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Inverted barriers in tailings storage facilities: lessons learnt

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ABSTRACT

Tailings Storage Facilities (TSFs) are increasingly regulated as waste containment systems, yet their barrier system is inherited from municipal solid waste (MSW) practices, which differ significantly in scale, waste behavior, and pore pressure regime. Inverted barrier systems have been successfully used in TSFs, where tailings contribute to the barrier function in conjunction with a geomembrane. Lessons from design, construction, and operations are discussed, emphasizing the importance of subgrade conditions, tailings uniformity, compaction, and drainage system. Key challenges include achieving consistent permeability, managing differential settlement, and ensuring long-term stability under high loads are discussed. Proper implementation, however, requires careful attention to shear behavior, drainage design, and early-stage deposition planning which shall be considered within a robust CQA plant.

Keywords: tailings, TSF, inverted barrier

1 INTRODUCTION

Tailings Storage Facilities (TSF) contain the “tail” of the mining process, which is essentially crushed rock to a silt fraction where the minerals are extracted through different processes. The extraction process of primary minerals generally produce byproducts which are hazardous to the environment as for instance cadmium and aluminum for zinc, oxidation during smelting producing Chrome VI and nitrates when blasting is used in mining operations. Furthermo, tailings are characterized by a low pH.

In the early days of mining operations in the 1900’s TSF’s were unlined and many facilities around the world, particularly in South Africa, namely the Witwatersrand Gold Rush in the late 1800’s has left hundreds of TSF unlined as the mine waste was covered under mining regulations, rather than environmental, water and waste regulations.

Today’s regulations, mostly across the world, have agreed to treat tailings as a waste product, and therefore, they are treated like any other waste material. However, the barrier system which is applied to TSF is inherited from municipal solid waste (MSW) facilities which are very different from TSF as illustrated in Table 1. The design criteria differ significantly, ranging from footprint to temperature and the behaviour of the waste in terms of stability and pore pressure regime within the waste. Furthermore, the main difference is in the permeability as tailings could be several orders of magnitude less permeable than municipal solid waste, and in some instances, tailings has the same or lower permeability as a compacted clay liner (CCL) required by regulations.

Table 1. Differences between MSW and TSF

Design Criteria	MSW	TSF
Height (m)	20 – 30	100+
Topography	Impoundment	Varies
Behavior	Drained	Drained / Undrained
Pore pressure regime	300mm	0.5 x Height
Waste Permeability (cm/s)	10^{-4} - 10^{-6}	10^{-7} – 10^{-9}
Temperature (˚C)	25 – 70	25 TSF
Waste type	High	Moderate
Footprint (ha)	20 – 30	500+
Deposition	Mechanical	Varies

Fan and Rowe (2021) have developed formulas to calculate the leakage through a hole overlaid by a geomembrane, which results in a leakage rate between 100 and 1000 times lower than a single composite barrier system. Whilst the use of tailings to replace a CCL is welcomed in many aspects, several lessons from design, construction, and operations should be considered.

2 SUBGRADE

The use of tailings to form a composite barrier with the geomembrane meets the maximum particle size requirement of 3mm (SANS 10409), as most tailings will not exceed the 1mm fraction. However, whereas for a traditional barrier, the subgrade is not a concern, given the protection of a CCL, for an inverted barrier, the subgrade comes into intimate contact with the geomembrane, and therefore, a higher level of care is required.

If the subgrade had a permeability higher than 10^{-5}m/s, the risk of piping could occur (Rowe et al. (2017). Viceversa, for a subgrade with a permeability of 10^{-2}m/s (poorly graded pea gravel) with geotextile with a mass of 580 g/m^2, the measured flow rate was slightly greater than a silty-sand underliner.

Due to the high variability of subgrade over TSF areas, it could be challenging to ensure the subgrade meets the specifications required to be in contact with an HPDE geomembrane, therefore as a good practice a protection geotextile with a mass above 1 500gr/m^2 if polyester or 2 000 gr/m^2 if polypropylene is used to meet both protection criteria below the HDPE, but also to ensure that if the subgrade could potentially suffer piping failure, the geotextile will avoid it, reducing the QA/QC on the subgrade and the risk of failure by introducing a relatively cost-effective geosynthetic.

