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Avoiding dam failures: is filtration the best solution?

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Abstract

Tailings storage has been marred with numerous catastrophic tailings dam failures in recent decades, resulting in hundreds of deaths and significant environmental damage. The mining industry has sought to develop and implement alternative methods of tailings storage in an attempt to limit the risks associated with dammed storage.

Underground storage of tailings slurries and pastes has provided a partial solution at mines with underground workings, but this typically enables only a minor percentage of the total tailings stream to be stored. It can therefore not be considered a total solution for most mines, and still leaves the majority of the tailings requiring a dedicated storage facility above ground.

Canadian professor Eli Robinsky introduced his concept of thickened discharge in the 1970s, featuring the central thickened discharge scheme for flat terrain and the down valley discharge scheme for steep and sloping terrain. This approach has been successfully implemented at more than 60 mines around the world with no reported major geotechnical failures or major environmental damage to date.

Manufacturers of filter presses and other filtration devices have gradually developed larger equipment that can process greater volumes more economically. In recent years, more attention has been focused on the use of filtration technology for tailings storage, with some workers suggesting that it provides the ultimate solution for tailings storage in terms of the geotechnical stability and closure advantages.

Geotextile tubes have also been presented as a possible damless tailings storage solution.

This paper discusses the relative risks and advantages between filtered tailings and thickened discharge for tailings storage. The reliability of the technology, the cost of installation and operation, the geotechnical stability of the deposited tailings, the environmental impacts, the closure of the tailings storage facility, and the record to date for each of these two technologies will be compared and discussed.

Finally, the paper questions the popularity of conventional tailings dams, and why alternative technologies like thickened discharge and filter stacking are not being more widely used instead of conventional dams.

Keywords: *tailings, thickened, filtration, dry stack, tailings storage facility*

1 Introduction

Tailings storage has been marred with numerous catastrophic tailings dam failures in recent decades, resulting in hundreds of deaths and significant environmental damage. The mining industry has sought to develop and implement alternative methods of tailings storage to avoid the risks associated with dammed storage. Broadly, the damless methods of tailings storage can be listed as follows:

- Underground storage.
- In-pit storage.
- Thickened discharge.
- Filter stack.
- Sub-sea storage.
- Geotextile tubes.

1.1 Underground storage

Underground storage of tailings slurries and pastes has provided a partial solution at mines with underground workings, but this typically enables only a minor percentage of the total tailings stream to be stored. It can therefore not be considered a total solution for most mines, and still leaves the majority of the tailings requiring another storage facility elsewhere.

1.2 In-pit disposal

In-pit disposal can be implemented wherever an old open cut pit has been mined out. This method of tailings storage is highly economical, but is not available if the mine has only one pit that is still being actively mined. It is therefore not possible to suggest this method as an alternative to other damless tailings storage methods, but it is useful as a possible storage method whenever an unused pit is available.

1.3 Thickened discharge

Thickened discharge is a tailings storage method that was introduced by Canadian professor Eli Robinsky in the 1970s, featuring the central thickened discharge (CTD) scheme for flat terrain and the down valley discharge (DVD) scheme for steep and sloping terrain. In both situations, the tailings slurry is thickened to a concentration that prevents the particles from segregating as they are hydraulically transported and deposited on the beach. This approach has been successfully implemented at more than 60 mines around the world with no reported major geotechnical failures or major environmental damage to date. It must be noted, however, that thickened tailings storages usually feature a dam. In the case of a CTD, the dam might possibly be less than two metres high if the underlying terrain is very flat, so one could argue that a CTD in this terrain can be considered to be effectively damless. However, for a DVD, it is more typical for the dam to be more than 20 m in height. The Miduk tailings storage facility (TSF) in Iran, for example, features an embankment that is about 60 m in height, and the nearby Sar Cheshmeh TSF also features an embankment of a comparable height. Whilst these DVD schemes cannot be considered as damless, there is an important distinction from conventional tailings dams that should be highlighted here, which is that a significant portion of the deposited tailings in a DVD are not saturated. This is relevant when one considers a catastrophic dam failure such as that which occurred at the Brumadinho TSF in Brazil in 2019, in which some 75% of the stored tailings liquefied and flowed from the impoundment within five minutes (Stark et al. 2022). The Brumadinho TSF was a conventional dammed storage with a decant pond on top of the tailings. This liquefaction was able to occur because most of the tailings in the Brumadinho TSF were saturated. In a DVD, the decant pond is usually small, and most of the deposited tailings have been deposited further up the valley, at a level that is higher than the pond level that prevailed at the time of deposition. The dry surface of the beach, and the gradual hydraulic deposition of thin layers of tailings, enables evaporative drying to effectively consolidate and strengthen the tailings deposit. In some DVD schemes, such as the Century TSF, the decant pond is kept in a separate impoundment further downstream, which enables the vast majority of the deposited tailings to remain unsaturated.

