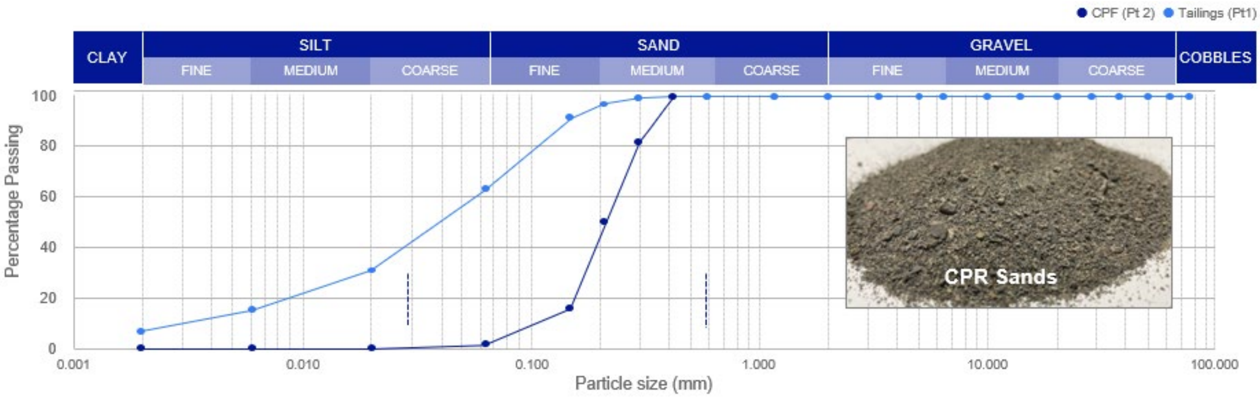

Figure 3 PSD of El Soldado Tailings and CPR sands

HDS exploits the existing distribution system for the tailings, utilising traditional perimeter spigot disposal. Tailings are placed until they are within ~0.2 m of the sand channel crest, and then left to consolidate; the tailings closer to the sand channels consolidate demonstrably more quickly than the tailings more distant (see Section 3).

The above process continues with the sand channels being constructed in 1.5m lifts and the tailings being sequentially placed into the 'paddocks' created by these channels. Water removal is facilitated through these drainage channels which immediately remove the water without saturating – this may not be the case for the lower parts of the channels as the tailings stack rises. The water quality is good, initial (limited) geochemical data suggests that the water quality is on a par with the material currently being reclaimed from the main tailings dam but the main difference is the quantity (more water) and speed (faster) of the water removal.

One of the risks of this approach is the robustness of the interface between the tailings and the sand. Although theoretically, the sands appear to be an excellent match to the tailings, it was critical to understand the actual performance in the field. After the completion of Phase 1 and after consolidation of the tailings was completed, a section of tailings/sand was collected and inspected. Figure 4 shows the results of this sample collection; the interface remains extremely clean (as it was during the proof of concept testing) and an area of higher moisture content is noted in the sands close to the interface layer.

Figure 4 Photograph of tailings/sand interface after consolidation

It is expected that the tailings deposition exploiting the HDS approach will dewater and consolidate faster; Phase 2 and 3 results will be available towards the end of 2023 and will deliver important information for design criteria development for the first commercial applications, expected in 2024/25.

The issue of the final dry density is important and can deliver a significant value driver for the technology; an additional year or more of capacity from a tailings facility can add many billions of dollars of value. The dry density values generated to date have been only slightly higher than those estimated in our existing facility but additional consolidation is likely to occur as the stack evolves.

As a conventional tailings facility approaches closure, thoughts turn to access; to cover the facility and shape a final landform suitable for closure. HDS can deliver an unsaturated tailings facility that facilitates rapid access and the CPR sands that deliver the omnipresent drainage can be stockpiled ahead of closure and provide a ready cover material. Hence the final, and perhaps, greatest source of value is the ability to deliver a rapid and low-cost closure solution that adds real value to local stakeholders. Although a significant source of value, it is difficult to incorporate into conventional NPV/IRR valuation techniques, which discount revenue/cost savings that can be many years into the future. Work is ongoing at a number of levels to better quantify 'Stakeholder Value' and deliver a robust evaluation process that can drive decision-making.

