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Laboratory Scale Tests - Hydraulic Dewatered Stacking (HDS) Technology - Anglo American Chile

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ABSTRACT

The increase in water recovery from tailings storage facilities (TSF) allows for a sustainable use of water within the life of mine while generating a series of benefits associated with the physical and chemical stability of the structure. There are various type of technologies designed to increase the recovery of water from integral or full stream tailings prior deposition, e.g. use of filters, high capacity thickeners, etc. However, there are limited options when it comes to recover water from already deposited tailings.

In this context, Anglo American has developed a system called Hydraulic Dewatered Stacking (HDS) that increases the rate of consolidation of fresh tailings and the rate of recovery of the drained water. This patented technology takes advantage of soil mechanics principles, consolidation phenomena, and compressibility and size distribution of the tailings while reducing overall costs in the implementation of the technology.

During initial trials of the HDS, Anglo American commissioned the Universidad Técnica Federico Santa María (UTFSM) to carry out HDS tests in the laboratory using a 1.6 m high consolidation chamber under controlled laboratory conditions. The tests assessed the performance of the technology in terms of consolidation rates, desaturation of tailings and water balance. Similarly, the response of the materials and the evolution of physical properties and soil conditions were continuously monitored: piezometric head, total pressures, volumetric water content, unit weight, suction and temperature.

This article presents the main characteristics of the HDS technology, and the results of the laboratory tests carried out at UTFSM with emphasis on consolidation phenomena and water balance.

INTRODUCTION

Design, construction, operation and closure of tailings storage facilities are best implemented when risk is assessed, managed and informed. Implementation of good engineering practices for a Tailings Storage Facility (TSF) for the life of mine is of paramount importance for the mining industry. The recent publication of several Guidelines and Standards (e.g. the Global Industry Standard on Tailings Management, GISTM) have highlighted the need for proper management of tailings storage facilities with focus not only on physical stability (for identified potential failure modes) but also on rational use of resources such as water.

The concentration of minerals results in a substantial amount of slurry tailings which are typically at a low concentration of solids content. Dewatering of tailings through thickening (using high-capacity thickeners or filter presses) is implemented in most, or all cases, in large mining operations. Thickening results in significant improvements in solids content, however, tailings upon discharge in the TFS are still fully saturated and release significant amount of water due to sedimentation and consolidation.

The balance of water in the facility depends on various phenomena, such as evaporation, water retained in tailings matrix (in a saturated or partially saturated condition), water in the pond, collected seepage, additional water entering the facility, and infiltration to the subsoil. Once the tailings are deposited there exist limited options to recover water from tailings entrainment. In the context of water scarcity, there has been few isolated technologies implemented for this purpose, e.g. the use of electrokinetics, controlled blasting to increase pore water pressure, use of local wick drains and pumping from boreholes, among others (e.g. Davies et al. 2010). Although some results are promising (e.g. application of electrokinetic at low power consumption), the cost-effective scalability of these technologies to meet global requirements of large TSF is still uncertain.

In this context, Anglo American has developed a system called Hydraulic Dewatered Stacking (HDS) technology that increases the rate of consolidation of fresh tailings and the rate of recovery of the interstitial water. This patented technology takes advantage of soil mechanics principles, consolidation phenomena, and compressibility and size distribution of the tailings while reducing overall costs in the implementation of the technology.

ABOUT THE HDS SYSTEM

With more than 80 per cent of Anglo American's assets globally located in water-constrained areas, the company is aiming to achieve closed loop operations with respect to water, targeting a 50% reduction in fresh water withdrawals in water scarce areas. HDS is part of the initiative FutureSmart Mining™ which is an innovation-led approach to mining as to decrease mining footprint.

HDS uses Coarse Particle Recovery (CPR), which delivers a coarse well graded sandy reject prior to final flotation in base metal sulphides, to create preferential flow paths within a tailings mass. The CPR interbedded within tailings is aimed to accelerate consolidation and desaturation of the tailings material. The technology is expected to increase stability of the facility (through mitigation of liquefaction risk), improved water recovery, encourage air entry into the soil matrix, decrease seepage to subsoil, reduce cost over other technologies such as filtered tailings, improve storage capacity and facilitate closure of the facility, among others.

The HDS concept involves construction of several vertical and horizontal drainage channels, eventually connected with contiguous planar drains, across a tailings facility, as shown in Figure 1.

The CPR sands are low fines materials (less than 5% particles <100µm) and are deemed free draining under gravity in comparison to fine grained tailings.

