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Successes with Hydraulic Dewatered Stacking at the El Soldado Demonstration Facility

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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 150,000m^3 capacity greenfield tailings facility at the El Soldado Mine in Chile. This paper presents the results of the first 9 months of operation, detailing the lessons learned from the highly instrumented facility.

The demonstration has delivered significant insights on real time moisture content and consolidation monitoring, revealing the zone of influence of the drainage channels. Lessons have been learned on dealing with extensive instrumentation with a view to developing fit-for-purpose real-time monitoring solutions for tailings facilities.

HDS is delivering on the promise shown through PoC testing and modelling and has generated significant interest from the industry. The accelerated roll-out of the technology is under-way, with studies completed or in progress at both AA sites and 3rd party facilities.

1.0 Introduction

The El Soldado HDS Demonstration is an industry first and has enable this new engineered co-disposal approach to be tested in a highly controlled and instrumented environment. The technology was first presented in Newman et al (2022) with a detailed description of the hypothesis, the geotechnical testing, proof of concept and the design of the 150,000m^3 demonstration project in Chile. This paper presents an update on the trial, presenting the conclusions from the successful completion of Phase 1 of the 18 month trial.

2.0 Instrumentation

A wide range of geotechnical monitoring instrumentation has been installed within the HDS to provide real time data on consolidation and dewatering behaviour. In addition to instruments associated with the proof of concept, a series of sensors have been installed to monitor the facility from a dam safety perspective. The sensors are linked through a LoraWAN system to the facilities online dashboard which allows real time data monitoring via an internet connection. The plan location of the Phase 1 instrumentation, installed at various depths of CPR sands and tailings, can be seen in Figure 1.

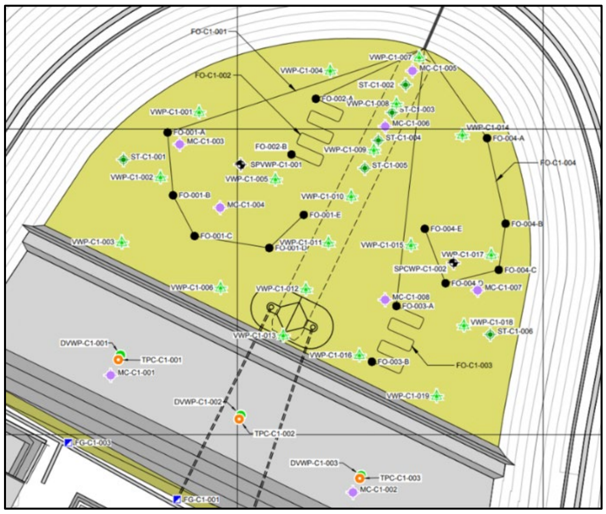

Figure 1 Phase 1 instrumentation plan

2.1 Consolidation

The reduction in tailings void ratio is desirable in achieving a significant reduction in the level of risk associated with the potential for, and consequence of, catastrophic failure. Consolidation of the HDS tailings has been monitored through daily lidar scans using the Leica P60 scanner. As original postulated at the PoC stage, it was known that there would be a correlation between the proximity of the central sand berm and the speed and degree of dewatering of the tailings.

The survey results from Cell A have been considered in this paper. During sequential raise construction of the central sand berm, overflow from the self-propelled cyclone unit (SPCU) was deposited to Cell B resulting in a supernatant pond that restricted survey. Figure 2 presents two lines each plotted through consistently surveyed points. The influence of the central sand berm is clear, and appears to have a significant influence zone of approximately 20 m to 30 m. Furthermore, the proximity to the main wall of the facility appears to have an influence. It is hypothesized that this may be associated with developed suction pressures being maintained for longer due to slower air entry being permitted closer to the outlet of the basal drainage system. This may be inferred from the moisture content probe data presented in Figure 3 where instruments installed closer to the basal drain outlet remain saturated for longer due to the presence of a supernatant pond, with a much slower rate of desaturation associated with the volume of water being evacuated via the basal drains.

