ABSTRACT: Under current environmental legislation in South Africa, tailings are viewed as potentially hazardous waste which needs to be disposed of in compliance with the minimum requirements for that type of waste. The platinum tailings in this case study classified as a hazardous waste requiring an HDPE liner as a key component of the pollution control barrier for the disposal of the tailings. Traditionally, tailings dams in South Africa have been built on top of the in-situ soils. The use of liners is a relatively new phenomenon in tailings dam construction in Southern Africa and brings with it its own set of challenges. For example: where before the in-situ soils may have acted as a natural drainage medium for the tailings dam, all drainage must now be artificially added; stability of the tailings dam needs to be assessed in new ways as different possible failure mechanism need to be considered; and management of stormwater during construction must be carefully planned. This paper will present a case study highlighting how some of these challenges were addressed in a project where an HDPE liner was included in the design of the tailings dam.

1 INTRODUCTION

1.1 The requirement for a liner in South Africa

The regulations promulgated under the National Environmental Management Act (Regulations 632, 634, 635 and 636) are currently administered by the Department of Water and Sanitation in South Africa. Under these regulations waste, including tailings, is assessed under Waste Acceptance Criteria for Disposal to Landfill (Refer to Figure 1), which determines the requirements for disposal of different types of waste. Under these regulations, various mineral residue deposits are found to require a geomembrane liner of sorts. It is usually not practical, and currently not mandatory, to retrofit a liner to existing tailings dams. However, there is an increase in the number of new tailings dams being constructed to include a geomembrane liner.

The Department of Water and Sanitation (DWS) no longer views South Africa’s historic philosophy of the past 20 years, which allowed for dilution of water contamination and dispersion relying on attenuation, as acceptable (Legge, 2019). Protection of water resources, and prevention of contamination in the first place, is now being sought in preference to mitigating contamination spread and pollution clean-up.

Apart from preventing polluted leachate from seeping into the groundwater, an additional benefit of lining a tailings dam is that more water in the tailings system can be captured and returned to the plant. This is useful in a water scarce country such as South Africa.
Since the tailings industry has not always included liners in its design or construction, there are learnings to be made, even by seasoned tailings consultants and contractors, on how to deal with these liners.

A document (proposed amendments to Regulation 632 (2016)) has been drafted whereby there could be a future possible relaxation of the regulations on a case-by-case basis following a risk-based approach. However, such regulations have yet to be promulgated into law. In the mean time, the current regulations apply to the disposal of tailings in the same way they apply to the disposal of any other waste to landfill.

<table>
<thead>
<tr>
<th>Waste Type</th>
<th>Landfill Disposal Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 0 Waste</td>
<td>The disposal of Type 0 waste to landfill is not allowed. The waste must be treated and re-assessed in terms of the Norma and Standards for Assessment of Waste for Landfill Disposal.</td>
</tr>
<tr>
<td>Type 1 Waste</td>
<td>Type 1 waste may only be disposed of at a Class A landfill designed in accordance with section 3(1) and (2) of these Norms and Standards, or, subject to section 3(4) of these Norms and Standards, may be disposed of at a landfill site designed in accordance with the requirements for a Hh / HH landfill as specified in the Minimum Requirements for Waste Disposal by Landfill (2nd Ed., Department of Water Affairs and Forestry, 1998).</td>
</tr>
<tr>
<td>Type 2 Waste</td>
<td>Type 2 waste may only be disposed of at a Class B landfill designed in accordance with section 3(1) and (2) of these Norms and Standards, or, subject to section 3(4) of these Norms and Standards, may be disposed of at a landfill site designed in accordance with the requirements for a GLB+ landfill as specified in the Minimum Requirements for Waste Disposal by Landfill (2nd Ed., DWAF, 1998).</td>
</tr>
<tr>
<td>Type 3 Waste</td>
<td>Type 3 waste may only be disposed of at a Class C landfill designed in accordance with section 3(1) and (2) of these Norms and Standards, or, subject to section 3(4) of these Norms and Standards, may be disposed of at a landfill site designed in accordance with the requirements for a GLB+ landfill as specified in the Minimum Requirements for Waste Disposal by Landfill (2nd Ed., DWAF, 1998).</td>
</tr>
<tr>
<td>Type 4 Waste</td>
<td>Type 4 waste may only be disposed of at a Class D landfill designed in accordance with section 3(1) and (2) of these Norms and Standards, or, subject to section 3(4) of these Norms and Standards, may be disposed of at a landfill site designed in accordance with the requirements for a GLB- landfill as specified in the Minimum Requirements for Waste Disposal by Landfill (2nd Ed., DWAF, 1998).</td>
</tr>
</tbody>
</table>