The important role of the subgrade is to ensure that the geomembrane does not strain under loading, which could occur locally through variation of the soil, thus the compaction requirements. Furthermore, there are also total settlements to consider as TSF can apply pressure above 2 MPa and more, considering megadams can reach up to 100m and more in height. Such a high load will require foundation improvement to prevent the geomembrane from straining excessively due to differential settlements between the toe and the crest.

For instance, a TSF with a maximum height of 50m constructed over a residual soil in central Africa, characterized by a m_v of 0.2 m^2/MN and a thickness of 10m, could expect settlement in the order of up to 2m.

This should be taken into account by ensuring that the geomembrane has built-in slack allowing to slide without developing strain. A classic example is for geomembrane to be connected to fixed structures, such as decant towers as illustrated in Fig.1, where the geomembrane was constructed to allow to deform as the penstock inlet has been built over a soil raft and the surrounding soil not.

Fig. 1. HPDE geomembrane excess around a fixed structure allowing for settlements.

3 TAILINGS PROPERTIES

3.1 Grading

As tailings become part of the barrier system, there shall be homogeneity across the area, ensuring the permeability is met according to the design.

Tailings is generally deposited hydraulically using delivery lines as illustrated in Fig 2. As the tailings settles, the coarser fraction will settle closer to the deposition point and the finer the material, the further away it will deposit.

Fig. 2. Hydraulic deposition of tailings over a geomembrane

Therefore the permeability, which is a function of the grain size will vary across the basin. For a chrome tailings deposited by means of cycloning, mechanically split is achieved for the coarse and fine fraction, Fig. 3 clearly illustrates the difference between overflow and underflow differing by one order of magnitude in permeability.

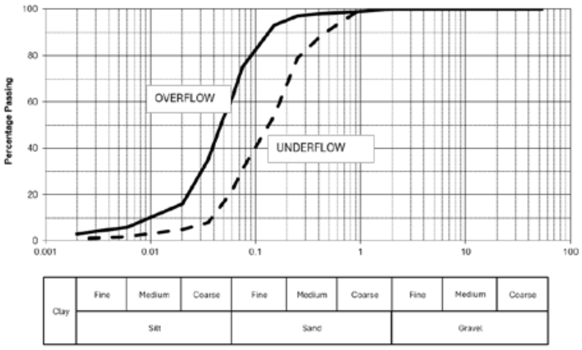

Fig. 3. Particle size distribution of overflow and underflow

3.2 Quantity and variation

The quantity of tailings required to cover the exposed geomembrane is in considerable as TSF basins are in the hundreds of hectares, therefore assuming a layer thick enough to protect the geomembrane if mechanical deposition is used which will require at least 300 to 500mm, the amount of tailings is around 1million tons. This quantity might not be an issue for instance a copper mine, which has a yearly thruput in the tens of millions per year; however, for a gold or platinum group metal (PGM), this tonnage could require a few years of production, which needs to be a taken into account.

Tailings is generally homogenous compared to natural materials as the parent rock is often the same and the milling process does not varies during life of mine. However, instances such as upgrading of the mine plant to allow a finer production (thus higher recovery) or a re-mining process will affect the particle size distribution. As well as changing the tailings from slurry to filter paste can affect the properties as often the filter presses require a stringent particle size distribution (capped D_{max}) to work within acceptable conditions.

3.3 Construction

The behaviour of the tailings is fundamental for the stability of a TSF, as unless it is a fully impounded facility (ie, water dam), the strength properties of the tailings influence the stability (ICOLD, 2022). If tailings behaves in a brittle and contractive manner it shall be handled considering its residual strengths, resulting in very low shearing parameters and stability analysis requiring containment embankments.

In order to avoid a failure plane at the bottom of the facility provided by the tailings used for the inverted barrier, the first layer of tailings, varying between 300mm and 1m is included as part of the construction programme, rather than operations. This difference provides the following advantages:

- engineered deposition of the tailings, which often at later stage becomes the culprit for weak zones in the TSF (due to incorrect deposition);
- stricter QA/QC on the tailings layer which is tested both for compaction and permeability, ensuring specifications are met;
- protection of the geomembrane under controlled conditions;
- deposition of tailings prior to completing the project.