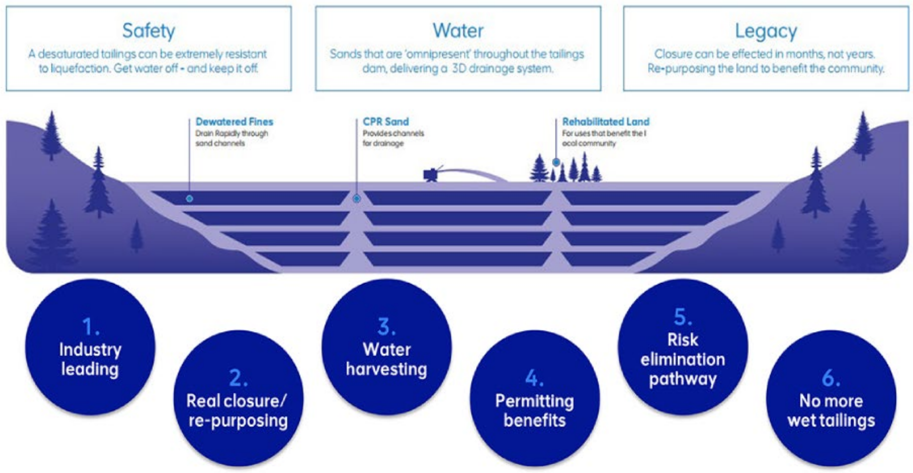

Figure 1 Schematic of the HDS technology.

The HDS concept was developed by Anglo American and WSP Golder in 2019. The proof of concept included numerical modelling and large-scale laboratory trials which were conducted at Universidad Técnica Federico Santa Maria (UTFSM) in 2021. In the laboratory, the HDS performance was assessed based on key performance criteria such as desaturation capacity, total stress distribution, seepage rates and water balance as to ascertain how well the interbedded tailings and sand lenses may drain in a field scale operation. In 2022 a large-scale demonstration facility started, and a 150,000 m^3 capacity HDS tailings facility commissioned at El Soldado copper mine in Chile.

In this article, the results from laboratory test at UTFSM are presented and discussed.

In a separate article, the experience gained at El Soldado implementing the technology is presented.

METHODOLOGY

Performance Criteria

The intent of the tests conducted at UTFSM were as follows:

- Verify that HDS can effectively shorten flow distances during consolidation, accelerating the dewatering of tailings, and improving water recovery.
- Establish if tailings can undergo significant desaturation and develop matric suction below the air entry value or equivalent to saturation degrees below 80%. If this is observed, the material is unlikely to liquefy upon cyclic loading, i.e. Cyclic Resistance Ratio should double at this saturation (Yoshimi et al. 1989). This is preliminary assumption.

Large Cell Apparatus

As to reproduce the use of HDS in the field, a large consolidation chamber was implemented and commissioned in the Geotechnical Laboratory at UTFSM. The benefits of interbedding compacted CPR sand layers within fine-grained tailings on consolidation of material mass was explored through instrumentation of the cell. Original design of the cell was proposed by Golder (2020) and the laboratory aspects described in the PhD Thesis by E.A. Torghabeh (2013) considered within the approach. Modifications of the cell were also undertaken by UTFSM to improve the concept.

A schematic of the cell apparatus is provided in Figure 2. The cell consists in three square compartments of transparent Perspex of 1.0 m x 1.0 m and 0.5 m in height, which are piled on to form a 1.5 m chamber. An approximate 1/10th vertical scale was selected with interbedded layers of CPR sands 150 mm thick and layers of tailings 350 mm thick. Three 500 mm layers are to be formed.

The compartments are connected through steel beams and bolts which are supported by a steel frame that provides stability to the assembly but allow visual monitoring of the test and free access to instruments and sensors. A total of 32 horizontal outlets are located on cell walls while 4 holes are located at the bottom of the cell. Drainage through valves is regulated using valves protected with a porous stone and filter paper (Figure 2).

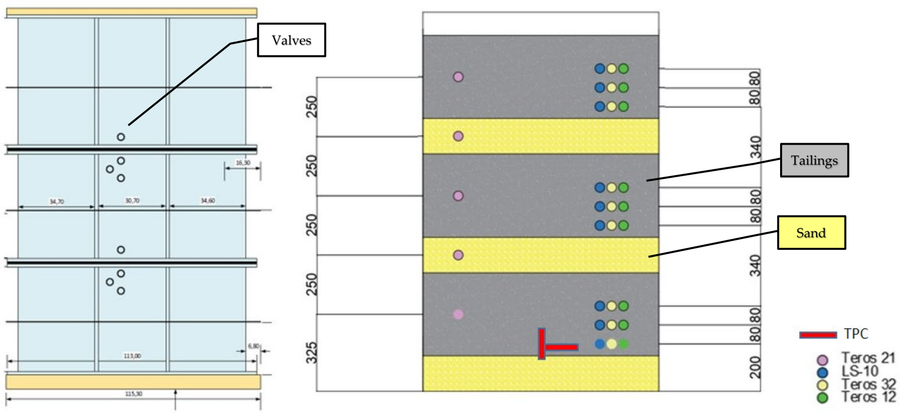

Figure 2 Schematic representation of large cell apparatus.