Opportunities for tailings facilities in the future are only constrained by our imagination and although solar power facilities and agriculture are oft-quoted options; the industry needs to continue to challenge itself in terms of how tailings facilities can be designed from the start to add real value to the region.

3 Data collection

3.1 Saturation

HDS exploits much of the existing tailings management infrastructure and is hydraulically placed. Hence it is unlikely that the final state of the tailings mass will be dense enough to be considered resistant to liquefaction, therefore it is necessary to demonstrate that the degree of saturation achieved is commensurate with achieving this desired end state.

A number of different instruments have been used in the field trial to assess the degree of saturation within the stack, with the plan to install these throughout the stack at different levels. The intention being to assess how quickly the steady-state is achieved, the degree of saturation at the steady state, as well as the potential for re-saturation from successive layer placement and the subsequent desaturation achieved.

Three different instrument types have been used for the purposes of assessing saturation: volumetric moisture content probes, suction transducers and self-heating fibre-optics. Further to this, vibrating wire piezometers are used to assess the pore pressures and steady-state hydrostatic head within the stack.

An example of the layout of instrumentation in the first layer of tailings can be seen in Figure 5, with discrete locations throughout the layer being achieved with individual instruments and the broader coverage being achieved with the fibre-optics layouts. Each layer will repeat the arrangement to assess the state of each layer and to enable observation of the wetting fronts passing through the stack.

Unfortunately, the self-heating fibre-optics malfunctioned during initial commissioning and no results were obtained during Phase 1 of the field trial. The equipment has subsequently been repaired and should provide data for future phases of the trial.