For not fully impounded TSF, the deposition plan is part of the design as deposition dictates the rate of rise, drying cycle, and construction methodology, which might require a coarse outer shell and a fine fraction inside. This activity is provided by the TSF operator, a specialist contractor which has knowledge of how a TSF is constructed (could be within the mine or external). Ensuring that the first layer of tailings is controlled under the construction programme allows the engineer to have input on the deposition programme, as well as be on site to monitor if the deposition programme is adequate for the site conditions.

Lastly, allowing the deposition of tailings prior to project completion enables the mine to plan for early tailings deposition, which could relieve other TSFs or even allow the mine to continue production. However, this requires careful consideration, as, for instance, if tailings are placed, downstream infrastructure should be in place to cater for stormwater, and the designer shall ensure the unlined areas are protected.

For a barrier system in a TSF the installation rate is generally around 10 000m^2/day, achieved by using several teams on site. Therefore, if the TSF is 700 ha, the installation of the geomembrane will take about 3 years, plus 6 months for regulatory approvals. However, allowing tailings to be deposited during construction has the advantage of covering the geomembrane and protecting and handing it over to the client if the entire CQA process is completed. The designer, together with the mine, could and should consider a phased commissioning, which could require some enhancement to the stormwater management and deposition cycle, allowing a controlled deposition and early commissioning.

4 DRAINAGE AND STORMWATER

In an MSW barrier system, a leakage and drainage collection system is present below the barrier system, and a drainage system is present above the barrier system, respectively. In an inverted barrier configuration, the leakage detection system could become a preferential flow path as if a standard subsoil drainage with geotextile and gravel is used, tailings could go in piping due to the geotextile been selected aiming for permeability rather than retention, thus creating a risk of preferential flow path for tailings.

The drainage collection system above the barrier system ensures the phreatic surface is managed by ensuring there are sub-hydrostatic conditions ensuring stability of the TSF body. For fully impounded facilities with a downstream raised, this conditions is reduced as the TSF is actually designed similarly to a water dam requiring only a toe drain, whilst for upstream dams, the outer wall is designed to have a drained behaviour and a system of toe drain, blanket or chimney drain is cater to allow the drop of phreatic surface leaving a dry outer shell as illustrated in Fig.4 (Wates, 2023).

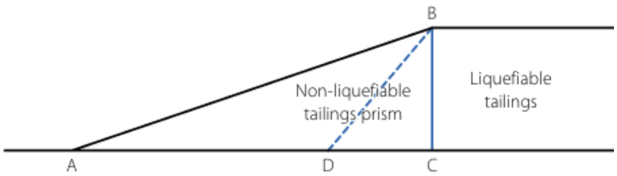

Fig.4. Outer shell configuration developed by reducing the phreatic surface using drainage collection drains

It is imperative that the drainage system is designed to be resilient over the entire TSF, and with closure in mind, the drainage system shall be in place even after the TSF is rehabilitated, as the phreatic surface will take years to reduce, assuming a non-infiltration capping or a negative water balance applies.

For a MSW barrier system the hydraulic head over the barrier is generally considered as the thickness of the drainage system, whilst for a TSF with a wet deposition, the phreatic surface is generally a percentage of the full height and generally linked to the supernatant pool, resulting in hydraulic head equals to the height of the TSF. As the barrier system is provided by the combination of intimate contact between HDPE and tailings, the drainage system needs to be placed above the tailings, otherwise if a hole in the geomembrane is present over a porous medium leakage will occur as the conditions of inverted barrier is not longer valid.

However, raising the drainage system above the tailings barrier system will result in fully saturated conditions of the tailings below requiring the tailings to be compacted to a density ensuring a dilative behaviour under shearing conditions. In Fig.5 the drainage system has been placed over 100mm of tailings which ensure the pore pressure on the tailings dam were as low as possible for stability purpose. However, to ensure the geomembrane is not damaged during the placement of the tailings, it is often recommended to have a layer thickness of at least 300mm as the pore pressure is still negligible.