The variation in results between the first and second stages of tailings deposition provides an insight into the influence of the anisotropy of the tailings on the rate at which it can dewater. In the first stage the tailings are deposited directly on top of the basal drain, in this period there will be some vertical drainage of the tailings. The results of the second stage of deposition when the fresh slurry is deposited on top of consolidated tailings shows that the impact of distance from central sand berm is more significant. This is likely due to the flow of water laterally through the tailings being the prominent drainage pathway for the material to dewater.

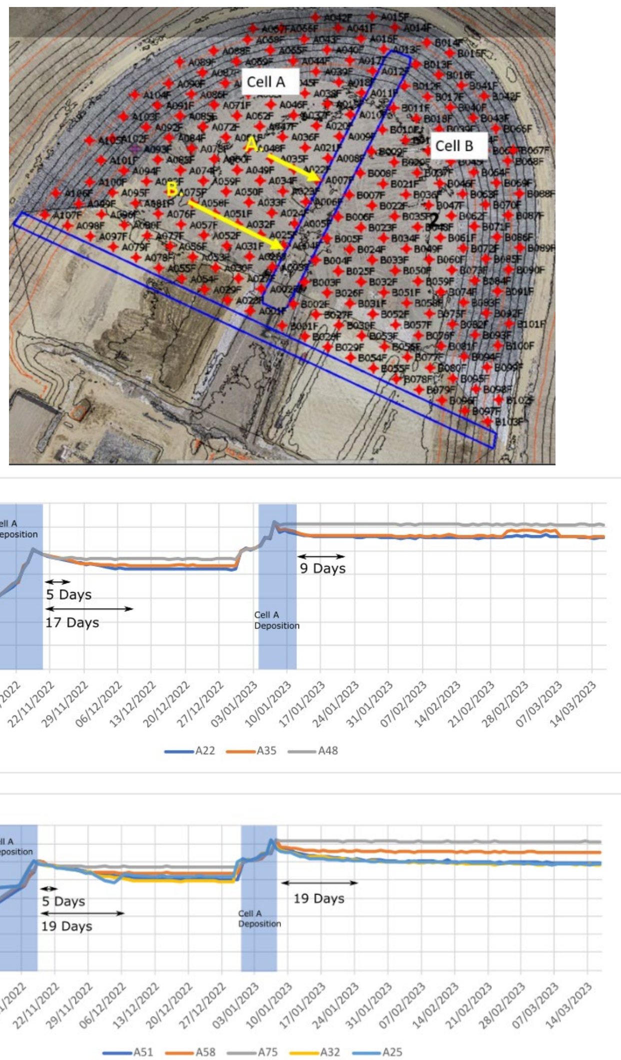

Figure 2 Settlement plots and cell plan

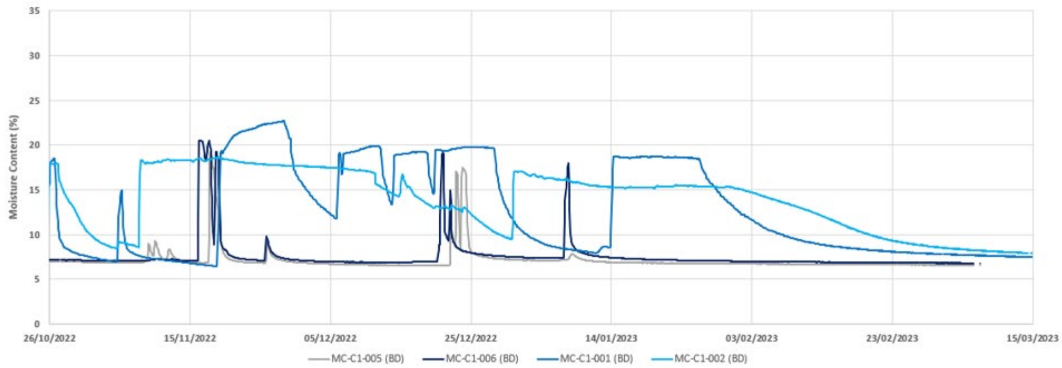

Figure 3 Gravimetric moisture content in basal drain

2.2 Moisture Content

The monitoring of the tailings and CPR sand moisture contents within the stack is paramount to demonstrating the efficacy of the tailings management approach. Moisture content probes and self-heated (active) fibre optics have been employed in the trail for this purpose. Due to a myriad of operational issues with the fibre optics, no data was collected from Phase 1 operations.