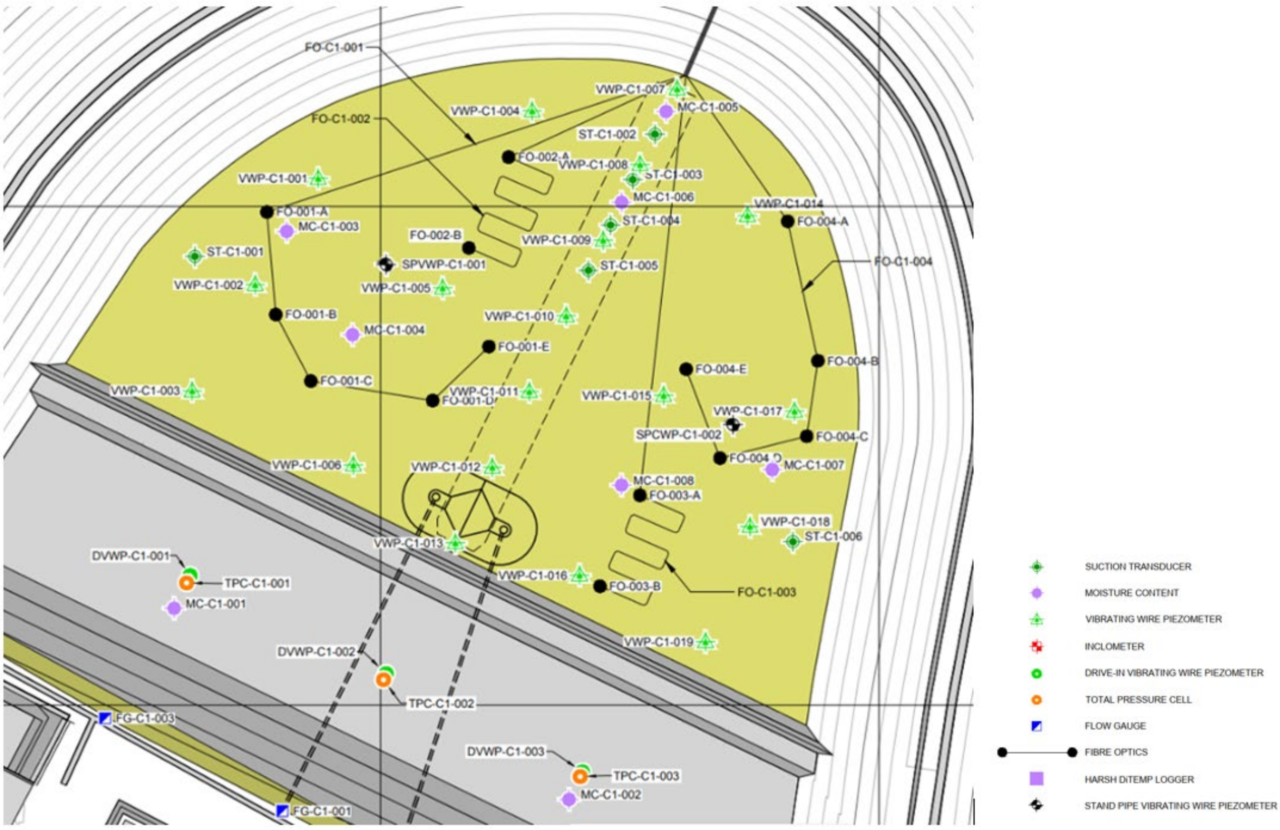

Figure 5 Phase 1 instrumentation layout

3.1.1 Moisture content probes

Moisture content probes show that steady-state moisture content was achieved in the tailings after around 40 days (Figure 6), although some nominal drainage was still ongoing, the majority of the liberated interstitial water had been evacuated from the stack. CPR sands drained down within just a few days of placement in the central sand berm, and the sand blanket drain reached steady-state about 10 days after the tailings above.

Volumetric moisture content probes were calibrated for the tailings and CPR sands in the laboratory at a density of 1.45 t/m^3, as such any variation in density may offer some variance to the calculated moisture content. The results are considered a means to assess variation rather than absolute values, with absolute values to be assessed at the end of the trial with extensive intrusive investigations planned.

In order to estimate the degree of saturation an average in-situ dry density was assessed. A total of five sand replacement tests were conducted in each cell, and a back calculated average density was assessed for each cell from tailings throughput and topographical survey data. The twelve data points were averaged giving a density of 1.52 t/m^3. The reported gravimetric moisture contents were then used to estimate the degree of saturation achieved in the steady-state condition. The degree of saturation from moisture content probes after steady-state conditions had been reached ranged from 72 to 80% with an average value of 76%.

Figure 6 Gravimetric moisture

3.1.2 Suction transducers

Soil water characteristic curves (SWCC) were developed in the laboratory for the tailings (Figure 8) and CPR sands. Suction generated in the stack was monitored and compared with the SWCCs to estimate the degree of saturation.

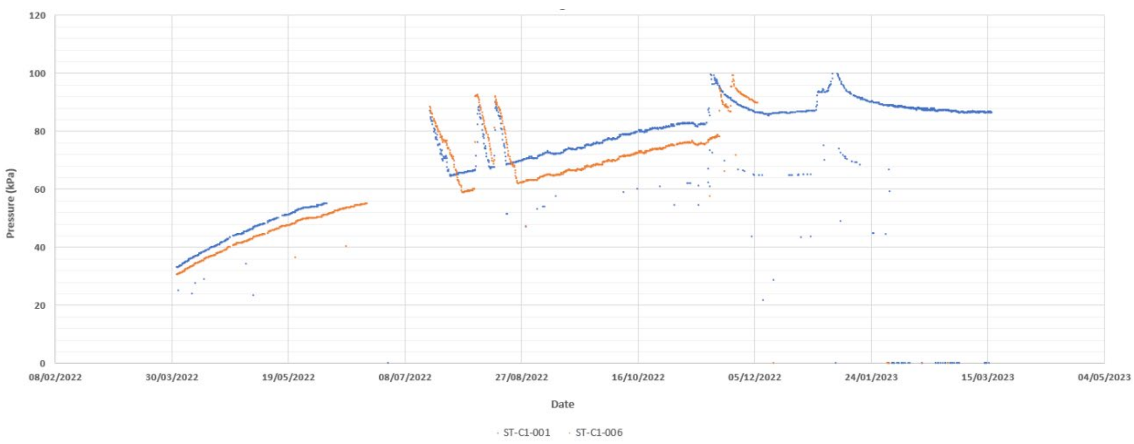

Figure 7 Suction pressures in tailings mass

Suction pressures in the tailings mass peaked during hydraulic deposition and reached steady-state within about 30 days after deposition ceased, see Figure 7. Steady-state pressures were maintained at around 87 kPa, resulting in a moisture content of approximately 16%. Assuming the same conditions as that assumed in the assessments for moisture content probes, the resultant degree of saturation was estimated to be only 54%.

