Hydraulic Dewatered Stacking – delivering desaturated tailings management without the capital cost of filtration

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ABSTRACT

Hydraulic Dewatered Stacking (HDS) is an engineered co-disposal tailings management system, developed by Anglo American that delivers a desaturated tailings facility with benefits on safety, water recovery and significantly changes the approach to closure generating social, environmental and cost benefits.

Conventional tailings dams have basal drainage layers but vertical permeability is poor and many tailings facilities remain saturated throughout their life and beyond mine closure. Horizontal permeability is up to 10x greater and HDS leverages dedicated drainage channels (built with sand derived from the tailings themselves) to create a 3-dimensional drainage system to continuously dewater the facility.

Results at our 150,000m^3 demonstration facility have exceeded expectations although challenges remain in the scaling of the system to the target application – a large copper porphyry in a water scarce region such as Chile / Perú.

Access across the tailings has been rapid, and consolidation / moisture content measurements have shown that the zone of influence of the vertical drainage channel has been approximately 20m. Phase 2 (of 3) of the demonstration is now underway and the trial will be completed in Q3, 2024.

This paper talks to the benefits of pursuing a desaturated tailings storage solution and presents the results of a techno-economic analysis comparing filtered stacking and HDS for an indicative 3000 tph copper project in Chile.

Keywords: *Hydraulic Dewatered Stacking, filtered tailings, tailings management*

INTRODUCTION

The mining industry faces several unique risks. From a business perspective, most mines are price takers and prices fluctuate, demand may change and extended high prices can drive substitution. Geological uncertainty can only be partially mitigated through drilling or other exploration techniques. Mother nature decides where the orebody lies and hence geopolitical risks can weigh heavily on investment decisions.

Social, health and environmental risks, driven by increasing public awareness and agency, are, it could be argued, among the greatest, and most difficult to quantify, risks faced by mining companies; regardless of whether they are a greenfield explorer or a seasoned operator who is decades into a 100+ yr mine life.

Tailings management often represents the greatest risk a mining operation can face with recent well-publicised failures in 2015 and 2019 causing significant loss of life and environmental damage, resulting in many billions of dollars of value impact on the companies involved. Not to mention the reputational impact on the mining industry.

Filtered tailings addresses water-induced risks

Water is the problem when it comes to tailings management; it provides the transport medium for mass flows of the kind witnessed in recent TSF failures; it is water that transports polluted plumes from seepage and it is water that transports acid drainage laden waters away from poorly managed sites into the surrounding environment.

Mechanical filtration will remove the most water from a tailings stream and delivers a low moisture product that can be stacked within a tailings management facility without many of the risks. The benefits of mechanical filtration can be both technical and economic. Decreased water loss can deliver the opportunity (in an unconstrained mining environment) to increase production; or maintain production if the mine is in an area with scarce water supplies. This is likely the largest contributor to a positive business case economically.

In some jurisdictions, permitting constraints associated with wet tailings facilities can essentially preclude their use and hence mechanical filtration and stacking is often pursued as the preferred option for the mine.

The stability of a filtered tailings stack must still be monitored and the role of the geotechnical engineer and adherence to placement method statements are essential but given the benefits listed above, one may reasonably ask the question as to why filtered tailings are not more widely adopted by the mining industry.

Cost remains the major hurdle to widespread adoption of filtered tailings and experience is limited at large scale (>50ktpd). How does the mining industry address this ‘business case conundrum’?

Desaturation is the key

How else can a tailings facility be constructed such that it attains (and maintains) desaturation? The introduction of multiple, 3-dimensional, drainage channels could perhaps assist but the availability of a suitable filter sand, at the quantities required, has historically been considered too expensive.

However, for many tailings, it is feasible to generate a suitable fines-free sand from the tailings themselves, through classification. Approximately 15-20% fines-free sand production facilitates a new type of tailings management system that consists of horizontally contiguous drainage channels extending vertically through the tailings facility.

The approach, called Hydraulic Dewatered Stacking (HDS), was hypothesized, developed and demonstrated by Anglo American between 2019 and 2024. Results have been positive and the approach has real potential to radically change tailings management going forward. More expensive than conventional disposal, but significantly less costly than filtration, the approach can deliver outstanding dewatering performance – an overview of the cost implications is presented in Table 1 below.