Moisture content probes show that steady-state moisture content was achieved in the tailings after around 40 days (Figure 4). Although some nominal drainage was still ongoing, most 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 basal drain reached steady-state about 10 days after the tailings were placed.

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 of in situ density will result in some variance to the reported 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.

To estimate the degree of saturation an average in situ dry density was used. 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 combined average density was calculated at 1.52 t/m^3. The reported gravimetric moisture contents were used to estimate the stead-state degree of saturation for the tailings. The values ranged from 72 to 80% with an average value of 76% across both cells.

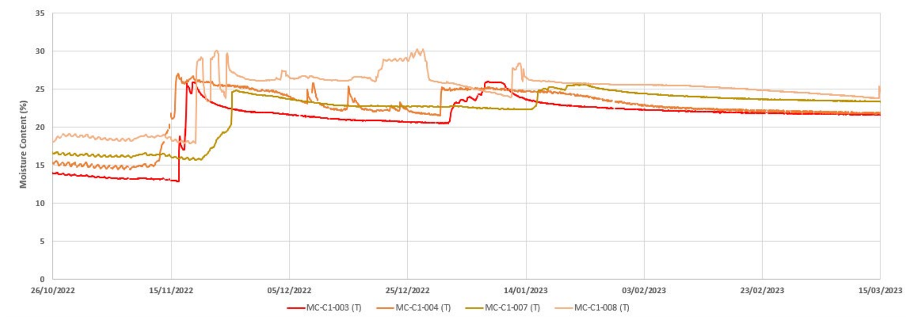

Figure 4 Gravimetric moisture content

2.3 Suction

Suction Transducers were installed within the tailings and central sand berm to provide an understanding of the suctions developed within the stack which will be critical exceeding normal consolidation and provide gravitational dewatering after compression has ceased squeezing water from the pore spaces.

Soil water characteristic curves (SWCC) were developed in the laboratory for the tailings and CPR sands, SWCC for tailings is presented in Figure 5. Suction generated was monitored and compared with the SWCC to estimate the degree of saturation.