The equipment monitors the following variables: settlement, pore water pressure, matric suction, water and volumetric water content, and horizontal and vertical stresses. The apparatus was fitted with a large array of instruments as summarised in Table 1. Measurements from the instruments were taken hourly using a datalogger.

Table 1 Characteristic and specification of sensors used in HDS large chamber in laboratory.

Sensor	Variable	Range	Resolution
Teros 32	Matric Suction	85-50 (kPa)	0.00012 (kPa)
Teros 21	Matric Suction	5-100.000 (kPa)	0.1 (kPa)
Teros 12	Volumetric Water Content	0-0.7 (m^3/m^3)	0.001 (m^3/m^3)
LS-10	Piezometric head	0-0.25 (Bar)	0.0001 (Bar)
Total Pressure Cell: VWTPC-4000	Total Pressure	0-345 (kPa)	0.025%FS
Atmos 14	Relative Humidity	0-100 (%)	0.1 (%)
	Temperature	40-80 (°C)	0.1 (°C)
	Vapor Pressure	0-47 (kPa)	0.01 (kPa)
	Barometric Pressure	50-110 (kPa)	0.01 (kPa)

Materials

The materials (CPR and fine-grained tailings) were supplied by El Soldado copper mine, Region de Valparaíso, Chile. Main characteristics of the materials are summarised in Table 2. The initial void ratio in the table was found from column tests.

Table 2 Summary of material's index properties

Parameter	Tailings	CPR Sands
Specific Gravity	2.796	2.728
Plasticity Index	Non Plastic	Non Plastic
USCS Classification	ML	SP
Fines Content (%)	51	4
Initial Dry Density, γ_d	-	1.49 g/cm^3
Initial Voids Ratio, e_0	-	0.83
Permeability at e_0	-	3.39x10^{-4} m/s

Of interest for this research was the air entry value (AEV) of the material and the desaturation curve, which is shown in Figure 3.

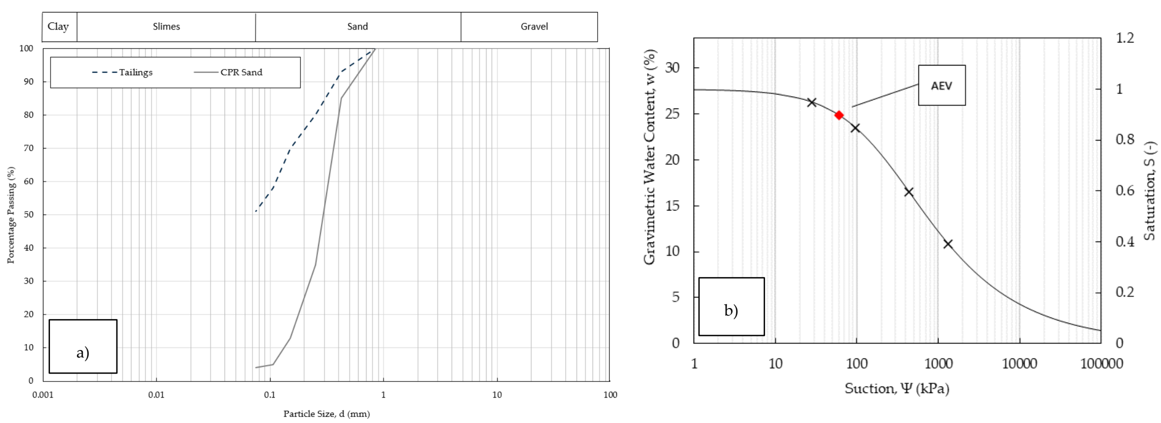

Figure 3 a) Particle Size Distribution; and **b)** Soil Water Characteristic Curve for tailings El Soldado calibrated with Fredlund et al. (1994).

Deposition sequence

Once all the equipment was setup and stable, and sensors and other electronics properly integrated and valves closed, discharge of materials started following three stages, as described below.