1.4 Filter stacks

Filter stacks (or ‘dry stacks’ as they are often called) are mounds of tailings that have been dewatered and placed as a soil-like material, rather than a slurry. Vacuum filters or filter presses are typically used to extract water from the tailings slurry to the point that it can no longer be pumped, so that the tailings requires transport by conveyor belt or dump truck to get to the storage site. Manufacturers have gradually developed larger filter presses and vacuum filters that can process greater volumes of tailings at higher rates, which has enabled larger mines to operate filter stacks more economically than before.

For small mining operations, dry stacking can be achieved with the use of drying pans (or other existing conventional TSFs). This enables the avoidance of the installation (and capital cost) of a filtration plant whilst still creating dewatered tailings, but it does require remining and relocation of hydraulically deposited tailings that has had time to dry. This approach has been implemented at the Ballarat Gold Mine in recent years, due to their existing conventional tailings dam reaching capacity and its successor (currently under construction) not yet being ready to receive tailings. As a stop-gap measure, a third tailings storage area was set up for the placement of a dry stack. Since then, earthmoving equipment has been digging old tailings out of the old TSF and moving it to the dry stack site, where it has been dumped, spread and compacted (Victory Minerals n.d.). This process has enabled the process plant to continue operating, by discharging fresh tailings slurry into a series of new shallow voids excavated in the old TSF. In this particular situation, this process is workable because of the trafficability of the old tailings. In other small-scale mining operations where the tailings is less trafficable, a series of shallow drying pans would enable a similar process to operate. At other old mining areas, a similar dry stacking approach would potentially enable the remining of old tailings without the need for construction (or permitting) for a new wet tailings impoundment.

In recent years, more attention has been focused on the use of filtration technology for tailings storage, with some workers suggesting that it provides the ultimate solution for tailings storage in terms of the total lifecycle costs, minimal land usage and closure advantages (Carneiro & Fourie 2019).

Large dams are not usually used for the storage of filtered tailings, but smaller toe embankments are fairly common (Vargas & Campomanes 2022). These toe dams may be designed to provide some stability to the stack, but are more often intended to prevent eroded tailings from washing away from the site. It is also noted that many filter stacks appear to have no toe dam at all, and can therefore be considered to be truly damless tailings storages.

1.5 Sub-sea storage

Sub-sea storage of tailings is relatively uncommon in comparison to terranean storage methods, but it does occur at a handful of mines. This method of storage places the tailings on the seabed in an unconfined manner, which potentially exposes the environment to considerable harm. Proponents for this disposal method claim that it is safe for the environment if the tailings can be placed in deep water, but many nations (including Australia) do not permit it. Due to this prohibition in so many countries, this paper will not devote any more attention to sub-sea storage.

1.6 Geotextile tubes

Geotextile tubes (also known as geobags or ‘geotubes’, as one manufacturer has named their product) are another relatively new technology that has been presented as an alternative to dammed storage of tailings. A geobag consists of a woven geotextile fabric sack that has been sewn to create a long sausage-like bag, up to 100 m in length, and up to 11 m in diameter. The woven fabric can be manufactured with varying tensile strengths, permeabilities and pore sizes, so the geobags can serve to capture solid particles and release water at a range of flow rates. The author has witnessed the successful use of geobags to store secondary flocculated tailings whilst allowing the decant water to flow out through the pores in the fabric.