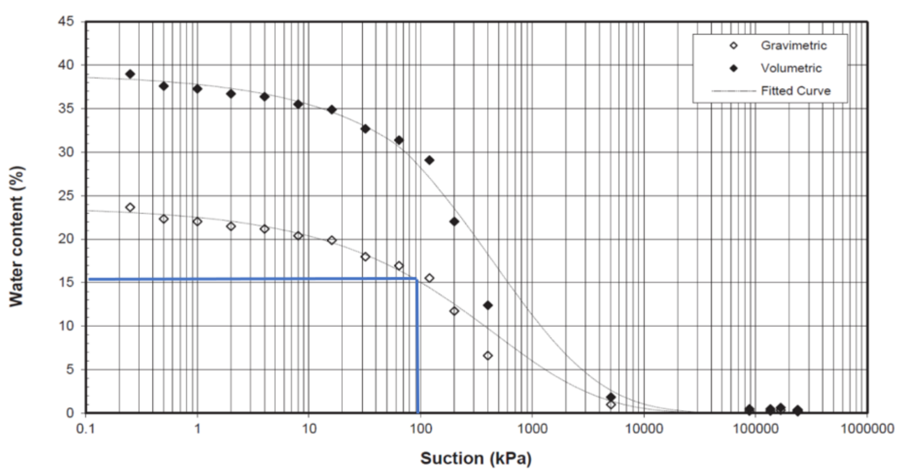

Figure 5 Soil water characteristic curve for copper tailings

Suction pressures in the tailings mass peaked during hydraulic deposition and reached steady-state within about 30 days after deposition ceased, see Figure 6 where blue and green zones indicate periods of tailings deposition and yellow, the placement of the CPR sand berm. 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, resulting in a moisture content of approximately 6 %, similar to the steady-state values observed from moisture content probes. The suction transducers have run into some operational issues that in some cases have rendered the instruments unresponsive. These issues are discussed in the lessons learnt section below.

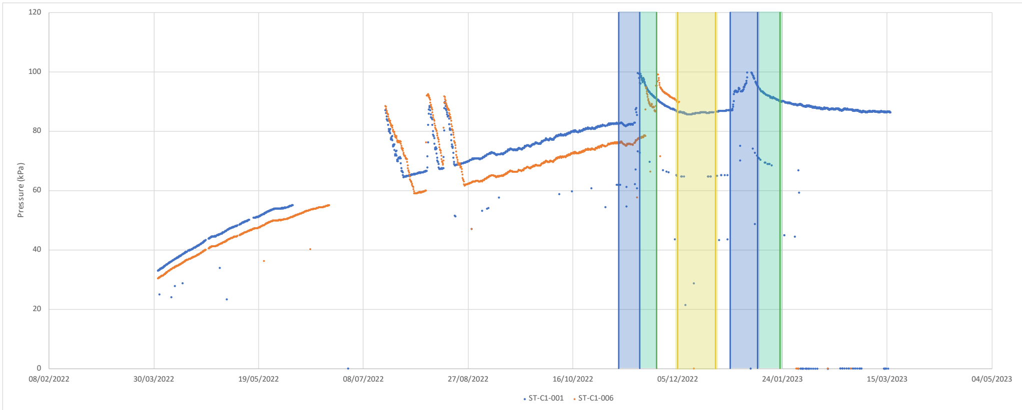

Figure 6 Gravimetric moisture content

2.4 Voids ratio

Based on in situ dry density data discussed earlier, the tailings voids ratio was assessed to range from 0.87 to 0.97 with an average of 0.92 in Cell A and 0.87 to 1.02 with an average of 0.95 in Cell B. Based on the average calculated dry density of 1.52 t/m^3 the average voids ratio was estimated to be 0.83. This is higher than expected from slurry consolidometer test results and will be re-assessed throughout the trial and as part of the post-trial intrusive investigation.

It is noted that the theoretical time for completion of 90% consolidation of a 2 m thick layer of tailings with bi-directional drainage 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%

However, it is noted that the staged deposition of the tailings and three-dimensional nature of the drainage system has an influence on rate of consolidation. Figure 7 shows the settlement of a single point in the tailings surface near the central sand berm in Cell A. After deposition of tailings has ceased, primary consolidation appears to have been complete within approximately 40 days, with t90 perhaps being achieved within 30 days.