Suction pressures observed in the CPR sands typically remained steady at around 90 kPa to 97 kPa.

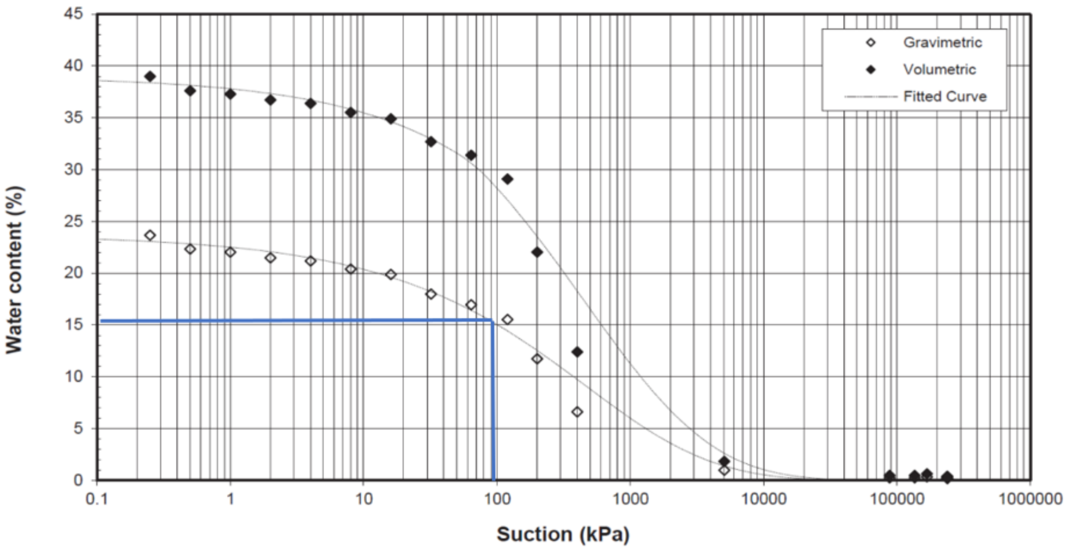

Figure 8 Soil water characteristic curve for copper tailings

3.2 Consolidation

The reduction in the voids ratio of the tailings at closure in the short-term condition is desirable in achieving a significant reduction in the level of risk associated with the potential for and consequence of catastrophic failure.

The estimated voids ratio of the tailings mass was assessed from the in-situ dry density and specific gravity. Based on sand replacement testing at surface, 0.4 m depth and 1.0 m depth, the voids ratio ranged from 0.87 to 0.97 with an average of 0.82 in Cell A and 0.87 to 1.02 with an average of 0.95 in Cell B. Based on the average calculated density of 1.52 t/m^3 the average voids ratio was estimated to be 0.83.

When we compare these values with the consolidation curves from oedometer testing conducted on tailings samples remoulded to a voids ratio of 1.253 based on column settlement testing, we see that the in situ voids ratio is somewhat higher than might have been expected, see Figure 9.

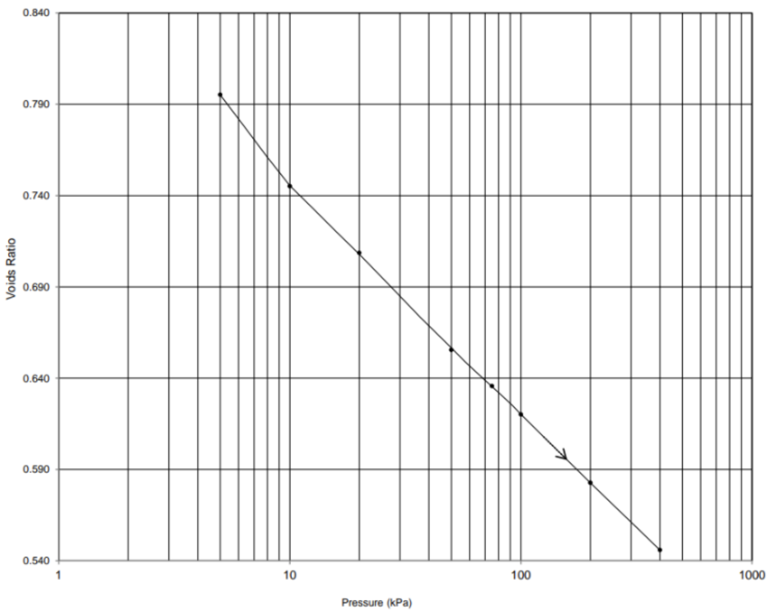

Figure 9 Oedometer test results

It is noted that the theoretical time for completion of 90% consolidation of a 2 m thick layer of tailings with bi-directional drainage, based on the coefficient of consolidation from lab testing in the pressure range of interest, is approximately 103 days; the field voids ratios were assessed much earlier than this as summarised in Table 1.