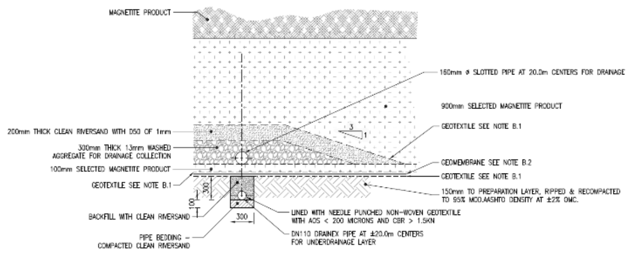

Fig.5. Typical section of an inverted barrier with drainage

5 STABILITY

The inclusion of preferential sliding plane governs the stability of waste containment structures, be it MSW or TSF. Usually for MSW or fully impounded TSF, the barrier system is placed over the containment walls; therefore, the sliding plane will follow the weakest shear interface at the base, cutting through the embankment or follow the liner up the embankement, depending on the weakest shear resistance (often is the geomembrane). However, for other configurations which result in the barrier system running below embankments or for upstream tailings dams, the geomembrane will govern the stability. Whilst shear interface resistance can be tested according to ASTM D5321, it shall be noted that the effective pressures from a tailings dam could be in order of ten times higher than normal MSW; therefore, loading up to 2Mpa should be considered in testing.

The most critical aspect is to ensure that no brittle behaviour is present. However, while geosynthetics to geosynthetics usually result in a plastic or ductile behaviour, the interface between tailings and geomembrane, especially when textured, will often provide a drop in shear resistance.

Recent stability design guidelines (ICOLD, 2022) require drained, undrained peak and undrained residual conditions to be met. This is based on the shearing behaviour of the tailings. However, with a barrier system, it should be considered that whilst the tailings is at peak (ie 3-5% strain), the shear interface of the barrier system might be in its residual stage, and therefore, the peak analysis will result in tailings at peak and shear interface at residual. Fig.6 illustrates two interfaces (A and B) and tailings. They are all brittle; however, with interface A, the tailings will dictate the peak stability, whilst with interface B, the interface will prevail over the tailings.

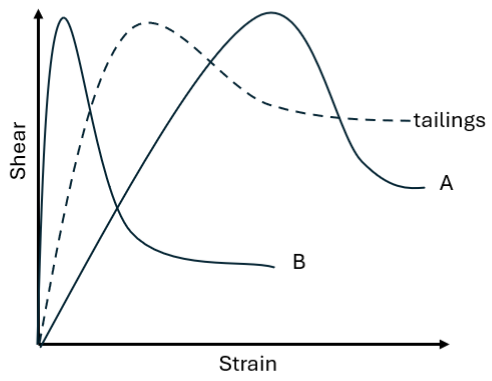

Fig.6. Shearing behaviour between tailings and barrier interface.

It is also essential to ensure that enough data are produced to understand the variation in shear resistance, as illustrated by Julien (2014) in Fig. 7, where the variation in shear interface led to lower values than those used in design.

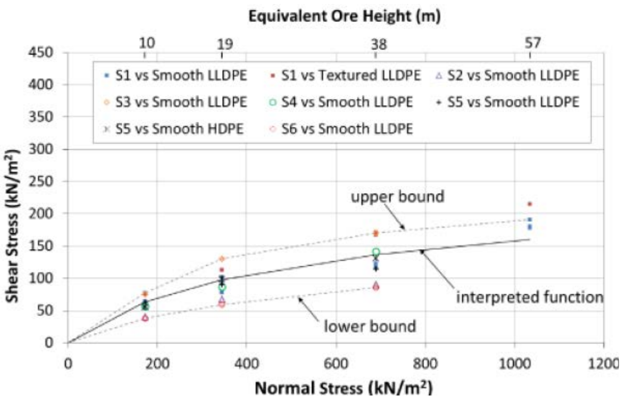

Fig.7. Access roads next to drainage collection system (Julien, 2014)

6 CONSTRUCTION QUALITY ASSURANCE

Nowadays robust construction quality assurance (CQA) is in place for the construction of barrier system, requiring not only a design engineer but also a CQA engineer which oversees the entire process.