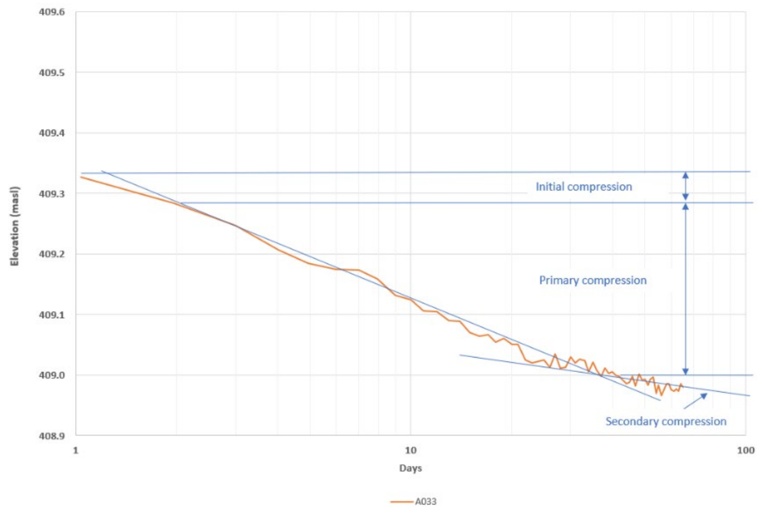

Figure 7 Consolidation rate achieved.

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.

2.5 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.

Phase 1 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 continued draw down was still ongoing.

The moisture content probe readings from the basal drain show that after completion of Phase 1 the basal drain took approximately 30 days to return to a water content comparable to that at the start of the trial. Sensors installed near the perimeter of the basal drain showed rapid dewatering, with a majority occurring over 24 hours. It is therefore anticipated that at the start of the next phase there will be an initial volume of water which is lost to the re-saturation of the basal drain and so initial water balance results are likely to indicate an inferior initial water recovery performance.

2.6 Lessons Learned

Upon completion of Phase 1 several learnings associated with instrumentation have been taken forward, these are discussed below.

2.6.1 Suction Transducers

During the laboratory trials both Teros 32 and 21 suction transducers were implemented, the former are tensiometers and the latter ceramic plate transducers. The results of the testing indicated the tensiometers worked more effectively, primarily due to the ceramic plate devices not gaining sufficient particle plate contact to accurately record suctions. The tensiometers were therefore selected for the field trial.

Over the course of Phase 1 of the trial, of the original six tensiometers installed, the signals from three sensors have been lost and only three remain active, one in the tailings (Cell A) and two in the central sand berm. Error readings from the sensors indicate that the loss of signal is due to a tilting of the sensors, causing them to fall out of the required operational orientation. This may be due to differential settlement within the cells causing a rotation and movement of the sensor.

In addition to the issue of sensor tilt, it is worth noting that the values recorded in the sensors are at the upper limit of the suction pressures that the sensors are capable of recording. When suction pressures around 92 kPa and higher are applied to the water stored in the tip of the tensiometer water may begin to evaporate and cause a desaturation of the tip. Once desaturated the resaturation of the sensor would require manual refilling, which due to the nature of the trial (the sensors are buried) is not possible.

One of the findings of the trial is that the suction transducers that are currently available in the market are not designed for the purpose we require. The need to re-saturate through manual refilling is something that renders the sensors not suitable for use where monitoring the degree of saturation is an important parameter. An alternative of using vibrating wire piezometers with low to negative pressures was also discounted due to the likelihood of high pressures being experienced over the course of the trial that would result in a failure of the diaphragm within the sensor. Refillable solutions are also present within the market, but the use of these sensors hinges on borehole installation and so could only be installed following completion of the trial, this therefore misses the operational phase where the results are most important however, these may be suitable for full scale operational applications.

2.6.2 Fibre Optics

The use of active fibre optics to provide a gauge for spatial variations in moisture content across each of the tailings cells has to date been unsuccessful. The equipment provided by SMARTEC has encountered several problems. Initially a failure of the hardware on the first day of operations resulted in a loss of data for most of the trial to date. Upon reinstallation inconsistencies between available power and power draw from the system resulted in outages and loss of readings, this combined with a complex rebooting process resulted in additional data loss. To date only a nominal number of readings have been recorded by the equipment, instead of the planned daily measurements over the project.

2.6.3 Sensors vs Samples

In addition to the results of the moisture content probes and suction transducers tailings samples were collected to conduct laboratory testing of the moisture content to correlate with the sensor results.