There have been some notable applications of geobags at scales of relevance to a tailings storage scheme. One application reportedly occurred at a mine in South Kalimantan in 2017 (Tencate 2020), in which 160,000 m^3 of slurry was pumped into six large geobags at a rate of 550 m^3/hour over a two week period. Each bag was 101 m long, with a 36.6 m circumference. It was reported that this campaign deposited 20,000 m^3 of dry cake, which suggests that the geobags were able to bleed 140,000 m^3 of decant water out of the slurry. If the cake was to have a moisture content of 10 percent with a particle SG of 2.65, it is calculated that the effective solids feed rate would be 164 tonnes per hour, which is equivalent to 1.3 Mtpa in an 8,000 hour per year processing operation.

Another project of a relevant scale was carried out in New York state in 2012, in which geobags were successfully used over a two year period to store approximately 1.5 Mm^3 of sediments from the Onondaga Lake dredging project (Hague et al. 2016). The geobags (which numbered more than 1,000 units) were placed on a 24 ha consolidation pad, and were stacked on top of one another at least four layers high (da Silva 2023). Following the completion of the dredging works, the geobag stack was capped with topsoil and revegetated.

Both of these projects demonstrate the potential for geobags to store the entire tailings stream in a modest sized mining operation, without requiring a large dam. It is expected that careful consideration and planning would need to be applied for the set-up and filling of each bag, particularly in terms of the pipework and valve arrangement, and the manual handling and operation required. The footprint and drainage arrangement of the TSF would also require some engineering input.

The tensile strength of the geobags, their possible degradation under UV light, and their possible weathering or geochemical interactions with the tailings would also need to be considered. It is noted that geobags have been utilised in many locations around the world for revetment works along riverbanks and coastlines, which suggests that the geobags have some resistance to UV and weathering degradation.

The economics of geobag use for the storage of tailings, and the longer term performance of such a project are relatively unknown at the current time. The author is not familiar with any projects where 100% of the tailings stream has been stored in geobags. The Segovia gold mine TSF in Colombia is noted here as it used tailings-filled geobags to form an embankment, which in turn stored a large volume of impounded tailings (Garcia et al. 2020), but that project only stored a small fraction of the tailings in the geobags, and was certainly not damless. The recent paper presented by da Silva (2023) presents photos from only one project, and whilst that project was of a relevant scale, the geobags in that project were storing lake sediments, not tailings. Furthermore, crucial cost data was not presented in any references found. It is therefore considered that the geobags may well prove to offer an excellent and economical damless tailings storage and dewatering solution in certain situations, but at the present time, insufficient information is available to enable it to be compared fairly or adequately with other tailings storage options.

2 Thickened versus filtered tailings

Of the six damless tailings storage methods introduced here, it is considered that thickened discharge and filter stacking represent the two most viable, acceptable and proven above-ground storage methods. It is these two tailings storage methods that this paper will focus on. The relative risks and advantages between filter stacking and thickened discharge will be considered. The reliability of the technology, the environmental impacts, the cost of installation and operation, the geotechnical stability of the deposited tailings, the closure of the tailings storage facility, and the record to date for each of these two technologies will be compared and discussed.

2.1 Reliability of the technology

Both filter stacking and thickened discharge tailings storage methods have been improved and refined over recent decades, which has enabled the technology to be reasonably reliable. There have been unwelcome technological challenges encountered on some of the earlier projects that utilised each of the storage methods, but over time, lessons have been learned to enable the designers and equipment suppliers to avoid some of the problems.

In the case of thickened tailings, the accurate prediction of the beach slope has been a source of frustration in some projects early on, but over the past 20 years a greater amount of effort has been devoted to researching the issue and developing better methods for predicting the slope, and this effort has successfully enabled thickened discharge design to become more reliable.

Another cause of disappointment in some projects has been unrealistically optimistic expectations caused by non-representative tailings material being used in the design phase of the project, when the performance of the dewatering technology was being evaluated.

