Challenges in ensuring stability whilst providing environmental compliance for existing TSF's

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Abstract. The stringent requirements for tailings storage facilities (TSF) following the publishing of the Global Industry Standards for Tailings Management (GISTM) have required in depth stability supported by advance testing and modelling, where in the presence of a hazardous tailings facility would require knowledge of the barrier system. Often a buttress is required to increase the factor of safety from the one originally designed, complying with stability as well as environmental requirements, and most importantly without triggering any failure during construction. When the tailings and the buttress material classifies as waste, it adds one more level of complexity which needs to be accounted in the stability as well as in the barrier design system, especially when the materials requires different barriers system. The paper aim to present a project where the facility requires a buttress as the original design in the early 2000's was not acceptable in today's requirements. The stability pivot over a multi-layered barrier system (which does not allow Mohr-Coulomb failure criterion) and the different waste classification between the tailings and the buttress material, requiring different barrier requirements, yet to all be tailored in a constructible solution, without affecting the stability of the TSF.

1 Background

The publishing of the Global Industry Standard for Tailings Management (GISTM) in 2020 [1], following several failures with catastrophic consequences on the social and environmental surroundings has been marked as a milestone in the mining industry by the International Council of Mining Metallurgy (ICMM).

Many mining companies around the world had strenuously worked to achieve compliance in December 2023 for extreme and significant structures and by 2025 all TSF's shall comply with the 47 principles defined in the GISTM standard.

Tailings storage facilities (TSF) have been around for centuries, man made structures to contain tailings (crushed rock up to a silt like particles) and mostly hydraulically deposited. Several deposition methods have been used based on the site topography (ie. valley dam or impoundment), built with tailings in an upstream, centerline, downstream methodology (raised direction of the crest compared to the toe of the dam). In South Africa, the most common deposition methodology has been upstream, being the most cost-effective construction methodology and supported by a dry climate, low seismicity and low rate of rise

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(how fast the TSF grows over one year, expressed in m/year); opposite to regions such Brasil, with a high rainfall and high seismicity where upstream deposition following the failure of the Feijão Dam have been banned.

The embracing of GISTM has required a deeper analysis in terms of understanding the behaviour of tailings, especially its undrained response under shearing, which if exhibiting a contractive behaviour and a brittle response, it would lead to liquefaction (complete loss of strength). In GISTM, within Principle 4 requires the understanding of all possible failure modes and the use acceptable factor of safety for slope stability to account. Therefore, over and above the static drained case, undrained scenario in both peak and residual behaviour is required if the tailings will behave undrained.

Once GISTM is applied to South African facilities, it resulted in improvement remediations to meet the more stringent requirements (ie. drained factor of safety of 1.5 rather than 1.3), which often results in buttressing of the facility as rockfill is often freely available and there are no space restrictions.

GISTM Principle 5 address the environmental compliance which is further defined in South Africa, through the waste management framework published in the National Environmental Management Waste Act, 2008 (NEM:WA) [2] and following Regulations, based on the concentration of pollutants and the receiving environment, the barrier system is tailored to reduce the leakage the higher the concentration is. Four types of wastes are classified: Type 0 being the most hazardous to Type 4, the least hazardous. Barrier systems are presented in Regulations 636 [3] for the various types of waste (note Type 0 shall be treated to a lower type prior to be disposed), from Class A to Class D barrier system.

2 Project background

An undisclosed tailings dam has been constructed in several phases (in the 90's, 2000 and 2012). The tailings is classified as waste Type A, according to R636 and a barrier system was installed at foundation level to limit groundwater contamination. Following geotechnical investigation comprising of cone penetration testing with pore pressure measurements (CPTu) a stability analysis was developed highlighting low factor of safety compared to current mine own regulations.

A first TSF was built in the 90's but no records area available. An extension was then built in 2000 (prior to waste regulations) where a barrier system comprising of a 1mm HDPE geomembrane over a 300mm in situ compacted clay as a primary barrier and a further 450mm compacted clay below the leakage collection system was built. Only As-Built drawings were available for the extension and no records are available in terms of design criteria and stability analysis were available. Currently this TSF is dormant (no active deposition) taking place.

The second TSF was built in 2012 were a 2mm textured geomembrane was used over a 10mm geosynthetic clay liner (GCL) and a further 300mm of compacted clay liner as a primary barrier, whereas a 1.5mm textured HDPE geomembrane over a 300mm compacted clay was used as secondary barrier. No information of the geosynthetics area available in terms of performance and construction quality assurance. Currently this TSF is about 5m height with a design heigh of 10m at end of life.

The stability of the second TSF considered the textured geomembrane as the weakest failure plane and modelled as a soil with a certain thickness characterised by friction angle of 22° and a cohesion of 6 kPa. No testing was reference in the design report, and it is assumed that those values were based on reference and shear interface testing was not conducted.

The entire barrier system was modelled in the stability analysis (with a determined thickness to allow the software to consider the failure plane), however the author deems the weakest failure plane would actually be the GCL in contact with the compacted clay.

Furthermore, it shall be noted that the compacted clay is sourced from residual soil present in the area, well known for its high PI (more than 30) and low shearing resistance.

2.1.1 Original stability

For the extension of the TSF, only as-built drawings were available and no design report was found. For the second TSF a design report was available where the stability was calculated with both factor of safety and probability of failure. No reference or testing have been provided with regards to the range of values for the strength parameters dictating the probabilistic analysis, thus it is excluded from the discussion, the stability was performed using a block failure mechanism over the various shear interface with the lowest factor of safety recorded of 1.31 in static drained conditions. No stability in undrained peak or undrained residual were calculated.