The sampling of the tailings generally shows a lower moisture content (6 – 21 %) than the results of the probes (20 – 24 %), but most of these samples were collected in the outer edges of the facility where drainage and dewatering would be anticipated to be greater. The suction transducers and moisture content probes have shown good conformance when calibrated.

Additional Phase 1 samples have been collected to cover a wider area of the cell and to try to observe any additional variation in in-situ moisture contents. For the following phases of the trial additional sampling will be conducted to provide greater confidence in the results.

2.6.4 Pond Operations

Due to the small trial area the development of the operational pond across the cells impacts the availability of beach surface for lidar surveys. This is not anticipated to be an issue for full scale operation since the ratio of pond area to beach will be much smaller and it is unlikely that surveys would be carried out more frequently than on a monthly timestep. Furthermore, the lidar solution employed would likely be replaced by a point cloud solution for comparison of surfaces rather than the individual fixed point survey system employed for the purposes of the trial.

2.7 Ground Investigation

Following the completion of the trial a ground investigation campaign will be completed. The campaign will consist of cone penetration testing combined with Mostap high quality sampling and a series of boreholes and undisturbed sampling techniques. The investigation will be aimed at providing data on the resultant in-situ state of the tailings and CPR sands. This will then be compared to instrumentation data and used in the calibration of unsaturated flow seepage models.

3.0 Industrial scale evaluation for HDS

The remaining challenge for the technology is the implementation of the system within a continuous and dynamic operational environment, incorporating flexibility and robustness to deal with the typical contingencies present in a modern-day mining operation. Ongoing studies at both Cu and PGM operations has shown that the HDS methodology can be flexible and adapted to the realities of each operation depending on its characteristics. Greenfield or brownfield projects, conventional or thickened tailings, with or without a CPR plant and different tailings PSDs all impact the physical and economic feasibility. In short, the analysis must be carried out on a case-by-case basis.

In presentations and discussions on the suitability of HDS for a particular asset, questions regarding the economics are often asked and, for the sake of clarity an indicative case study is presented below.

3.1 Concept study for a brownfield copper mine with a CPR plant

For the purposes of this case study the following mine characteristics have been assumed:

- Brownfield, large scale copper mine that incorporates CPR within the flowsheet
- Throughput: ~120 ktpd
- CPR sands produced: ~1500 tph
- Sands required for wall construction: ~500 tph

3.1.1 Solution:

Most large scale copper mines incorporate cycloned sand for dam construction and if this too high, it might result in a lack of sands for a total or partial HDS approach at the site. In this case study, there is sand required for wall construction (for the existing TSF), but there remains sufficient sands to generate an independent sand stack inside the existing TSF footprint. Such a sand stack will operate as a sand "lung" that will allow the rapid water recovery liberated from the sands once they are discharged (through a drainage system); the sands will be hydraulically transported directly from the CPR plant to the stack. This sand stack can also act as a evaporation-free water storage facility (see below).

As the facility continues to expand, HDS sand drainage channels connected to the sand stack will be built to capture water and draw it towards this catchment point (Figure 8). The channels will extend towards the centre of the TSF basin, implementing the HDS method in that area, with the channels acting to "wick" the water contained in the tailings discharged between the sand channels (similar to a paddock-type operation).