The Centinela copper mine in Chile provides an example of a thickened discharge project that encountered such technical challenges. The TSF was designed as a DVD scheme, but the required beach slopes were not achieved because the required thickener underflow concentration was not achieved (McPhail et al. 2017). In response to this underperformance of the thickeners, the TSF was modified to feature a series of embankments running across the slope, with each embankment retaining some of the tailings.

In the case of filter stacking, the Karara Iron Ore Mine in Western Australia was reported to have experienced a similar type of frustration. It is understood that the tailings sample that was used to evaluate the performance of the filtration equipment was not representative of the actual tailings that would be produced at the mine (de Kretser 2018). This resulted in the filter presses being unable to treat the full stream of tailings, and the need for a wet tailings storage facility to be operated during this period of underperformance (Hore & Luppnow 2014). It is understood that additional filter presses have more recently been installed at the mine, enabling the full tailings stream to be processed satisfactorily (Gleeson 2021).

Some other technical or operational problems have been documented for filter stack projects. Ulrich (2019) suggests that some of the technical risks include:

- Overly moist cake that is not trafficable for mobile conveyors, dozers or compactors
- Slumping problems
- Liquefaction risk
- Drainage issues
- Unexpected problems with wet weather
- Unexpected problems with filter performance due to changes in the ore throughout the life of the mine.

Historically, it is fair to say that most thickened discharge projects and filter stack projects have been largely successful. Over the past 50 years, about 66 thickened discharge schemes have been implemented, with the majority working well. Similarly, about 26 filter stacking schemes have been set up around the world over the past 20 years, with the majority of these performing well too (Vargas & Campomanes 2022).

2.2 Cost of installation and operation

Cost information was recently obtained from seven individuals who represent three reputable suppliers of thickening and filtration equipment. The names of these industry representatives are stated at the back of this paper in the acknowledgements section.

To each supplier, the author requested cost estimates for the capital and operational costs for filter stacking equipment and thickened discharge equipment for two hypothetical scenarios:

1. A gold mine in flat terrain that is processing 1 Mtpa for 20 years, with a TSF 5 km away.
2. A copper mine in flat terrain, producing 30 Mtpa of tailings for 20 years, with a TSF 5 km away.

Some additional input was required for the civil works and some of the other cost estimation, which has been provided by the author. Table 1 provides a summary of the major costs and some notes to explain the costings follow.

Table 1 Cost comparison for filter stack and central thickened discharge, for the two hypothetical scenarios

Filter stacking	1 Mtpa	30 Mtpa
Capex		
Equipment		
Thickeners	1.5	15
Pumps and pipelines	1.1	7.0
Filter presses	8.5	75
Stacking equipment	0	37
Decant pump and pipeline (for rainfall)	0.4	1.0
Equipment total	11.5	135
Construction and installation	23	270
Land acquisition	0.1	0.3
Toe embankment	0.5	2.3
Closure	3.0	14
Capex total	38.1	421.6
Annual opex		
Trucks (4 no 10 t)	3.6	
Excavator 30 t	1.7	
D7 dozer	2.6	
Compactor 10 t	1.0	
Electricity	2.5	38
Water	0.13	3.8
Filter cloths	0.4	3.7
Maintenance	2.0	8.0
Other consumables	0.2	1.9
Annual opex total	14.1	55.4

Central thickened discharge	1 Mtpa	30 Mtpa
Capex		
Equipment		
Thickeners	1.5	15
Pumps and pipelines	2.3	11
Decant pump and pipeline	0.7	3.0
Equipment total	4.5	29
Construction and installation	9.0	58
Land acquisition	0.3	1.5
Perimeter bund and starter ramp	1.8	9.00
Closure	14	45
Capex total	25.1	113.5
Annual opex		
Ramp raises	0.1	0.2
Electricity	1.5	8.0
Water	0.33	10.0
Maintenance	0.8	3.0
Other consumables	0.1	1.5
Annual opex total	2.83	22.7

Notes for Table 1:

1. All figures are stated in millions of Australian dollars.
2. For both of the filtration scenarios, filter presses have been proposed, rather than vacuum filters.
3. For the 1 Mtpa scenario, the equipment suppliers suggested trucks for transporting the cake, rather than using conveyors and stackers.
4. As a rough rule of thumb, the equipment suppliers suggested that construction and installation costs for mechanical equipment is about twice the value of the equipment itself.
5. It is assumed that the thickeners produce an underflow slurry of 60% solids concentration by weight, and that the filters produce a cake of 80% solids by weight.
6. Land acquisition has been assumed to be AUD 3,000 per hectare.
7. The CTD central ramp will be raised periodically. This cost has been amortised to an annual one, even though the actual raises may be spaced further apart (such as every two years).

Table 2 presents the net present cost (NPC) for each of the four scenarios. Two NPCs have been presented for each scenario; the first using a discounting rate of 2% per year, and the second using 10% per year. These particular discount rates have been selected to enable comparisons to a cost exercise that was presented by Carneiro & Fourie (2019).

Table 2 Net present cost comparison for filter stack and central thickened discharge, for the two hypothetical scenarios

Filter stacking	1 Mtpa	30 Mtpa
Capex total	38.1	422.6
Upfront capex	35.1	408.6
Closure	3	14
Opex total	14.13	55.4
NPC 2%	268	1324
NPC 10%	156	882

Central thickened discharge	1 Mtpa	30 Mtpa
Capex total	26.1	126.5
Upfront capex	12.1	81.5
Closure	14	45
Opex total	2.83	22.7
NPC 2%	68	483
NPC 10%	38	281

The findings of this economic comparison suggest that a CTD is about one quarter of the price for a filter stack of the same capacity. This is not too dissimilar to the result that Carniero & Fourie (2019) calculated before they tested a high land purchase cost scenario.

2.2.1 Cost of land

It is of interest to note that Carniero & Fourie (2019) came to the conclusion that filter stacking was cheaper than thickened discharge when the ‘potential total lifecycle costs’ were considered. Amongst the potential lifecycle costs that were tested by those authors, the most influential was a proposed land purchase price of AUD 1 M per hectare. Indeed this would have a significant impact on the economics of a CTD scheme, if a mine was going to be set-up in a location where land cost that much. The AUD 3,000 per hectare cost used in this study is based on the median price paid for agricultural land in Western Australia in the year 2019, which was reported at AUD 2,569 (Bennett 2020). It is expected that the cost of land in the Western Australian goldfields would be lower than this median price paid for agricultural land, given that many mines in this region are located in areas that are too dry and saline for any agriculture to be viable.

2.2.2 Cost of water

In the arid climatic conditions posed for this exercise, evaporative water losses from the TSF are expected to be high. Filtration of the tailings to 80% solids (by weight) recovers a significant amount of water in comparison to the thickened discharge option. It is expected that the filter cake will not bleed any more water once deposited on the dry stack, so the process plant will therefore require make-up water to replace all the water that the filters don’t extract.

The thickened discharge option recovers far less water from the tailings slurry, with the thickener underflow assumed to contain 60% solids (w/w). Upon discharge into the TSF, it is expected that some of the decant water will bleed to the surface and trickle towards the decant pond, but most of this bleed water will be lost to evaporation, as will most of the decant water that remains in the deposited tailings mass. At nighttime, some of the bleed water will be recovered in the decant pond, and during any rainfall events there will also be some harvesting of runoff, but for the purpose of assessing the cost implication of the worst possible scenario, it has been assumed that all of the decant water will be lost, and require replacement.

For the costing exercise, it has been assumed that the make-up water will come from local groundwater bores at a nominal cost of AUD 0.50 per m^3.

The calculated water consumption figures for each of the scenarios are presented in Table 3.

Table 3 Water consumption figures for the two scenarios

Filter stacking	1 Mtpa	30 Mtpa
Make-up water (Mm^3/year)	0.25	7.5

Central thickened discharge	1 Mtpa	30 Mtpa
Make-up water (Mm^3/year)	0.67	20.0

The findings of this economic comparison suggest that a CTD will require approximately 2.7 times the amount of make-up water, compared to a filter stack.