Table 1 Cost item discussion for different surface disposal approaches

Cost Item	Conventional Wet Disposal	Filtered Tailings	Hydraulic Dewatered Stacking
Mechanical Equipment to prepare tailings	Limited (thickener)	Significant (filters)	Limited (cyclones when needed)
Transportation of tailings to TSF	Via slurry pumps, cyclones and spigots	Conveyors, stackers, and/or trucks and other HME	Via slurry pumps and sand placement infrastructure/ equipment*
Water management	Water recovery system at TSF	All done at plant	Water recovery system at TSF
Dam requirements	Main focus of engineering	Stack design can avoid dam Stack compaction to reach stability criteria at seismic areas	Dam required at present** Containment needed due to hydraulic placement of the tailings; dewatering happens with time
Operations	Low cost – focus is on the engineering of the dam	Higher plant opex, high placement cost	Sand placement (20% of total) is high cost, other costs as per conventional

*Proven at 20ktpd, scaling prototype under construction (100-150ktpd)
**Self supporting stack is theoretically possible

What is Hydraulic Dewatered Stacking?

Coarse particle recovery (CPR) is a different approach to flotation (ref: Arburo et al, 2022), using a fluidised bed that allows recovery of particles that only have a few % mineralised surface exposure. It raises the possibility of rejecting a sizeable proportion of the flotation feed (15-25%) before final grinding with minimum (or no) recovery deterioration. It also delivers a fines-free-sand (FFS) which dewaters in real time (Figures 1 and 2).

It was quickly realised that separately stacking these sands would deliver a significant water advantage (ref: Filmer et al, 2016; Filmer et al, 2017) and it was hypothesised that drainage layers placed within a tailings facility could potentially wick the water from the conventional tailings (ref: Filmer et al, 2020).

Hydraulic dewatered stacking (HDS) is an engineered co-disposal method utilising a fines-free sand, derived from the tailings themselves, to create contiguous sand channels that greatly reduce drainage paths within the stack, delivering accelerated dewatering and consolidation of the tailings facility.

To test this idea, geotechnical tests were conducted, followed by an informative and successful proof of concept using a 1m x 1m x 1.5m highly instrumented Perspex box (ref: Musso et al, 2023); into which alternate layers of sand and tailings were placed with dewatering / consolidation behaviour observed and data collected.

We then progressed with confidence to build a large-scale demonstration facility (150,000m^3 capacity) at our El Soldado Mine in Chile (ref: Newman et al, 2022; Newman et al, 2023). At the time of writing this paper we are over halfway through the trial and the results have been positive (see details below).

The El Soldado CPR plant consistently delivers a fines free reject sand, significantly different to the total tailings. This material is ideally suited to act as a filter for the total tailings, situated in the middle of the Terzaghi filter limits and experience at our HDS pilot facility has shown that the interface between these two materials is maintained, with a sharp interface noted between the tailings and sands, and moisture seen in the area closest to the tailings.

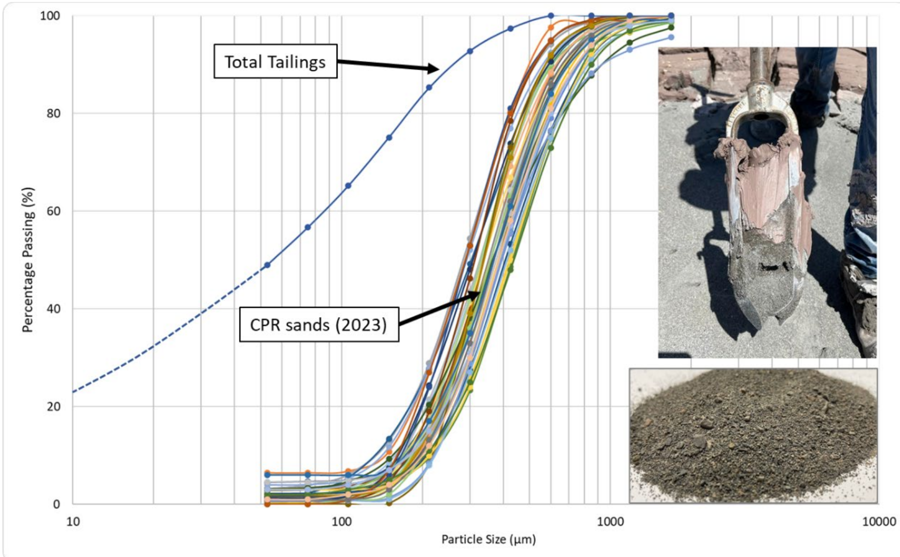

Figure 1 Consistent fines-free-sand from CPR plant at El Soldado (2023 operations)

(a) **(b)**

Figure 2 (a) Day 1 of demonstration, roping issues with CPR sands; (b) Real-time dewatering

The objective of the trial is two-fold:

1. To provide at scale confirmation of the hypothesis that sand channels will accelerate dewatering and consolidation.
2. Test initial sand placement concepts and understand the challenges and constraints associated with a large-scale implementation of the technology.