Table 1 Consolidation rate achieved

	Cell A	**Cell B**
Time of consolidation in field	55 days	41 days
Theoretical degree of consolidation	45%	33%
Field consolidation achieved	80%	54%

Figure 10 shows the settlement of a single point in the tailings surface of Cell A after deposition of tailings ceased. Primary consolidation appears to have been completed within approximately 40 days.

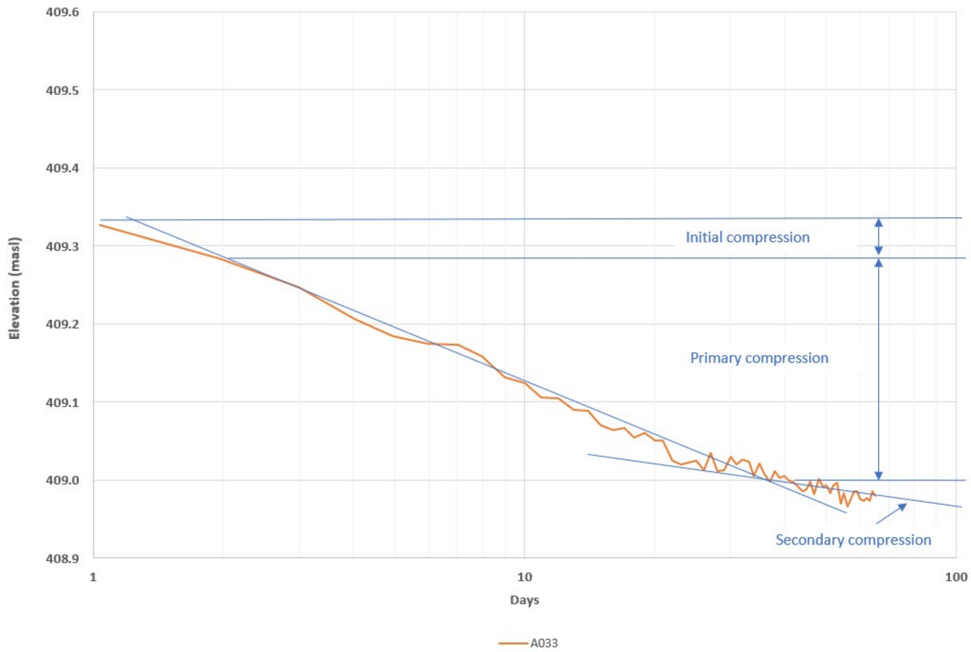

Figure 10 Consolidation rate achieved

This suggests that the rate of consolidation in the field is higher than if we base it on simple 2D drainage assumptions. It is too early in the trial to tell if the achievable voids ratios will improve beyond theoretical values, but this is something that will be of interest as the trial proceeds.

Furthermore, since the rate of consolidation is a function of the square of the drainage path distance, as the trial progresses it will be possible to compare the rate of consolidation achieved for the whole stack and compare this to the theoretical rates that might be achieved if there were no interbedding of tailings and sands.

Analyses of beach settlement from point cloud lidar data obtained daily across the entire tailings surface indicates that within 40 m of a horizontal drainage systems the influence on total consolidation is significant, see Figure 11.