It is understood that some copper mines in the Atacama Desert in Chile pay up to USD 5 for a cubic metre of water. Previous exercises in the impact of that high cost of water have had mixed results. Carneiro & Fourie (2019) tested the impact of a water cost of AUD 5 per cubic metre, and found that the CTD was about half the cost of the filter stack, but Fitton & Roshdieh (2013) found that the filter stack cost a similar amount to the CTD when a water cost of USD 5/m^3 was evaluated.

2.2.3 Transport costs

The cost of transporting filter cake is significantly higher than the cost of pumping thickened tailings slurry. Conveyors are often used for transporting filter cake at operations with large tailings production rates, whilst trucks are more typically used for transporting the cake at smaller operations.

For thickened tailings slurry, positive displacement pumps are sometimes needed for pumping paste and thickened tailings if the slurry is particularly viscous, or if the pipeline is particularly long, but many thickened discharge schemes are able to operate with centrifugal pumps. It is also worth noting that some DVD schemes do not need to pump the thickened tailings slurry at all. At the Sar Cheshmeh copper mine in Iran, the thickener underflow discharges onto the ground from the base of the thickeners, and then runs by gravity down a valley to the TSF.

2.2.4 Spreading and compaction of the tailings within the tailings storage facility

A major advantage of all thickened discharge schemes is that once the slurry is discharged onto the TSF from its discharge point, it runs down the beach by gravity flow, and requires no mechanical assistance to reach its final deposition location. This hydraulic deposition process spreads the slurry in thin sheets, typically 5–10 cm thick. This is thin enough for evaporation to extract moisture from the full depth of the layer (in dry climatic conditions), causing the deposited tailings to achieve relatively high dry densities and shear strengths.

Filter stacks require mobile tripper conveyors, radial stackers, bulldozers or graders to move the cake to its deposition location. Filter cake generally requires mechanical compaction in order to achieve target densities and shear strengths.

These differences in the transport, placement, spreading and compaction of the tailings add to the cost of operating a filter stack. It is in this aspect of the process where thickened tailings has a strong economic advantage over filtered tailings. Thickened tailings also enjoy a geotechnical advantage over the filtered tailings in this aspect of the process, as explained in Section 2.3.

2.3 Geotechnical stability of the deposited tailings

The hydraulic deposition process that occurs on the tailings beach in a CTD or DVD results in the slurry being spread into thin layers before it comes to a stop. The layers are thin enough for evaporation to extract moisture from their entire depth, and cause the consolidation and strengthening of that layer. The deposited tailings in a mature CTD or DVD (one that is more than a few weeks old) in a dry environment will be unsaturated for most of their depth (Seddon & Albee 2015).

The surface of the deposited tailings on a CTD or DVD will also be sloping at an angle of 1–3 degrees typically. In the case of a CTD on flat terrain where there is no large embankment supporting the tailings, the geotechnical stability of the deposited tailings is very high, because of this very flat geometry. Compared to a filter stack (or any other type of above-ground TSF, such as a conventional tailings dam), the CTD offers significantly greater stability.

A DVD usually features a large dam, as discussed in Section 1.3. This does present a geotechnical stability risk, and the embankment needs to be designed and constructed with care. However, compared with conventional dammed tailings storages, a significant portion of the tailings stored in a DVD are not saturated. This also provides an advantage from a geotechnical stability perspective.

Filter stacks have the potential to be very stable geotechnically, providing the moisture content, the degree of compaction, and the side slope geometry are all favourable.

Filter stacks often feature flat surfaces. These surfaces may be smooth after compaction of the deposited tailings, or furrowed beforehand, such as that shown in Figure 1, at the La Coipa dry stack TSF. These flat surfaces soak up rainfall, particularly in a furrowed surface, due to the poor surface drainage. This rainfall infiltration has a negative impact on the shear strength of the stored tailings, effectively reducing the Factor of Safety.