- **Stage 1a (layer 1-CPR):** A slurry of CPR sand, at a solids content of 50%, was deposited as to complete a first layer of 150 mm (Figure 4b). Once sedimentation was completed, supernatant water was syphoned off. The sand was leveled and compacted using a 3.4 kg steel rod. The water exuded was also drained off the cell but keeping the sand always saturated.
- **Stage 1b (layer 1-Tailings):** Tailings were poured from a height of less than 20 mm to a total thickness of 350mm over the course of 9 days. The rate of rise was scaled to represent a field rate of rise of approximately 2 m per year. The tailings were at a solids content of 50% (From

Figure 4c to Figure 4f). Then the valves, located on each face of the apparatus, were slowly opened, and the material allowed to drain and consolidate under self-weight over a period of 26 days (Figure 4e and 4f). The rate of flow from the apparatus, at the end of this stage, reached approximately 1 liter per day (lower than the 0.5 liter per day criteria established to halt the test). Over this stage, the cell is covered to avoid evaporation and desiccation of the top layer.

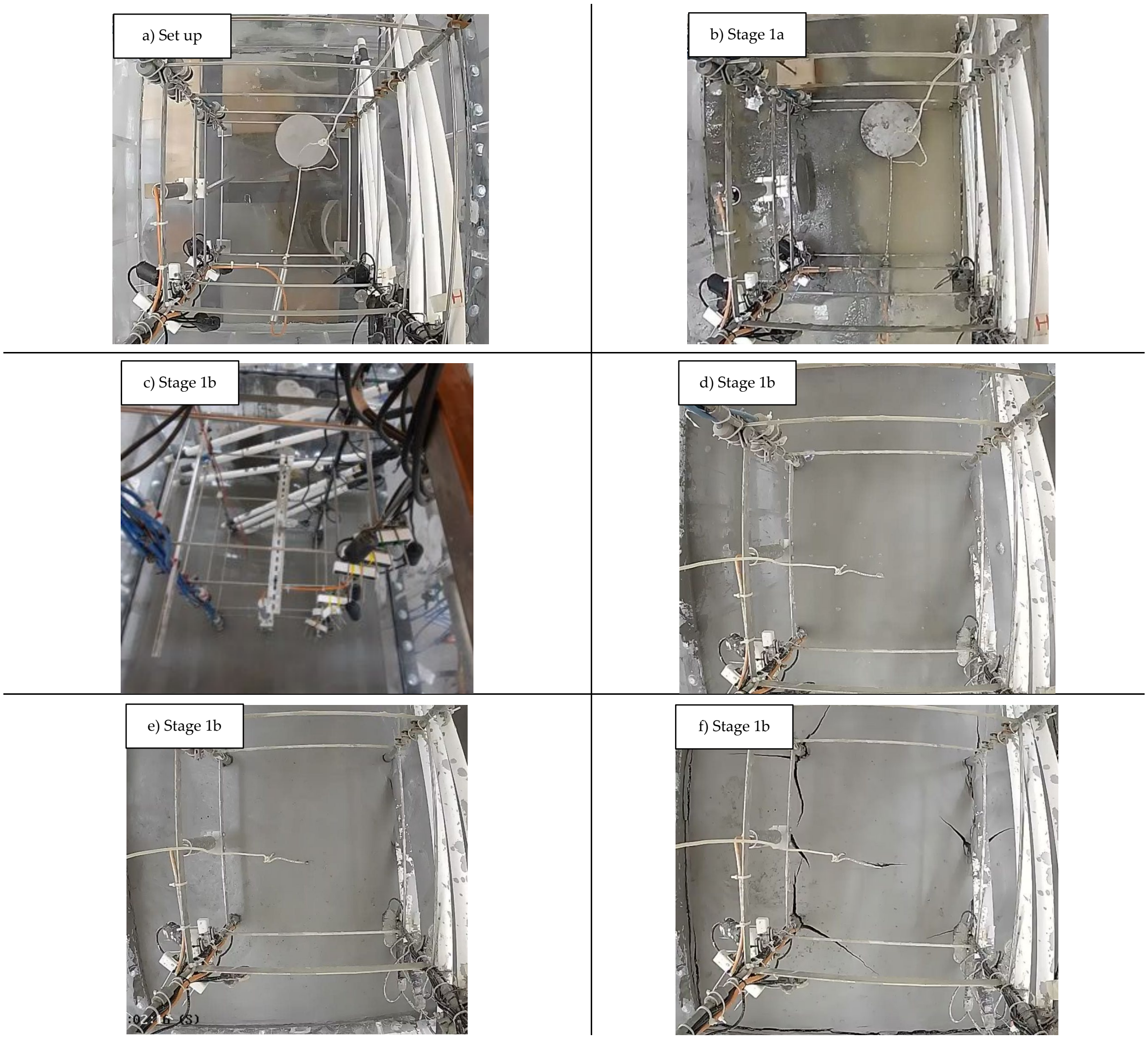

Figure 4 Instrumentation HDS test and process of depositing tailings and CPR sands **a)** Initial Set up; **b)** Stage 1a: Saturated sands prior to tailings deposition ; **c)** Stage 1b: Start of the tailings deposition process; **d)** Stage 1b: End of tailings disposal; **e)** Stage 1b: Superficially dry tailings; and **f)** Stage 1b: Final stage of consolidation/drainage of tailings.