Figure 1  Class C landfill engineering requirements (NEMA Reg 636)

1.2 Case Study – Marula tailings dam
Marula Platinum Mine is located approximately 32 km northwest of the town of Burgersfort in Limpopo Province, South Africa. The pre-deposition works for the mine’s existing tailings dam was constructed in 2003 as an unlined facility, in line with the legal requirements at that time. The existing tailings dam is approaching it’s end of life and a new tailings storage facility (TSF) is currently under construction to accommodate the mine’s future tailings production. The footprint of the new tailings dam (77 Ha) is shown in Figure 2 in relation to the location of the existing tailings dam. The new tailings dam is planned to abut the existing facility and rise over the southern portion of the existing facility by some 5 m, to a maximum height of 47 m. The new tailings dam is planned for a design life of 20 years.
The site for the new tailings dam slopes gently, at an approximate slope of 1:60, downwards toward the northwest. The geology of the site comprises part of the Eastern Limb of the Bushveld Igneous Complex (BIC). Typically, the top 1.5 m of the soil profile comprises topsoil and firm to stiff clay (residual norite, also known as black turf). Beneath this, soft rock Gabbro-norite is encountered. The Moopetsi river is located approximately 500m to the west of the new facility.

The new tailings dam is designed to accommodate the full tailings stream from the Marula plant, so that operation of the new tailings dam is independent of any disposal requirements on the existing tailings dam. Since the new tailings dam will receive tailings from the same source as the existing tailings dam, its design is based on material properties derived from in-situ and laboratory testing of the tailings on the existing tailings dam. The design has also tried to keep the design boundary conditions similar for the new design as for the existing tailings dam, such as a Rate of Rise (RoR) of 2.5 m/year.

Various studies were undertaken, which show that the Marula tailings classifies as Type 3 waste according to Regulation 635 (2013). This is mainly due to the tailings leachate having elevated nitrate (N03) levels, in excess of the minimum leachable concentration threshold (LCT) for which no barrier system would have been required. It is understood that much of the nitrates result from the explosives used in the mining process.

Scavenger wells have been implemented around the existing tailings dam, to limit the migration of the pollution plume into the groundwater. However, the DWS no longer view interception as an acceptable solution where prevention in the first instance is possible.

According to Regulation 636, a Class C landfill barrier system, or a barrier of equivalent performance, is required for disposal of Type 3 waste. Thus, the new tailings dam will require a Class C barrier system or equivalent at its base. The components which make up a Class C barrier system are shown in Figure 3. Notably the system comprises:
• Barrier components – a 1.5 mm thick HDPE geomembrane over a 300 mm thick clay liner,
• Protection components – geotextile or fine material to preserve the integrity of barrier components, and
• Drainage above and below the barrier components.

Figure 3  Class C landfill engineering requirements (NEMA Reg 636)

The inclusion of a barrier system into a tailings dam, not only increases the complexity of the tailings dam design, but also the construction and operation of the tailings dam. There are various unique challenges which had to be dealt with in this project however, this paper focuses only on the challenges specifically relating to the introduction of a liner into the design.

2  DESIGN CHALLENGES

2.1  Drainage considerations
As soon as a low permeability barrier system is introduced as part of a tailings dam design, drainage needs to be carefully considered. It is generally the drains which make the incorporation of a liner into a design expensive, and not so much the cost of the liner material itself.