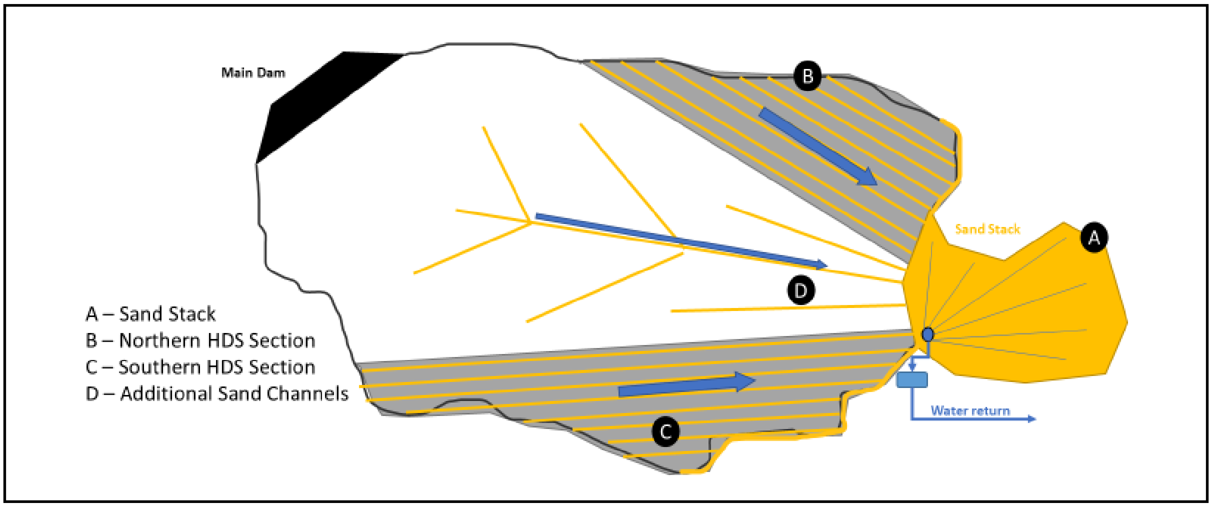

Figure 8 Possible brownfield TSF application of HDS Technologies (Sand Stack + HDS)

Having a mixed configuration, sand stack/HDS, is an attractive alternative for cases where there is sufficient sand and has the benefit of giving greater flexibility to the overall operation of the TSF. The construction and operation of a sand stack is simple and offers operational contingency should HDS drainage channel construction be disrupted in any way. In addition, the sand stack, due to its high permeability, can eventually operate as a water reservoir (within its void space, as a *fake* aquifer), storing water inside the TSF without exposure to evaporation.

3.1.2 Results

A high-level water balance focused on the reduction in the retention losses in the stack and HDS area result in 100 to 140 l/s of extra available water that can be recovered. The Opex related to the sand stack and HDS operation is around 2.5-3.5 USD/m^3. Alternative solutions for fresh water supply are estimated within a range of 6.5-9.0 USD/m^3, so the benefit can be calculated:

- Water recovery: 120 l/s
- Water benefit: ~3.8M m3/year
- Potential savings: ~15-20 MUSD/year (nominal value)

With the conceptual capital cost estimate, the NPV is positive which is highly encouraging given the expected higher operating cost of HDS and the fact that additional intangible benefits are not currently included in the analysis.

These benefits include reduced risk, significantly reduced closure cost, and improved resilience against water related production disruption.

3.2 HDS technology options where sand availability is low

According to information available to date, the implementation of HDS Technologies requires 15-20% sand as a proportion of the total tailings produced (this should always be evaluated on a case-by-case basis depending on tailings characterization). For scenarios where the amount of sand is not sufficient (due to a fine grind, or if significant quantities of sand are required for wall construction), there are alternatives that allow to still make an attractive business case, through the partial adoption of HDS Technologies.

If the availability of sand does not allow the construction of the necessary number of channels to achieve the optimum distance, the channels could be constructed at a greater distance, accepting that a strip of saturated tailings will remain unaffected within the HDS area (Figure 9), or will take longer to dewater. The resultant facility will still deliver an increase in water recovery, and a reduction in liquefaction risk.