The target market for this technology is large (>100ktpd) copper operations located in water-scarce regions (e.g. Chile, Perú, SW USA). Anglo American has 3 such assets and understands completely the growing cost and increasing business risk associated with water scarcity.

Therefore, and recognizing that both technologies allow in different ways to increase the water recovery from tailings, this paper presents a cost comparison between filtered stacking and HDS for an indicative large scale copper operation.

Potential impact on water recovery

When assessing tailings management options for a new (or existing asset) a significant value driver is the recovery of water, particularly in water scarce regions where the cost of water is inexorably rising. The implementation of HDS is anticipated to recover ~0.1m^3 of water per ton of ore processed from thickened tailings (~55 wt%) and ~0.2m^3 of water per ton of ore processed from conventional tailings. To quantify potential water recovery impact of HDS, it is critical to have a view of the water use efficiency of each candidate site based on the validated water consumption intensity relative to the ore processed.

For the target market operations where water scarcity is an issue and the tailings storage facility type is either thickened or conventional tailings based, analysis looking at the validated water consumption for 30 such sites suggested a total water saving of 150Mm^3/yr.

The data represents the potential water recovery and *actual* water recovery will likely be less given site constraints, topography and economics. Discussions are ongoing with some of the operations captured in the data set below and when assessing the applicability of HDS, there are several factors to consider:

a) CPR – if the facility is using (or considering the use of) coarse particle flotation then the availability of fines-free sand is assured and is essentially free (at the plant). Without CPR, then the PSD of the tailings will drive the quantity and cost of fines-free sand available for building drainage channels within the TSF.
b) Dam construction – concurrent construction of a downstream cycloned tailings dam is the most common containment solution and at present this remains unchanged when considering HDS. If the 'dam volume' to 'storage volume' efficiency results in a high percentage of the tailings diverted to wall sand production, then HDS can be challenging.
c) Topography – sand production, transportation and placement drive the operating cost of an HDS facility and long distances between plant and TSF has cost implications. However, given the significant cost savings associated with HDS over filtered tailings solutions; there

is still scope for HDS being the most cost-effective way of achieving a safe, water productive, unsaturated tailings storage solution.

d) PAG – care must be taken for tailings with acid generating potential, the approach could be detrimental if the fines-free sand contains sulphides.

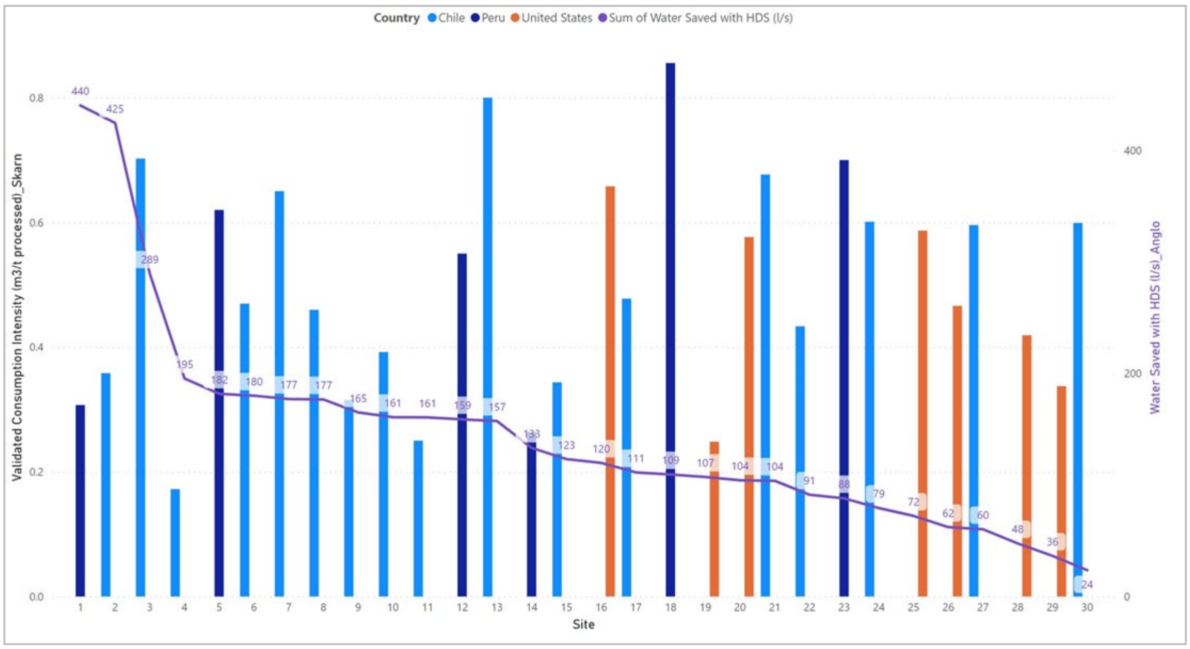

Figure 3 Water saving potential of HDS for Chile/Perú/USA copper mines estimated using Anglo American assumptions (consumption intensity ref: Skarn Associates, 2022)