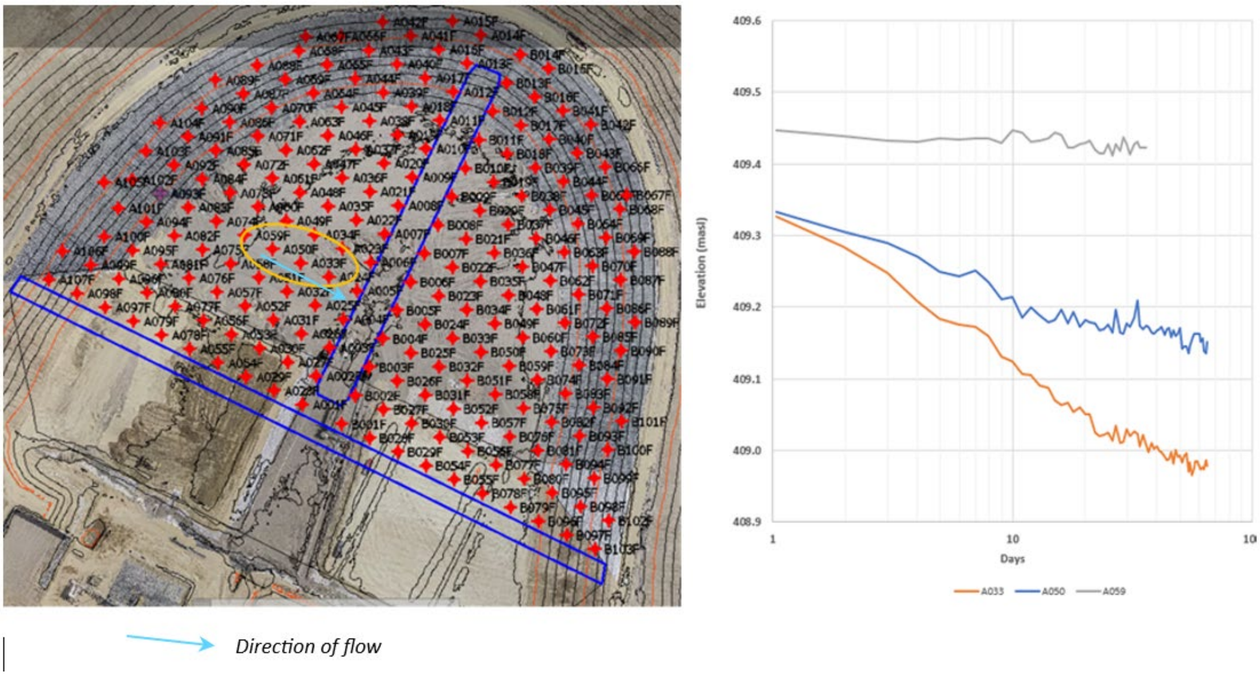

Figure 11 Influence of horizontal drainage on consolidation

3.3 Water balance

A live water balance model takes input flows including process water and precipitation and output flows including seepage from the basal drain and supernatant water flow from the decant structures, measured independently, to estimate the water recovery from the HDS facility. After the first phase of operation, water recovery was at 78% of the process water inflows (recycle), with no remaining supernatant pond on the facility. It is noted that nominal seepage flows from the basal drainage system continued beyond the point at which the next stage of the trial commenced, indicating continue draw down was still ongoing.

4. Discussion

The findings from the first phase of the trial are encouraging, with excellent suction development in tailings and sand layers leading to accelerated consolidation rates and low degree of saturation.

The next phases of the trial will be critical in understanding the potential for interbedded sand layers to interrupt wetting fronts and continue to accelerate consolidation and drainage of tailings enabling rapid closure and repurposing of the facility landform. Interruption of wetting fronts will be key for prevention of long-term recharge from infiltration without the requirement for potentially expensive and challenging impervious covers.

The integral drainage systems including the sand berms (column drains) and interbedded sand layers that discharge via the basal drain system, as well as the supernatant water decant towers provide a means of long-term management of run-off and infiltration recharge and as such should reduce the need for additional measures to be considered at closure.

The application of HDS has been considered at a number of sites at a conceptual level and can be employed in a manner that promotes progressive rehabilitation through the development of cells or paddocks, particularly applicable in valley type arrangements.

The HDS solution has also been considered for application to the vertical expansion of existing tailings storage facilities with the inclusion of a vertical wick drain system in the existing tailings mass to accelerate consolidation of the underlying tailings mass while harvesting water from the interstitial pore spaces. The effectiveness of vertical wick drains appears to extend to approximately 40 m depth of tailings, depending on permeability within reasonable grid spacings not less than 1.5 m apart. Not only would this provide a valuable water resource but would potentially increase water recovery during operation and have the added closure benefits of HDS.