The purpose of the above-liner drains is to:
• Draw down the phreatic surface (loosely equivalent to the water table) for structural stability purposes,
• Reduce the head on the liner, thus reducing the seepage gradient, and
• Reduce the liquefaction potential of the tailings material.

The purpose of the under-liner drains is to:
• Mitigate against construction issues related to water trapped beneath the liner forming “whales”, softening the foundations etc.,
• Provide a leakage detection layer, and
• In this particular case, because the new tailings dam abuts the existing tailings dam, to drain seepage from the existing tailings dam.

Above liner drains need to be designed with protection from stormwater damage in mind. They also need to be designed so that the fine tailings which are first deposited over them do not cause them to blind, which would render them useless for the remainder of the tailings dam’s life.
2.2 Drainage design

Various alternatives were considered for the drainage above and below the liner. The final drainage design, presented to and accepted by the DWS, constituted a herringbone structure of drains on a 50 m spacing as shown in Figure 4. Steady state finite element seepage models were undertaken, which confirmed that this spacing reduces the head on the liner to 5 m for the worst case. This reduces the seepage gradient and hence possible seepage across the liner.

A robust toe and blanket drain were included in this above liner drainage, designed with consideration of the closed form solutions and other recommendations presented by van Zyl and Robertson (1980). These are the primary drains responsible for drawing down the phreatic surface under the outer slope, which is required for structural stability of the tailings dam. The outlets from the blanket and toe drains are separate to the rest of the basin drainage, also on a 50 m spacing. This means that, in a worst-case scenario, if some of the inner basin drains were to block, the blanket and toe drains could continue to operate independently.

The herringbone drains across the basin of the tailings dam collect into three major arterials, which serve as outlets to these drains. The herringbone drains, in addition to reducing the head on the liner as already mentioned, attempt to mimic the basal drainage observed through piezocone test work on the existing tailings dam. In the existing tailings dam downwards seepage in the tailings basin can flow, to a limited extent, into the in-situ soils, which act as a natural drainage medium for the flows. In the lined tailings dam, drains need to be artificially added which will permit equivalent flows.

![Figure 4 Above liner drain layout](image)

A section through a typical drain is shown in
Figure 5. There are 0.5 m high bunds, covered with the liner, on both sides of the drain, to protect the drain from stormwater damage. Sacrificial geotextile, which is removed before deposition, temporarily covers the drain, also to protect it from stormwater damage. A layer of coarse tailings is included as the topmost filter layer of the drain. This is to prevent the sand layer of the drain from blinding, were the finest tailings material otherwise to be deposited directly over it. A substantial geomembrane (A8) is included in the drains between the lowest gravel filter layer and the geomembrane. This is to protect the geomembrane from puncture by the gravel, and to limit strains in the geomembrane which would otherwise contribute to service life reduction (Brachman, 2008).

To cater for uncertainties which exist around how all the drains will perform, redundancy has been introduced in the number of pipes in the drains. This redundancy comes at a relatively minor cost compared to the major reassurance this redundancy brings with it.

2.3 Liner design
During the conceptual phase, alternatives to the geomembrane liner were considered, ranging from a 7.4 m thick clay only liner to vast amounts of drainage material only without a liner. In the end a 2 mm thick HDPE geomembrane was selected, overlying a 300 mm thick compacted layer of clay. The 2 mm thick geomembrane is thicker than the stipulated Class C landfill 1.5 mm thick geomembrane, however, it was chosen as it would be more robust against damage during installation, and until the liner was covered everywhere with a protective layer of tailings. A double-sided textured liner was chosen beneath the crest of the tailings dam to improve the interface friction between the liner and the underlying clay/overlying tailings (refer to Section 2.4).