Other HDS Benefits

Beyond water recovery, HDS delivers additional benefits that in some cases can be more valuable:

Safety – an unsaturated tailings facility reduces both the risk, and consequence, of liquefaction. With GISTM standards, a reassessment of many tailings facilities has indicated that additional safety measures are required and HDS can be implemented as a brownfield improvement to reduce risk.

Legacy – the implementation of HDS can be considered a form of progressive closure and does allow rapid access to the facility and facilitates landform development before the last tonne of tailings is deposited. Both reduce closure costs significantly and allows the re-purposing of the TSF to be planned with confidence, reducing the negative impact and perception of large tracts of sterilised land.

Also related to legacy is the use of HDS for tailings storage when assessing the re-processing of old / abandoned / orphaned tailings. Discussions with various governments regarding the monetisation of existing liability sites, particularly given the current Critical Minerals initiatives, have been positive since the implementation of HDS can be done with relatively little infrastructure compared to other desaturated tailings storage options.

EL SOLDADO DEMONSTRATION RESULTS TO DATE

The HDS demonstration at the El Soldado Mine in Chile will be completed in Q3 2024. The site was designed with significant instrumentation and has provided a plethora of data, providing some real insights into the way in which water flows through unsaturated soils and interacts with the rapidly draining fines-free sand channels.

The trial layout is shown below in Figure 4, with an inset showing the instrumentation layout for layer 1.

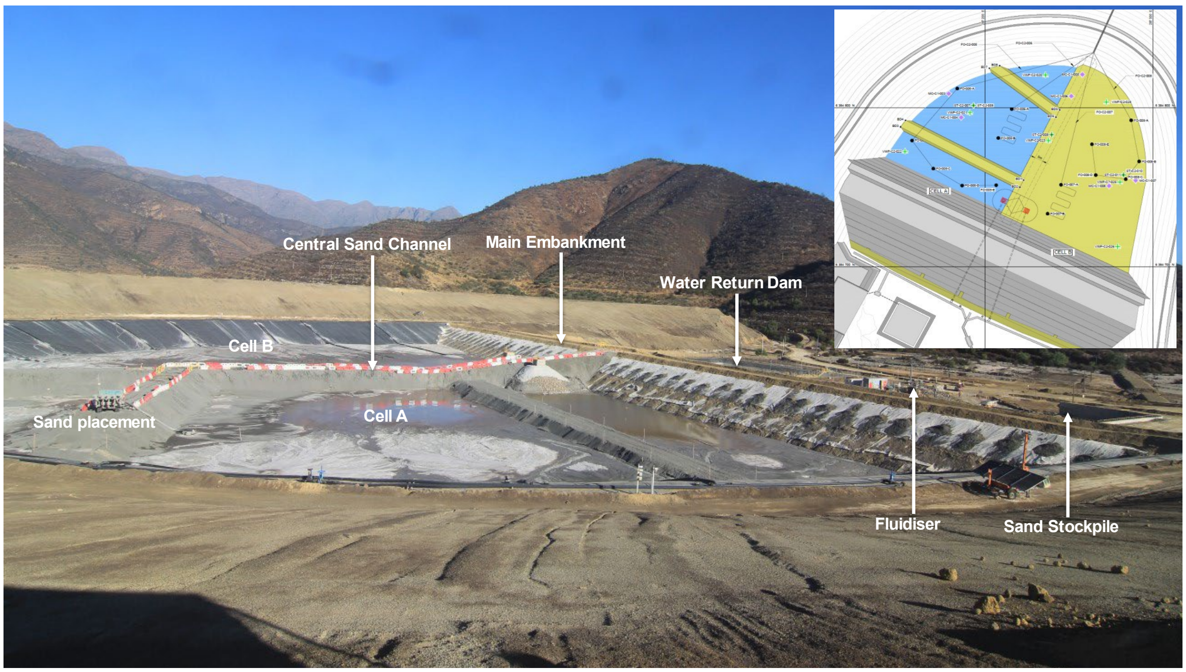

Figure 4 HDS Demonstration (March 2024, nearing Phase 2 completion)

Two approaches to HDS are being tested at El Soldado. Cell A consists of a basal drain and two lateral drainage channels, while Cell B has intermediate drainage blankets.