HDS may be considered to form part of the "working smarter" approach to mining, not only offering operational benefits but with clear benefits associated with designing for and work towards closure, see Figure 12.

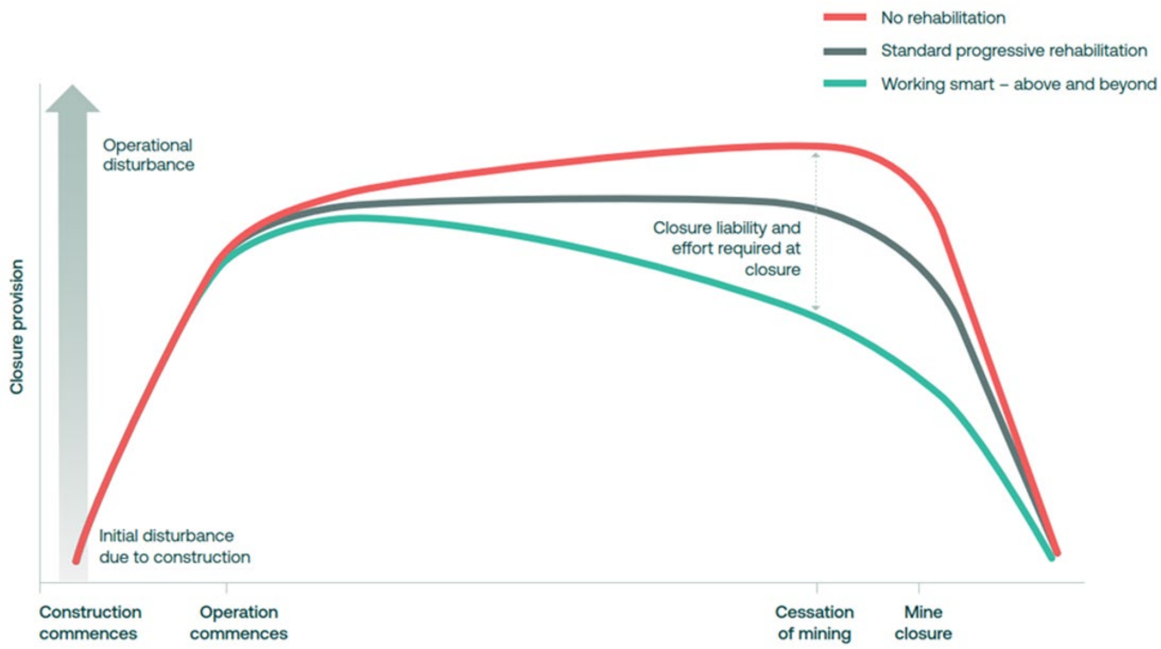

Figure 12 Extract from ICMM Integrated Mine Closure Good Practice Guide, 2nd Edition

5. Conclusion

The following conclusions are drawn:

1. HDS technology and/or separate sand stacking of CPR sands delivers significant optionality for closure of a tailings facility;
2. The ability to gain access within weeks of closure saves significant time and reduces the often onerous requirement for a mine to source and condition very large quantities of fill / waste rock;
3. The technology is still under development although to date the scientific hypothesis of accelerated water removal and desaturation of the tailings appears to be supported by data;
4. Engineering challenges remain and as these are overcome the application of HDS will grow;
5. Even within a brownfield application, HDS has the potential to deliver quick access and facilitate water harvesting from the balance of the facility. This provides much quicker access onto the facility for closure;
6. Start with the end in mind – there is no doubt that HDS (like other stacking technologies) can deliver increased optionality for closure. But, external stakeholders will want to see closure (re-purposing) happening quicker and there is an argument for building a greater number of smaller facilities, that can be re-used (to the value of the local community) more quickly than a closure date that may be many decades in the future;
7. Depending on the local community, topography and other industries – HDS technology can help facilitate a more open dialogue about how to use the tailings generated from a mining operation to benefit the region, rather than put that region at risk, and
8. Smaller, more frequently closed facilities, will incur additional cost but could also reduce the risk of disruption and accelerate the global application of the HDS – primarily to deliver more water recovery but increasingly, to deliver long term value accretive post-closure use.

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