CQA associated with TSF is generally easier than for MSW, as the geometry and associated infrastructure are generally less extensive (no sumps, extensive drainage, etc.); however, the size could be challenging, where lining could extend up to 600–1000 ha with multiple welding crews working simultaneously.

If the first layer of tailings is part of the construction, this means that project specifications and construction quality assurance (CQA) applies. This is very important as it ensures the foundation layer of the TSF is correct, and if any deviation is highlighted (often low densities or a finer fraction is produced at the starting up of the plant), the engineer, in concert with the contractor and the mine, can develop deviation to the design which are recorded.

The simplicity of inverted barrier is reflected in a easier CQA as if a protection geotextile is used below the geomembrane, the in-situ soil requirements are strongly relaxed with just compaction requirements needed. What is critical is the tailings as it could be deposited hydraulically or mechanically. The size of the tailings is often less than 3mm, which is the maximum allowable size for a geomembrane; however, in certain processes (ie ash dams), there could be a concern due to bottom ash being deposited directly over the geomembrane. For tailings, this is not an issue. The CQA is often concentrated on related infrastructure, such as construction of the drains or even accessing the facility, which results in access roads built next to the drain, as shown in Fig 8.

Fig.8. Access roads next to drainage collection system.

Two issues need to be considered in electric leak location (ELL). The first consideration is whether a geotextile is present below the geomembrane for protection, and if the subgrade does not have sufficient moisture, the ELL may not function effectively because the layer below the geomembrane is dry. The other one is when tailings is deposited hydraulically, and access is challenging. To overcome these challenges, depending on the area's climate (wet or dry), specifications allow for pre-wetting of the geotextile to trap sufficient moisture. For the tailings, mechanical deposition is often recommended for constructing the barrier system. Fig. 9 illustrates the findings from an ELL for an inverted barrier where once investigated it was found that it was caused by a wrinkle in the geomembrane.

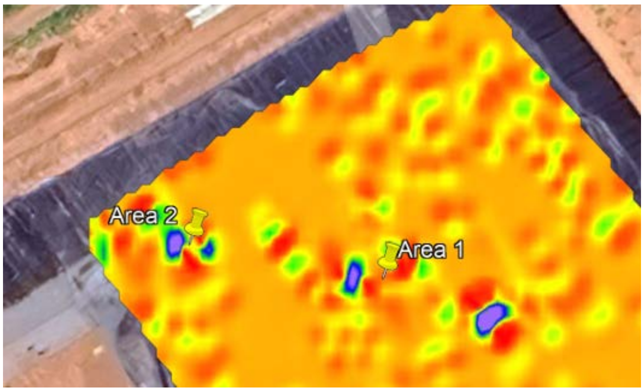

Fig.9. Electric leak location map

As the tailings is constructed and not deposited, CQA will require a compaction and a permeability test. Whilst compaction can be easily obtained as the material does not vary, assuming adequate construction machines are utilized (ie, dozers and rollers), the permeability could be challenging as a double ring infiltrometer could take a long time and rather refer to the Guelph infiltrometer test.

Lastly, the tailings production for covering the geomembrane could be in the order of years and protection should be considered to not leave the geomembrane exposed for large period of time which could be damaged by normal operations (ie. operator driving over it) or weather such as wind, but most critical are wildfires.

7 CONCLUSIONS

Barrier design for tailings dams has been adopted from MSW barriers, however the composition of the tailings, pore pressure, operations and stability is very different than the ones for a MSW system.

The introduction of an inverted barrier, by using the tailings to provide the composite barrier system to gather with a geomembrane, has simplified the design and construction, as well as provided a financial saving and easier CQA to the system.

Consideration of drainage collection systems and compaction of tailings to ensure a dilative response below and the correct shear interface behaviour are items which are critical for an efficient design and robust operations, ensuring the stability is not affected and the environment is preserved.

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