Figure 1 The Rako filter stack tailings storage facility at the La Coipa mine (Vargas & Campomanes 2022)

Ulrich (2019) spoke of filter stacks that were not trafficable, due to the moisture content of the cake being too high. He also spoke of the potential for the moisture content to be affected by changes in the ore or grind size. This saturation of the cake can have detrimental impacts on the stack stability.

The trafficability issue also prevents the deposited cake from being compacted, which in turn prevents it from achieving the targeted shear strengths that are called for in the design. This also threatens the stability of the stack.

The side slopes of filter stacks can be shaped mechanically (with dozers, for example), or naturally, by allowing the cake to stack at its own angle of repose. The side slopes on the filter stack at the Poderosa TSF in Peru are reported to be 1.5 H:1.0 V (Vargas & Campomanes 2022). These side slopes are interspersed with horizontal benches of 2 m width to achieve an overall slope of 1.7 H:1.0 V. It is possible that the local topography prevents a flatter slope from being practically achievable, but in any case, this stack slope is quite steep, which presents a greater geotechnical stability risk than a CTD. Other filter stacks may not be quite as steep as the Poderosa stack, but all of the 28 stacks listed in the Vargas paper have side slopes that are considerably steeper than a typical CTD.

2.4 Environmental impacts

2.4.1 Dust

Both methods of tailings disposal are susceptible to producing dust. It might be argued that the thickened discharge TSF is likely to produce more dust because of its larger surface area than a dry stack of a similar capacity, but conversely, it might also be argued that the steeper side slopes on the dry stack could be more susceptible to creating dust. Progressive reclamation might be a practical option for the side slopes of the dry stack, and might also be possible for part of the CTD too, if it is being developed in a linear direction. The application of dust suppressants might also be possible for both options, depending on trafficability.

2.4.2 Erosion

Dry stacks are potentially more susceptible to erosion than a thickened tailings deposit, due to the steeper slopes that typically prevail on a dry stack. The damless filter stack (where a toe dam is not constructed) may allow tailings to be washed from the slopes of the dry stack and migrate into the downstream environment. It is expected that some sort of toe dam, bund, or sediment dam will be needed to prevent this.

2.4.3 Groundwater impact

It is expected that both types of tailings storage will have very little impact on groundwater, given that the majority of the stored tailings is expected to be unsaturated. Some workers have presented evidence to show that the majority of tailings in a CTD are unsaturated, and therefore, not allowing decant water to seep into the ground below (Williams et al. 2008; Seddon & Albee 2015). For filter stacks, the author has not yet found any similar published information, but it is suggested that the filter stack will have no impact on groundwater if the filtered tailings can be kept drier than the saturation point.

2.4.4 Carbon emissions

A filter stacking operation generally produces significantly more atmospheric carbon dioxide emissions than a thickened discharge TSF because of the amount of energy that is required for the dewatering process and the transport, distribution and compaction of the cake. Carneiro & Fourie (2019) estimated that the filter stack would create about seven times the carbon emissions of the equivalent sized CTD.

2.5 Closure considerations

Thickened discharge schemes generally cover a much larger footprint than a filter stack. On this basis, it is generally expected that the closure costs for a CTD or DVD will be greater than an equivalently sized filter stack. With that said, it should be noted that the side slopes of filter stacks range between 1.5:1 to 2.5:1 (Vargas & Campomanes 2022). These are quite steep gradients to cap, particularly if the capping is expected to be resistant to erosion. Given that so few filter stacks have been closed because of the relative novelty of the technology, this matter may be found to create challenges in future.