Monitoring Saturation within the HDS Demonstration

A wide range of geotechnical monitoring instrumentation has been installed within the HDS pilot to provide real time data on consolidation and dewatering behaviour. Some of the preliminary results (ref: Newman et al, 2023) are summarized below:

- Moisture content probes show that steady-state moisture content was achieved in the tailings after around 40 days. 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/m3, as such any variation of in situ density will result in some variance to the reported moisture content (to be confirmed after post-trial site investigation).

- To estimate the degree of saturation an average in situ dry density was used. 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.
- Suction Transducers were installed within the tailings and central sand berm to provide an understanding of the matric suctions developed within the stack which can also be used to assess the moisture content based on the soil water characteristic curves. Suction data was also used to base-line the calculated degree of saturation; where suction pressures reached zero full saturation was assumed. This occurred typically during initial deposition of tailings around the sensors as well as being observed due to the wetting front passing through the stack from subsequent tailings layer deposition. Maximum steady-state suction pressures of 13 kPa were reported in the tailings placed approximately 1 m above the base of the cell resulting in a degree of saturation ranging from 75% to 80%. Tailings at about 4 m above the base of the cell were reporting a steady-state suction of approximately 18 kPa resulting in a degree of saturation of approximately 30%. Some of this suction may be associated with drying and desiccation at the surface of the tailings and is expected to reduce as the final layers of tailings are placed in the stack.

As presented above, preliminary results from instrumentation indicate 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, and the expectation is that subsequent to further tailings deposition, the suction pressures will result in a similar degree of saturation being achieved in the next Phases of the trial and therefore in a full scale tailings operation.

It is worth mentioning that the information and results coming from the instruments is considered a means to assess variation to make operational decisions and evaluate changes of a particular parameter rather than absolute values, with absolute values to be assessed at the end of the trial with extensive intrusive investigations planned.

Updated information regarding the results and interpretation of the data coming from the trail at El Soldado are going to be available in Q4/2024 once the post-trial intrusive site investigation is finished.

Site Investigation Plan

Following the completion of the trial, a ground investigation campaign will be completed to assess the stack and determine the in-situ characteristics of the materials.

The site investigation is planned for Q3/2024 and will consist of in situ testing, including cone penetration testing (~40) combined with MOSTAP (Monster Steek Apparaat soil sampler) high quality sampling, a series of boreholes (~10) and undisturbed sampling techniques, plus specific in-situ tests like self-boring pressure meter (PMT) and seismic flat dilatometer tests (SDMT) and several basic and advanced laboratory testing. Several of the boreholes drilled are to be instrumented with standpipe piezometers.