- **Stage 2a (layer 2-CPR):** All valves were closed off and layer thickness measured as accurately as possible and the initial condition for current stage established. Then, CPR sand slurry was placed over the surface of the tailings. Disturbance of tailings was avoided using a funnel to pour the sand. The excess of water was drained off using the horizontal valve. Remaining water was siphoned off using a syringe.

- **Stage 2b (layer 2-Tailings):** similar to Stage 1b but tailings were allowed to drain over a period of 15 days.
- **Stage 3a (layer 3-CPR):** Similar to Stage 2a.
- **Stage 3b (layer 3-Tailings):** Similar to Stage 2b but tailings were allowed to drain over a period of 28 days.

During all the experiment the consolidation and desiccation of tailings was monitored using the various instruments. After completion of the tests (over the course of approximately 103 days), a series of geotechnical tests were completed at each compartment (CPR sands and tailings layers): gravimetric water content (GWC), degree of saturation (S), unit weight (γ) and void ratio (e).

RESULTS AND DISCUSSION

Suction measurements

The suction (ψ) measurements, as found from Teros 21 and Teros 32, at different locations in the cell are shown in Figure 5. During Stage 1a and Stage 1b, where slurry materials are deposited, suction was approximately $\psi \approx 0$ kPa. This is due to full saturation of material and initial formation of water table in layer 1 (despite water being siphoned off from top of CPR and tailings layer). As consolidation and drainage is permitted during Stage 1b, suction develops within tailings mass over a period of 8 days to values of approximately $\psi \approx 5$ kPa. These values are far from AEV of the material (Figure 3b). As Stage 2b starts and slurry CPR sand and tailings are deposited, suction is no longer observed due re-saturation of the material in layer 1. Suction is generated again as valves are open and consolidation and desiccation occur for materials in both layer 1 and layer 2. Suction raised to values similar to Stage 1, but generation occurs at a lower rate during Stage 2. The same saturation and desaturation behavior is observed in Stage 3a and 3b.

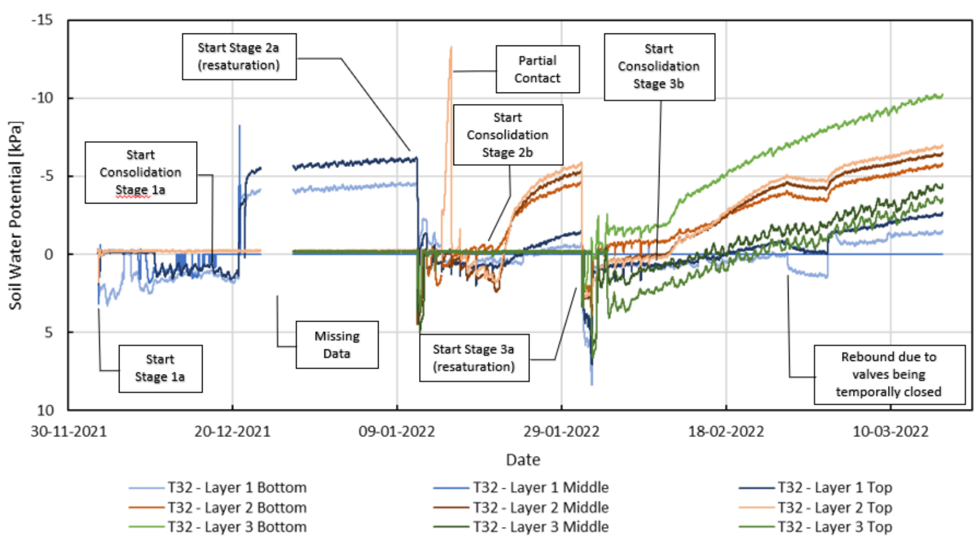

Figure 5 Matrix suction measurement as found from Teros 32 sensors.

In general, the suction probes located in the lower compartments (layer 1) develop lower suction in comparison to upper layers (layer 3). This was expected and attributed to desaturation occurring due to seepage which is controlled by gravity (an evaporation front was avoided using a plastic lid on top of the cell). Similarly, vertical flow through the cell was predominant in comparison to water evacuated horizontally, with the majority of water recovered from valves located in bottom layer of CPR sands in layer 1. The maximum suction recorded after 27 days was approximately $\psi \approx 10$ kPa.

These results generally agree with the evolution of recorded volumetric water content, but some significant differences exist, as discussed below.