2.4 Stability
The stability of a tailings dam is commonly determined using limit equilibrium methods. The tailings dam and its underlying soil horizons are considered as one “combined structure” when undertaking slope stability analysis. A factor of safety (FoS) of greater than 1.5 against large scale slope failure is considered acceptable under steady state drained conditions, for the stability of the combined structure. If
there are significantly weaker layers within the tailings dam or its underlying soil horizons, the failure slip circle will generally pass through these weaker layers.

In the case of the existing unlined facility, the black turf horizon presents a weak layer with a friction angle $\Phi = 21^\circ$. In the case of the new lined facility, the weakest layer is the interface of the soils/tailings with the liner. This interface is taken from literature to have a friction angle $\Phi = 16^\circ$. Specific shear interface testing, between samples of the actual materials from site and the actual chosen liners, is still underway. Figure 6 shows the output of a slope stability analysis undertaken for one of the sections of the new tailings dam. An overall outer slope of 1:4 is required to achieve a FoS of at least 1.5. This is flatter than the slope of 1:3 which is used in the existing facility. The flatter slope means a reduction in the airspace available for material storage within the sloped areas of the lined tailings dam compared to the unlined tailings dam.

The use of a double-sided textured liner beneath the crest of the tailings dam is also expected to improve the interface friction above the conservative design value of $16^\circ$. This will increase the level of confidence that the material properties on site are at least as good as the design properties.

The phreatic surface for the slope stability analysis was based on the output of the seepage analysis discussed in Section 2.2. In Figure 6 the assessment has assumed that all the drains are fully functional. Stability analyses were also undertaken for hypothetical scenarios where the blanket drain is blocked and non-functional. These analyses give a FoS of greater than 1.3 for drained conditions. This is considered acceptable for a short term, non-steady state condition, which could be rectified through remedial measures.

The geometry (i.e. width) of the coarser, more permeable tailings (outer desaturated zone) is known for the existing tailings dam from the results of piezocone test work undertaken there. By ensuring that the boundary conditions for the existing and new tailings dams are as similar as possible, knowledge of the tailings behaviour (i.e. width of the outer desaturated zone) on the existing tailings dam can be inferred to the new tailings dam.

![Figure 6: Output from slope stability analysis](image)

Overall slope = 1:4
2.5 **Paddocks**

It is common practice for unlined, upstream constructed tailings dams to include paddocks at their toes to help manage stormwater runoff from the tailings dam’s outer slopes. The catchment paddocks are designed to contain and store the stormwater runoff for later evaporation or seepage into the in-situ soils. Stormwater which runs over the outer tailings slopes is considered contaminated water which, if allowed to seep into the in-situ soils, would defeat the purpose of lining the tailings dam in the first place. The approach taken for this project was to combine the attenuation function of the catchment paddocks and the conveyance function of the solution trench into one system of in-line attenuation ponds (Janse van Rensburg, 2018). The solution trench was designed to accommodate not only the base seepage flow, but also the peak storm flows from the outer tailings slopes.

To avoid an excessively large solution trench channel area, containment walls were introduced every 100 m along the solution trench, to slow the time it took for all the water from upper catchments to join the downstream flows in the solution trench. Base flow is catered for by a slit in the wall, while peak flow will build up and overtop the wall.

![Figure 7 Typical containment wall in the solution trench](image)

3 **CONSTRUCTION CHALLENGES**

3.1 **Quality assurance**

The success of a lined facility in acting to limit the seepage of leachate relies on all components of the facility being constructed to the highest standard. The liner is manufactured to high quality standards, micrometre accuracy, and passed through numerous tests (in accordance with GRI-GM13) before even leaving the factory. Once construction starts, all of this can be lost if the same diligence is not applied during the installation of the liner.

Each roll of liner which arrives on site comes with its own quality certificate, so that if later there is a problem during the site inspections, it can be traced to a particular production batch at the factory. A panel layout is generated for the deployment of the liner panels (see Figure 8). Each position in the layout is numbered so it can be recorded which corresponding roll of liner is in which position. Many kilometres of
welded seams between the panels need to be inspected, tested and records kept relating back to the panel layout.