2.6 Record to date

2.6.1 Thickened discharge

Some 60 thickened discharge projects have been documented in the literature, with 35 listed by Williams et al. (2008), another 23 by Vargas & Pulido (2022), and a couple more documented separately (Fitton et al. 2018; Cooper & Smith 2011). In addition to these 60, the author suggests that five more projects can be added to the list to bring the total to 66: Aktogay (Kazakhstan), Bozshakol (Kazakhstan), Hera (NSW), CSA (NSW) and Bulga (NSW). This last project is somewhat unorthodox in comparison to other thickened discharge projects, as this TSF is at a coal mine that discharged secondary flocculated tailings to create conical mounds of tailings on top of existing coal tailings deposits for the purpose of capping the very soft underlying tailings. The mounds were hydraulically placed from a raised discharge point like a CTD, and the flocculation did effectively prevent segregation of the solids, but the slurry was not thickened beyond the segregation threshold prior to the flocculation. It might therefore be argued that this secondary flocculated conical deposition is not strictly a CTD, since the thickening is absent, but it has been found that the secondary flocculation process can cause slurries to exhibit depositional behaviour that can be practically exploited like that of thickened slurries.

2.6.2 Filter stacks

The literature reports 26 filter stacking schemes that have been set-up around the world over the past 30 years, with the majority of these located in (or near to) the Atacama Desert in South America (Vargas & Campomanes 2022). This is hardly surprising, given the scarcity of water in the Atacama, and the significant number of mining operations located there. It should be noted that most of those mines in the Atacama are more than 2,000 m above sea level (some more than 4,000 m), and so the cost of transporting water there from the ocean or other low-lying sources can drive the water cost beyond USD 5 per cubic metre.

3 Discussion

This paper started out with a focus on damless tailings storage methods as an approach to avoiding dam failures. Of course, not all dams fail. It is indeed possible to engineer dams safely, and many have been. However, it is worth considering the fact that overtopping has been one of the greatest causes of tailings dam failures over the years (Stark et al. 2022). The sad reality is that overtopping is one of the few causes of failure that can be fairly readily engineered out of the picture. Spillways, if adequately sized, will prevent an overtopping incident. Making spillways compulsory is an obvious idea for the avoidance of overtopping failures, even if it was to apply only in high rainfall areas. This would still make a significant difference, given the track record of so many mining companies that have gone broke and abandoned sites without proper closure. The ANCOLD guidelines, as an example of an internationally reputable dam design guideline, do recommend that spillways should be installed in dams, but they do not go so far as to make them compulsory. Such a change would reduce the number of dam failures, and improve the image of the mining industry. Any bonds that are forfeited by bankrupted mining companies could also be applied for spillway installations, particularly in high rainfall areas.

It should also be noted that many tailings dams have failed for other less predictable reasons. Some of these failed dams have received plenty of engineering input from reputable companies and individuals, but they failed anyway. Examples such as Mount Polley, Samarco or Cadia can be considered in this respect. Alternative technologies such as those discussed in this paper will enable such catastrophes to be mitigated or possibly avoided.

An obvious question is why we are still designing conventional dams for TSFs, when numerous published articles indicate that thickened discharge schemes are cheaper (Fitton & Roshdieh 2013; Carneiro & Fourie 2019), safer (Robinsky 1975, 1978; Williams et al. 2008) and environmentally superior to a conventional tailings dam with saturated tailings (Robinsky 1975, 1978; Williams et al. 2008). It would appear that a major cause of this poor adoption of CTDs and DVDs is poor communication by the engineers who understand the advantages of the technology, but who fail to get the message out there to others in the mining industry.

4 Conclusions

To address the question posed in the title of this paper, ‘Is filtration the best solution for tailings storge that avoids dam failures?’, the following responses are posited:

No, not for the majority of mines in the world. In flat terrain, A CTD generally offers far superior economics, much lower carbon emissions and superior stability in comparison to a filter stack. In sloping or mountainous terrain where water is available, a DVD will usually offer superior economics over a filter stack.

A filter stack does enable more process water to be recovered and recycled, which is of value in extremely dry areas. In situations such as these, a filter stack may well be the best tailings storage solution.

A filter stack also occupies less land than a CTD or DVD of the same capacity, so in areas with high land values (close to a city, for example), a filter stack may prove to be more economical. A small percentage of mines are located in areas with expensive land, but the vast majority of mines are not. In consideration of all the available information, it must be concluded that a thickened discharge scheme will offer a superior tailings storage solution for most mining operations.

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