Volumetric water content measurements

The volumetric water content, as measured by Teros 12, was observed (Figure 6) to remain at values of approximately θ≈50% when slurry material was deposited in the cell (tailings and CPR sands). This is consistent with suction measurements (which were near ψ≈0), confirming that slurry materials can re-saturate materials previously deposited. Inspection of measurements during Stage 1b, Stage 2b and Stage 3b (where valves were opened) shows significant desaturation of the material, especially during Stage 3, where a minimum of θ ≈15% was observed in the upper tailings layer (layer 3). If this is an accurate measurement, the material at this location was near capillary break, while other portion of tailings (layer 1 and 2) also allowed air entry. In general, tailings in the lower layers resulted in greater θ than the material in upper layers.

The evolution of suction θ and ψ over time are similar and reflect the capacity of the cell and CPR sands to promote consolidation and desaturation of the tailings. However, the low θ values observed are not consistent with the low suctions recorded at the same location by suction probes. This can be verified after inspection of the SWRC which shows that for values of θ ≈15% suction would have resulted in ψ≈800 kPa which was not observed in Teros 32 (acknowledging the limitations of the SWRC for the test setup and procedure). The differences observed are likely due to suction sensor accuracy at low suctions for the materials used, as later discussed.

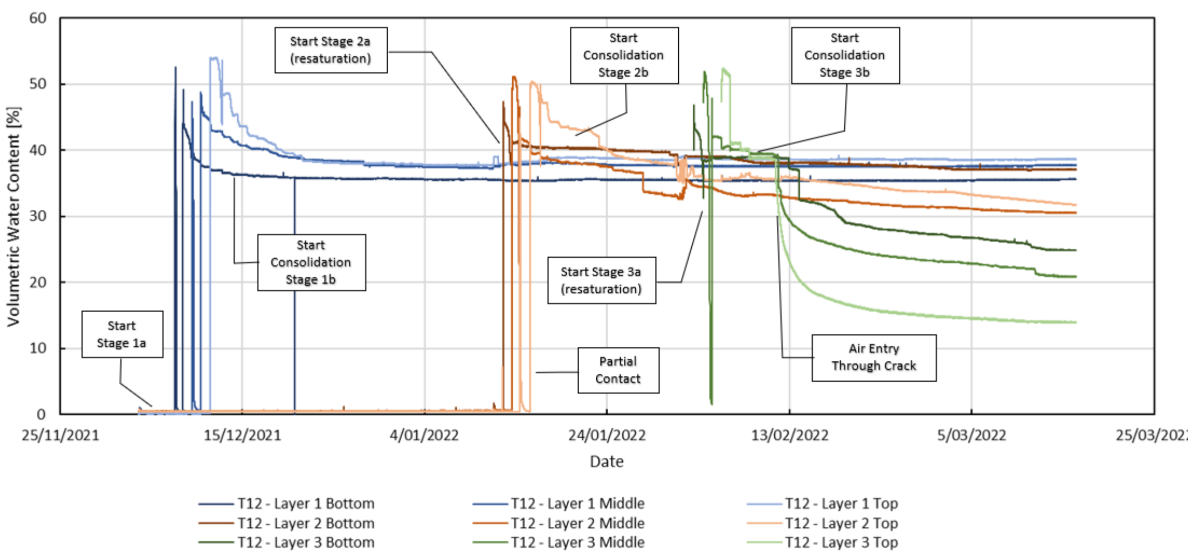

Figure 6 Volumetric Water Content measurement from Teros 12 sensors.

Piezometric head measurements

The phreatic surface was observable in the VW piezometers during slurry deposition (Figure 7). The sensor LS10 – Layer 1, which is at the bottom of the cell, shows a maximum resulting head of water in the cell of 200 mm, 400 mm and 800 mm for Stage 1a, Stage 2a, and Stage 3a, respectively. This is similar to layer thickness at each stage, suggesting full saturation of the column after deposition of slurry tailings. When valves were opened, rapid draw down of the water table was observed. The VW piezometers follow the behaviour and evolution of suction and volumetric water content recordings (Figure 5 and Figure 6, respectively). Nevertheless, the negative values recorded by VW cannot be considered as accurate since the sensors are not designed to measure matric suction. After completion of the test, no water table was observed in either layer, which is attributed to gravitational dewatering provided by the experimental arrangement (CPR sands and anisotropy of materials).