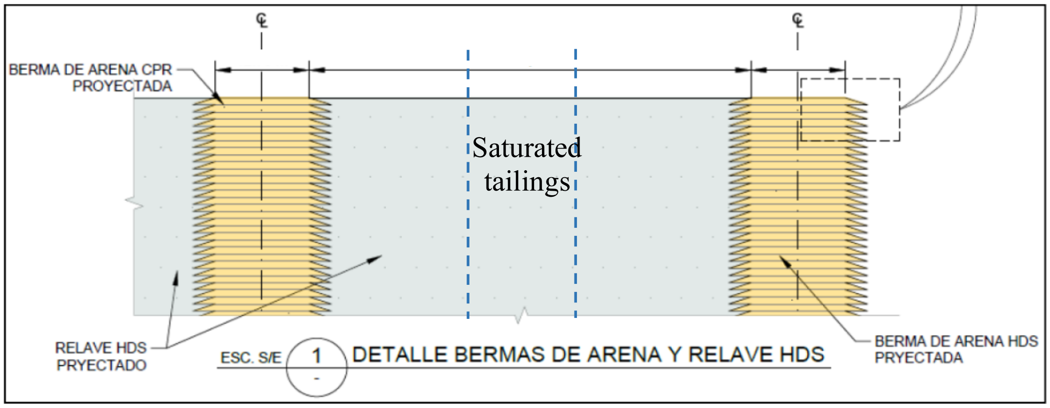

Figure 9 Partial HDS application can still deliver benefits

3.3 Sand Stack as a "Store and release aquifer"

In cases where the preferred solution is to independently store the fines-free-sands in a sand stack, and provided that the stack is not located in a sensitive area of the TSF and does not have a structural function (containment) then the stack can be used as a natural water reservoir (similar to an aquifer), storing the water between its pores within the TSF, reducing evaporation losses.

This alternative is especially attractive in arid areas with high levels of evapotranspiration and water scarcity, however if the tailings have the potential to generate acid drainage (PAG) this alternative should be analysed carefully or discarded if it poses a risk to the chemical stability of the facility.

3.4 Which are the best scenarios for HDS application?

Understanding that HDS applicability should be developed on a case-by-case basis and being cognisant that only a few simple and inexpensive tests are required to get an initial evaluation completed, we provide here some key aspects of an operation that improve the likelihood of an HDS approach being feasible:

- The current or proposed adoption of CPR within the process flowsheet – there are several different scenarios for CPR; and all of these increase the feasibility of HDS.
- In the absence of a CPR plant, the D80 of the flotation tailings should exceed 150u.
- The TSF containment structure is built with borrow or waste material (not with tailings-sands)
- The TSF does not require a containment structure (closed valley, or an old open-pit for example)
- The TSF is a large upstream facility (non-seismic area). In this case we presume that sand requirement for wall construction is low.
- The site is an arid/desert area, with high levels of evaporation, or water scarcity problems. In those cases, even a partial HDS approach will reduce water losses and generate value.
- Very large TSFs where it is possible to at least apply a partial HDS solution, combining a separate sand stack and HDS as a collector of rapidly drained water from the ongoing tailings deposition.

4.0 Conclusion

Although the large-scale field trial is in the early stages of development some key findings may already be drawn out of the results presented. It appears that suction pressures generated in the stack are leading to a significantly reduced steady-state degree of saturation in the tailings mass and CPR sand layers. The hope is that subsequent to further tailings deposition, the suction pressures will result in a similar degree of saturation being achieved in Phase 2 and 3.

The horizontal proximity to drainage channels appears to be a significant factor in increasing the degree of consolidation. This is likely to be a function of shortened drainage path and anisotropy of the placed tailings. Comparison of Cell A and Cell B through Phase 2 and 3 will provide greater clarity on the benefits of promoting horizontal drainage paths, where Cell A will utilise contiguous sand berms while Cell B will maintain the interbedded sand blanket approach.

While instrumentation is important in assessing the performance of the trial, post trial geotechnical investigations will be critical in understand the true in situ state of the stack. Upon completion of the trial and investigations calibration of the unsaturated seepage models developed for the trial will be critical in determining both the repeatability of design using proprietary tools as well as the reliance on instrumentation at full scale operation in assessing performance in line with design expectations.

5.0 Acknowledgements

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6.0 References

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