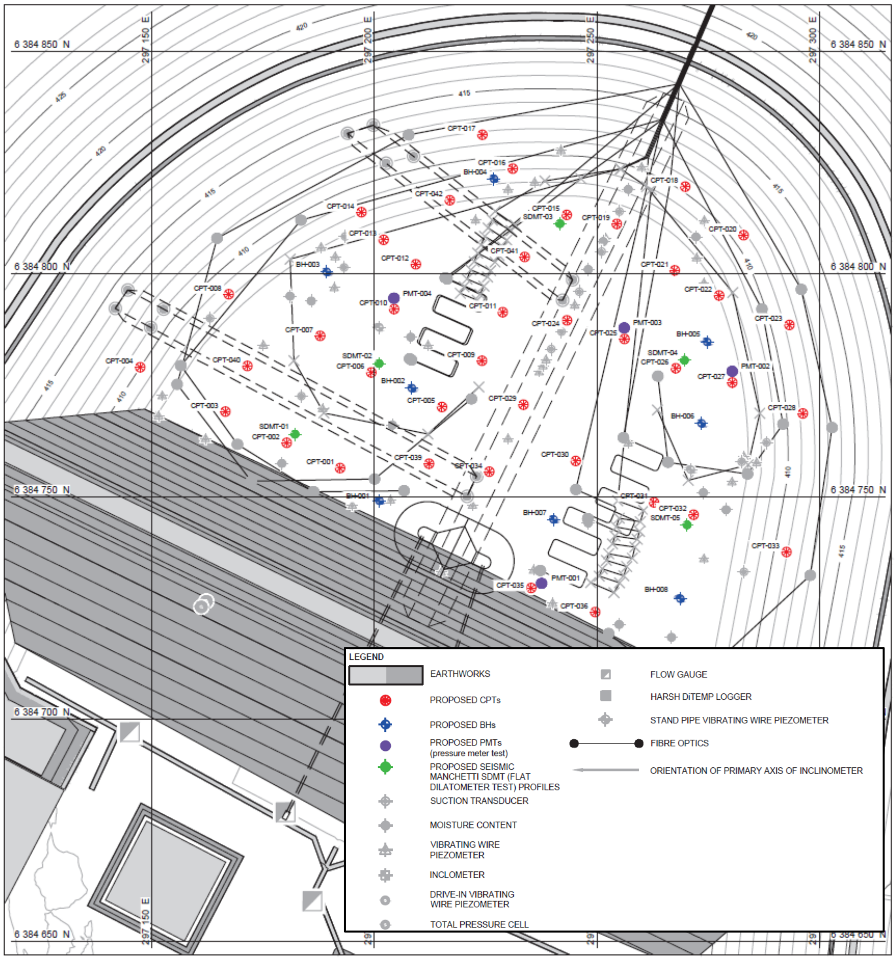

Figure 5 Preliminary geotechnical site investigation planned

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.

INDICATIVE COST ESTIMATES FOR HDS VS. FILTERED STACKING

When HDS was initially developed as a novel tailings management system, Anglo American was looking to its own sites for implementation and assessed the techno-economics in comparison with conventional wet disposal of tailings. Within such a scenario, there is additional capex and increased opex associated with implementing HDS and this is (often easily) offset by the financial benefit of enhanced water recovery, reduced closure costs and the potential to change the dam construction from downstream to centreline due to the reduced risk from delivering a desaturated tailings mass.

However, as data from the demonstration became available it became apparent that the HDS approach to tailings management has the potential to deliver geotechnical and water recovery performance close to that of a filtered tailings stack.

Below the authors have presented a detailed high level cost model comparing the capital and operating costs of the two approaches, applied to an indicative Greenfield copper porphyry operation, with a life of mine of 20 years at ~22Mtpa, located at an elevated altitude within a water scarce area (e.g. Northern Chile).

Design Criteria for the Assessment

The following technical assumptions have been used in the cost model:

Table 2 Design Criteria for Cost Assessment

Item	Filtered Tailings	Hydraulic Dewatered Stacking
Tailings production	3000 tph (22Mtpa)	
PSD of conv. tailings	P80 = 180μm	
PSD of CPR sands	P80 = 400 μm (~5%<75u)	
Distance to TSF location	2 km	
Major equipment (excluding main concentrator)	Pressure filters Delivery conveyors Stacker conveyors	Wall sand cyclone plant CPR sand dilution and dewatering plant
Tailings Storage Facility Geometry (see sketch)	4000m x 1500m stack 50m high with 1:3 side slopes	2000m cyclone sand embankment Max height 100m Valley impoundment 3000m long
Cost model input discount rate	12%	12%

The model looks to compare the costs of the two approaches, assuming the same concentrator design that incorporates CPR into the design, producing 20% of the tailings as a fines free sand.

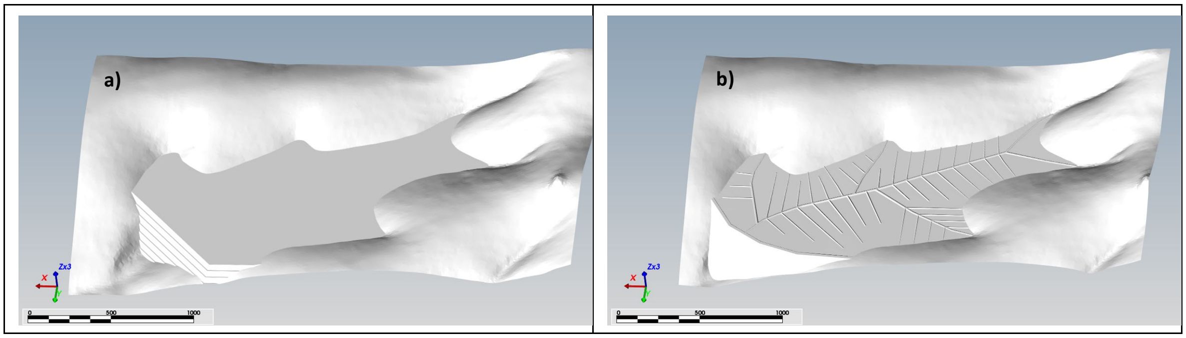

Figure 6 Indicative layout of TSF a) designed as a filtered stack and b) as an HDS facility

Cost Estimates and Assumptions

Plant capacity, conceptual definition of infrastructure needs and indicative layout sketches were developed by the research team for both options. Capacity factored, analogy check and judgment methods were applied as estimating method. Conceptual cost estimates were calculated as a combination of internal Anglo American estimates and project data (e.g. 20Mtpa approved filter facility), application of judgment by reference to third party benchmark data and existing projects, and publicly available third party research information.