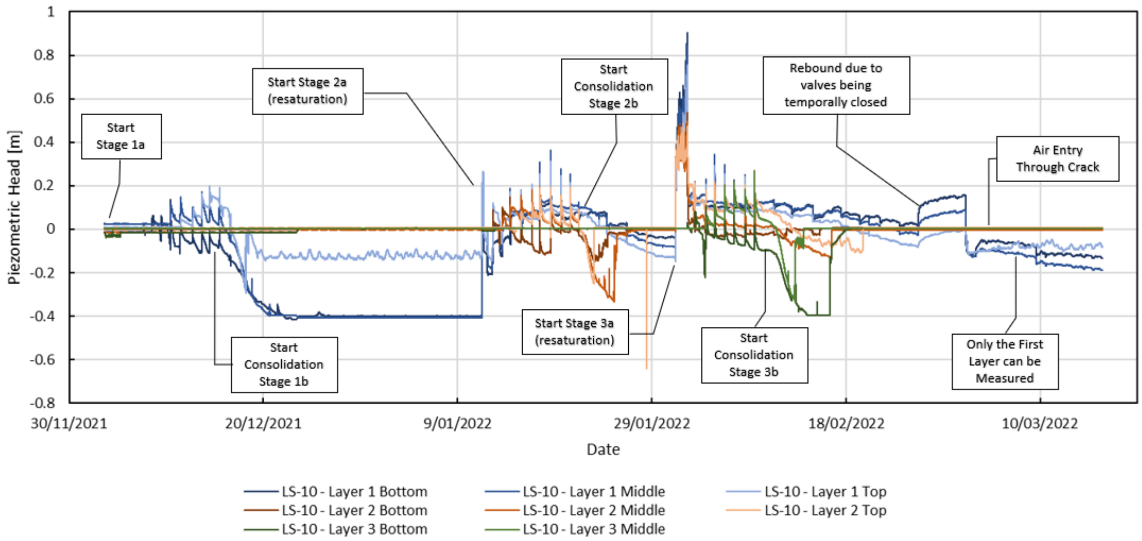

Figure 7 Piezometric head measurement from LS-10 sensors.

Sub-sampling and decommissioning

As to confirm whether significant suction and desaturation have occurred in the cell after completion of the test, sub-sampling from each layer was carried out. A series of thin-walled steel tubes were constructed and carefully pushed 50 mm down in the materials. The material was tested in the Laboratory for determination of water content, total unit weight and degree of saturation (Table 3).

Table 3 Sub-sampling results for tailings and CPR sands.

Layer	GWC (%)	ρ (gr/cm³)	VWC[1] (%)	S (%)	e (-)
Tailings 3 Top	*14.7*	*1.497*	*22.0*	*47.4*	*0.868*
Tailings 3 Middle	*18.8*	*1.471*	*27.7*	*58.4*	*0.901*
Tailings 3 Bottom	*14.1*	*1.474*	*20.8*	*44.0*	*0.897*
CPR Sand 3 Middle	*7.55*	*1.288*	*9.7*	*17.6*	*1.171*
Tailings 2 Top	*17.4*	*1.465*	*25.5*	*53.5*	*0.909*
Tailings 2 Middle	*17.2*	*1.482*	*25.5*	*54.2*	*0.887*
Tailings 2 Bottom	*18.9*	*1.507*	*28.5*	*61.8*	*0.855*
CPR Sand 2 Middle	*6.45*	*1.256*	*8.1*	*14.4*	*1.226*
Tailings 1 Top	*28.0*	*1.568*	*43.9*	*100.0*	*0.783*
Tailings 1 Middle	*30.2*	*1.517*	*45.7*	*100.0*	*0.843*
Tailings 1 Bottom	*31.5*	*1.487*	*46.8*	*100.0*	*0.880*
CPR Sand 1 Middle	*32.1*	*1.49*	*47.9*	*100.0*	*0.877*

[1] Calculated from Gravimetric Water Content (GWC) and Density (ρ)

The results show lower void ratio and greater unit weight as the overburden stress increases. The saturation of tailings increases in depth, which is expected regarding the consolidation phenomena in the cell (one-way, one-dimensional). The CPR sand and tailings in layer 3 are fully saturated at the end of the test, however, phreatic surface is not detected by piezometers. The saturation of tailings for layers 2 and 3 were well below unity. The average volumetric water content is approximately 25% for this material which is consistent with the readings of the Teros 12 sensors shown in Figure 6. As such, the tailings in the top layers underwent significant desaturation, well below the air entry value of the material.

Overburden stress and Ko

Figure 8 shows vertical and horizontal overburden stress for the total pressure cells located at the bottom of tailings layer 1. During discharge of slurry tailings in Stage 1b, Stage 2b and Stage 3b, the vertical stresses rapidly increase within the cell. However, as the material undergoes consolidation (and water is drained off the cell), and arching effects occur in the cell wall, the total stresses slightly decrease. The Ko tends to equilibrate at values of approximately 0.65 near the end of the test.