Such onerous quality assurance requirements during construction require a trained and meticulous workforce of quality inspectors.

3.2 Protection against stormwater damage
The timing for the construction of this project is such that a large portion of the liner installation will be constructed during the rainy season. Stormwater can flow very rapidly over the liner, as it does not have the roughness of the natural vegetation. Stormwater can pond on top of the liner, as it cannot infiltrate into the natural soils. High speed stormwater flows and ponding of water can cause significant damage to the above liner drainage.

In addition to the drain specific measures which have been taken to protect the drains from stormwater damage (See Section 2.2), other measures have also been implemented. A permanent stormwater cut-off trench is included on the upslope eastern and southern sides of the facility. It is likely that temporary cut-off trenches may be needed upslope of sections of the basin, to protect the liner works as they are proceeding. Intermediate penstocks have been included in the design, close to the inner toe of the tailings dam, to assist with decant of ponding stormwater during construction.

3.3 Phasing and sequencing of construction
Phased construction of the new tailings dam was considered. Apart from the usual benefits associated with phased construction, such as delaying capital expenditure, in the case of a lined facility there would be additional benefit in that the liner would lie exposed to the elements and to vandalism for a shorter period, before being covered by a protective layer of tailings. Closer inspection showed however, that in the case of the new Marula tailings dam, because the site is relatively flat, the entire tailings dam could be
covered by a relatively thin layer of protective tailings within the first few years. Phasing was not considered beneficial for this project.

The sequencing of construction works around the installation of a liner is complex but important. Once the liner has been laid, traffic cannot be allowed to pass over it, as this can damage the liner. Even pedestrian traffic must be limited, and labourers educated, as to the simple risk of dropping a cigarette or a pen knife onto the liner can have serious consequences. With the herringbone drains spaced every 50 m, this means that the liner and the drains have to be constructed concurrently. The liner cannot be trafficked over again to later go and place the drainage materials over it.

The liner cannot all be laid at once. Placement the liner will depend on the rate of the drain construction. The contractor either has to order shipments of liner in batches, which increases the risk that materials aren’t available on site when they are required, or the contractor must store a vast quantity of liner on site for a long time. It is approximately 9 months from when the first liner until the last liner is laid in the Marula tailings dam project programme.

Liner can deteriorate if stored for a long time exposed to the elements. Rolls of black liner can heat up if ventilation is not allowed through stacks of the liner. The upper exposed surface of a liner was recorded to heat up to 83 to 86°C at midday at various site in Limpopo (Legge, 2019). If covered with a thin (100 mm) layer of soil, or tailings, the temperature of the liner and number of associated wrinkles was found to reduce significantly. Getting a layer of tailings over the Marula tailings dam’s liner as soon as practical will be a priority.

### 4 COMMISIONING CHALLENGES

The project is not yet at the commissioning phase. However, the following are foreseen to be areas which will require careful attention when this phase is reached:

- Protection of drains from blinding. This is a challenge when commissioning any tailings dam. There are just that many more drains which need to be protected in the case of a lined tailings dam, so this activity needs to be that much more rigorous.
- Removal of the sacrificial geotextile covering every drain before depositing over it. The geotextile has not been designed as a filter layer, but is in place instead to protect the other filter layers from eroding.

### 5 CONCLUSIONS

Liners are becoming a legislative requirement for many new tailings dams in South Africa. Liners also offer an opportunity to capture more water within the tailings system and return this water to the plant, which is useful in a water scarce country.

Since the tailings industry has not always included liners in its design or construction, there are learnings to be made, even by seasoned tailings consultants and contractors. In particular, there are learnings to be made on how to deal with the liners, associated drain design and commissioning.

The inclusion of a barrier system into a tailings dam, not only increases the complexity of the tailings dam design, but also the construction and operation of the tailings dam. This has been illustrated through the case study presented in this paper.
ACKNOWLEDGEMENT

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REFERENCES