Implied cost estimate accuracy range for low maturity projects of this kind is -30% to +50%. Construction period for both options was assumed to be 24 months, followed by a 20-year operating life. Cash flows were calculated in real terms, pegged to US CPI, and a 27% tax rate (Chile) applied.

It should be noted that conceptual cost estimates quoted are built up with a very low level of engineering and design definition, as well as assuming perfect topography conditions and unrestricted land access.

Information is presented for the purpose of high-level comparison, and sensitivity analysis and the results are sensitive to the authors inputs. As a result of these constraints, and in cognisance of the wide variability of installed cost for different assets (driven by topography, mineralogy and other factors) – the costs are presented as the following:

- <u>Base Case</u>: based on published references and discussions with Engineering and OEM peers.
- <u>Low Case</u>: a low cost estimate for filtered tailings is also presented, with a 30% discount to the Base Case.
- <u>Low Case (pessimistic HDS)</u>: HDS is an emerging technology and although the base case did include conservatism to account for the current state of the technology (particularly at scale), in this case the HDS costs were uplifted (capex contingency to 50%, opex uplifted by 50%).

Table 3 Equipment list and capex assumptions for Base Case

Item	**Filtered Tailings**	**Hydraulic Dewatered Stacking**
Major Equipment & Facilities	Hi-rate thickener Flocculant system Slurry storage Filters Discharge conveyor Delivery conveyor (2-6km) Stacker conveyor Mobile equipment Water Management Ponds Permitting	Conv. thickener Flocculant system Overland Piping Wall Sand Cyclone Pumps HDS Placement System Wall sand sluicing & agitated tank Mobile Equipment Starter dam at TSF Permitting
Sustaining capital (as % of Major Equipment)	1% every 3 years	1% every 3 years
Avg Growth allowance (as % of Major equipment)	25%	25%
Indirect costs	EPCM Owners Costs	EPCM Owners Costs
Contingency (as % of Total Capex)	30%	30%

Table 4 Operating cost assumptions

Item	**Filtered Tailings**	**Hydraulic Dewatered Stacking**
Operating cost main categories	Hi-rate thickener Filter Cloth & Plates Spares Electricity Conveyors Maintenance Belt transportation costs Labour General & Administrative	Conv. thickener Wall Sand Cyclone HDS Sand Placement Electricity Pipeline Management Labour General & Administrative Technology licensing costs

Table 5 NPC Calculations

		Base		Low		Low (high HDS)	
		Filtered Tailings	HDS	Filtered Tailings	HDS	Filtered Tailings	HDS
				-30%		-30%	+50%*
NPC @12%	US$'M	937	309	733	309	733	401
Total Capex	US$'M	824	263	633	263	633	303
Opex	US$/t	3.85	1.1	3.05	1.1	3.05	1.64

**(capex contingency to 50%, opex uplifted by 50%)*

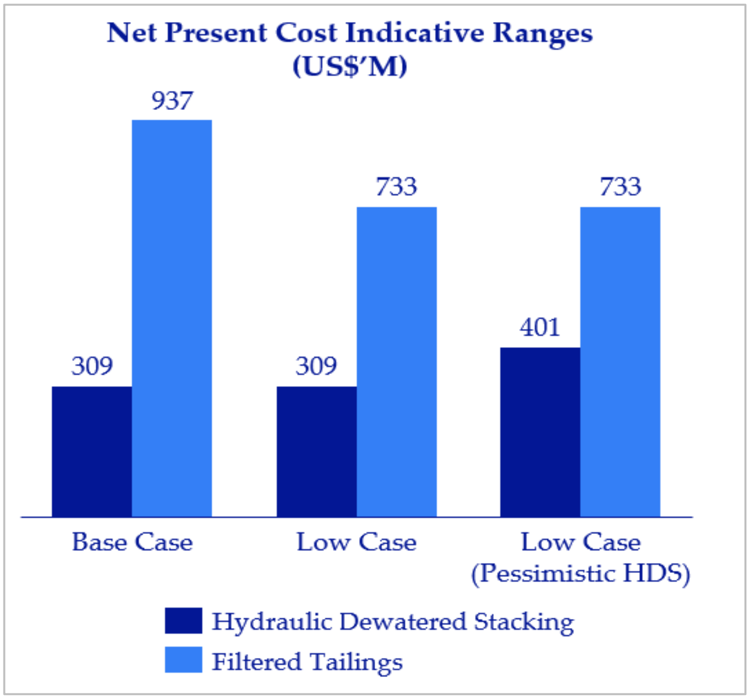

Figure 6 Net Present Cost Summary

Further, the following items were not contemplated in the cost estimate:

- Financing costs
- Closure / rehabilitation costs (see comments below)
- Royalties & other taxes
- Currency mix and possible exchange rate variations
- Financial guarantees
- Impact of offsetting potential capital associated with TSF, or any costs avoided in contrast to conventional tailings facilities
- Impact of incremental non-monetary value levers (e.g. safety, wider water savings and environmental impacts)

Cost Estimate – No CPR

The base case assumes the operation with a CPR facility, and the fines-free sand is assured and is essentially free (at the plant). Without CPR, then the PSD of the tailings will drive the quantity and cost of fines-free sand available for building drainage channels within the TSF. In this case, an additional capital cost for a classification system at the plant would be required and this could add up to US$100M to total capex and NPC value.

Water Balance comparison

Filtered tailings are a mechanical approach to dewatering and will certainly deliver the best dewatering performance with water recovery expected to be ~90%. This target is supported by the literature and is often cited by proponents of filtration. Dewatering performance of HDS is difficult to predict with certainty although the El Soldado trial has a target of 80-85% recovery, which it has been close to delivering through the progression of the trial.

In our model, we assume 81% water recovery which results in the filtered stack providing an additional 340m^3/hr of water compared to HDS.

Another way to assess the water efficiency of the two approaches is to look at the water loss per tonne of tailings placed. The filtered tailings number is an attractive 0.18m^3/t and the HDS number is determined to be 0.29m^3/t. For reference, the average water loss for a large scale (concentrator only) copper project in Chile/Perú/USA is 0.65m^3/t.

Closure Issues Comparison

We have reviewed the expected closure costs associated with the two options and found them to be similar.

Because the HDS facility is assumed to be placed into a valley, the cover costs are lower due to the lower exposed surface area requiring rehabilitation.

Within the HDS facility, the exposed fines-free-sand berms would need to be lined to avoid future preferential infiltration to the facility through these highly permeable channels.

Both filtered stacking and HDS offer significant closure advantages over a conventional tailings storage facility; the largest benefit being the possibility of progressive closure (i.e. initiating closure and altering deposition in the last few years to reduce closure costs). Filtered stacking does allow the potential closure of most of the facility ahead of closure, while HDS offers fast closure implementation (but after closure).

Both options deliver very significant benefits over conventional tailings storage.

CONCLUSION

Hydraulic dewatered stacking targets passive in-situ dewatering of tailings through the installation of multiple, contiguous and robust drainage channels that are co-disposed with the tailings. The sand for the drainage channels is derived from the tailings, either through the adoption of coarse particle recovery within the concentrator or a classification step after the concentrator.

Confidence in the science is growing with positive results being generated from a large-scale demonstration facility at the El Soldado Mine in Chile. Scaling the technology to make it a realistic alternative for large scale tailings deposition is now an engineering challenge and work is ongoing with a couple of highly regarded OEMs to deliver a higher capacity sand placement system.

The paper presents the results of a techno-economic analysis of the capital and operating costs and water recovery performance of HDS and filtered tailings deposition. HDS is more expensive than conventional tailings deposition and the operation of an HDS facility will require more personnel, more planning and additional infrastructure (associated with sand transportation and placement).

The geotechnical and water recovery performance of an HDS system will exceed that of a conventional tailings storage facility but not meet the excellent performance of a filtered stack; and for our fictional mining asset, filtered tailings does recycle additional water.

However, in the scenarios envisaged in the analysis filtered tailings represent a significant investment for the mining company. The most optimistic scenario, where a 30% reduction in the costs for filtered stacking are combined with a higher contingency for HDS capex and a 50% increase in operating costs, still results in a $332M saving in NPC (falling to ~$232M if CPR is not employed).

Risks exist for both systems, there is little experience at large scale (>50ktpd) for filtered stacking and scaling of the successful HDS operations to date still require further engineering. However there is "headroom" to engineer a robust and reliable sand transportation and placement system and the operating costs used in our analysis are likely to reduce further as this engineering progresses.

In the authors' opinion, HDS offers an interesting alternative to filtered tailings and is an important step in the elimination of long term storage of wet tailings, with the operational and post closure risk associated with the safe containment of saturated tailings.

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