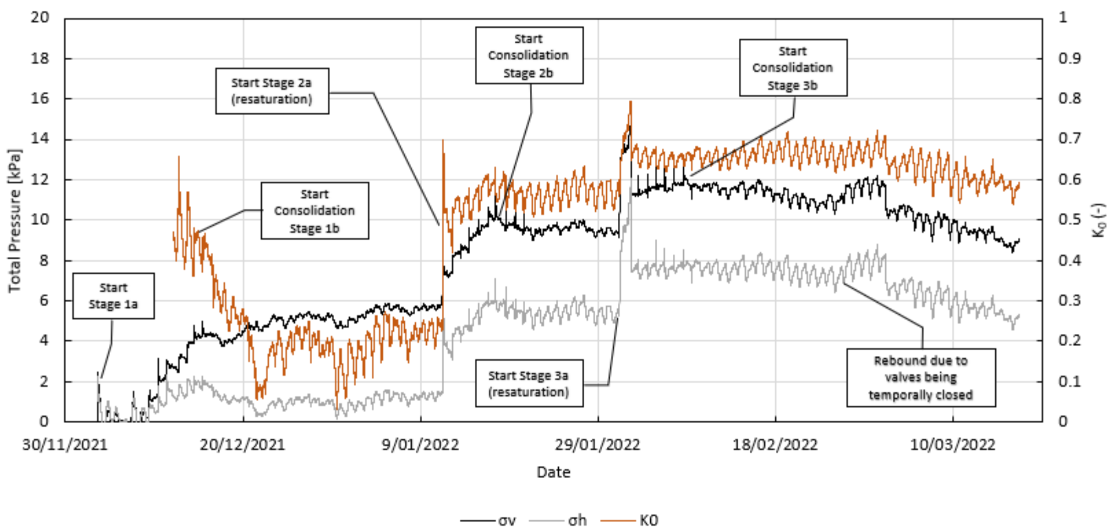

Figure 8 Total Pressure Cells measurement and K_0 from VWTPC-4000 sensors.

CONCLUSION

The placement of tailings with interbedded CPR sand layers shows promising results in terms of desaturation of tailings. For the test completed in the El Soldado Mine tailings, desaturation degree for the upper layers was well below 80% (performance criteria) with a significant decrease in resulting volumetric water content. The matric suction was likely greater than air entry value as per sub-sampling results, however, this needs to be confirmed after re-calibration of suction probes. The total water recovery was greater than 65% for the test conducted at UTFSM. The observed results reflect the capacity of the HDS technology to recover water from tailings while promoting increased physical stability of the materials.

The demonstration project of a 150,000 m^3 capacity state-of-the-art tailings facility in the heart of the El Soldado industrial complex continues in 2023. It is expected the facility allows to corroborate the results found herein and demonstrate the advantages of HDS over traditional tailings storage, particularly in areas of water scarcity. Preliminary results of the demonstration are presented in a separate technical paper.

ACKNOWLEDGEMENTS

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NOMENCLATURE

HDS	Hydraulic Dewatered Stacking
TSF	Tailings Storage Facilities
CPR	Coarse Particle Recovery
TDR	Time Domain Reflectometer
VWC	Volumetric Water Content
GWC	Gravimetric Water Content
S	Saturation
e	Voids Index
TPC	Total Pressure Cells
K_0	Coefficient of Earth Pressure at Rest
Φ	Friction Angle
SWCC	Soil Water Characteristic Curve
AEV	Air Entry Value

REFERENCES

Cacciuttolo, C., Atencio, E. (2022) 'An Alternative Technology to Obtain Dewatered Mine Tailings: Safe and Control Environmental Management of Filtered and Thickened Copper Mine Tailings in Chile', *Minerals, 12(10), 1334,* https://doi.org/10.3390/min12101334

Davies, M., Lupo, J., Martin, T., McRoberts, E., Musse, M., Ritche, D. (2010) 'Dewatered Tailings Practice – Trends and Observations', In proceedings of Tailings and Mine Waste '10, Balkema.

Fredlund, D. G., &; Xing, A. (1994). 'Equations for the soil-water characteristic curve', *Can. Geotech. J.*, 31(4), 521-532.

Newman, P., Burton, M., Burgos, J., Purrington, J. (2022) *Innovations in Tailings Management – Hydraulic "Dry" Stacking.*

Torghabeh, E. (2013) *Stabilization of Oil Sands Tailings Using Vacuum Consolidation*, 1st Edition, University of Alberta, Alberta, Canada.

Yoshimi, Y. Tanaka, K. and Tokimatsu, K. (1989) 'Liquefaction resistance of a partially saturated sand, Soils and Foundations' Japanese Society of Soil Mechanics and Foundation Engineering. Vol. 29 No. 3 157-162, 1989