2.1.2 Further geotechnical testing

With the publication of mine owned standards with regards to tailings management following worldwide recognised standards such as the Dam Safety Guidelines published by the Canadian Dam Association in 2012 [4], stringent factor of safety was adopted for TSF's, requiring compliance not only in static drained conditions, but also in undrained peak and residual or post liquefaction (complete loss of strength).

In order to develop the analysis a further geotechnical investigation comprising of SCPTu and laboratory testing was undertaken which provided further evaluation of the material strength. It shall be noted that whilst the failure is expected within the barrier system, no testing of the shear interface liner was not conducted in previous stability analysis. The outcome of analysis resulted in unsatisfactory factor of safety, requiring remediation measurements.

3 Remediation measurements

3.1.1 Design Criteria

The low factor of safety from the recent investigation resulted in a request by the mine to design a buttress as it is deemed to be the solution with the highest cost-benefit ratio as the material for the buttress is available by the mine and there are no space limitation around the TSF to increase the footprint. The buttress was designed considering current elevation for one TSF whilst final elevation (+5m higher than current) for the new one.

The tailings classified as Type 1 waste, requiring a Class A barrier system, whilst the buttress material classified as Type 3 waste, requiring a Class C barrier system according to Regulation 636.

The outer slope of the buttress was set a 1V:2.5H with a top berm width of 9.5m for the dormant TSF and a 1V:1.5H for the active one as the buttress is limited in height by the current TSF.

3.2 Barrier design

The current barrier system beneath both TSF's is deemed to be working based on the groundwater monitoring around the site and the leakage measured below the barrier system. The new barrier design was developed with the main principle to keep the waste stream independent from each other as the footprint of the buttress would require a considerable cost if a Class A barrier system was adopted throughout.

The presence of an existing toe wall as shown in figure 1 was considered as the boundary between the type 1 waste from the TSF and the type 3 waste from the buttress.

Fig. 1. Existing toe wall.

Due to the lack of information on the existing barrier performance (no record of MQC/MQA available for durability) and the sensitive nature of the site where excavation to extract geomembrane from the bottom of the TSF was not considered due to the low factor of safety, it was decided to use the existing barrier system as a secondary barrier and a new primary barrier brought over as shown in Figure 2.

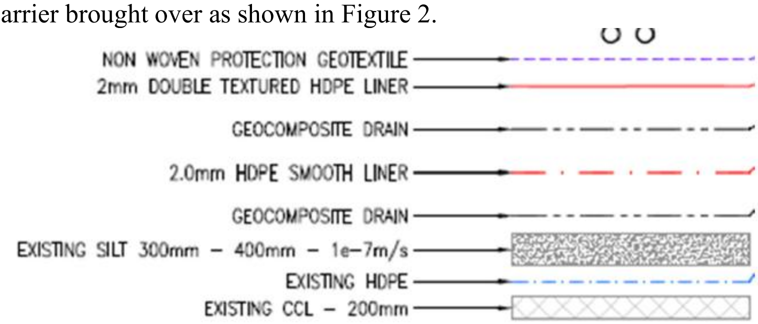


Fig. 2. Class A barrier system using existing barrier as secondary barrier.

The use of a double HDPE geomembrane was preferred over a compacted clay as the limited space would have damaged the existing liner and the compaction would have been challenging if not inadequate. Furthermore, chemical compatibility with the waste stream has shown from swell testing RMD calculation as per Benson and Meer [5] the presence of divalent cations (Mg and Ca) would have compromised the reaction of the montmorillonite of the GCL, resulting in a higher permeability.

From an hydraulic design, a seepage analysis was conducted in the dormant TSF which considered a worst case scenario of phreatic surface, plus a 1:50 year 1 day storm applied to calculate the run-off and the toe wall was deemed sufficiently high to contain the flow (500mm).

As the type 1 waste seepage was contained upstream the toe wall of the existing TSF, only the buttress material was considered in the barrier system, therefore requiring a Class C barrier system being a type 3. A Class C barrier is a single composite barrier was required and it was achieved by carrying the top HDPE geomembrane over the toe wall with beneath a GCL. As mentioned above the GCL has deemed to not performed as expected due to chemical compatibility (permeability testing are undergoing at the time of writing with the contractor sourced GCL) and as a further enhancement to the design, the geomembrane thickness was increased from 1.5mm to 2mm and the natural material as illustrated in figure 3, which in places has presence of residual soil (with permeability up to -11m/s) will be tested using a double ring infiltrometer to calculate the actual permeability on site. The choice of using the GCL rather than a double HDPE was for stability as otherwise a double geomembrane with a drainage layer in between would have resulted in a much lower shear interface angle, resulting in a wider footprint for the buttress.

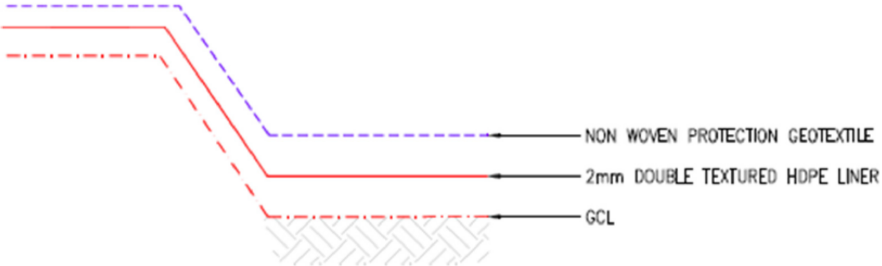


Fig. 3. Class C barrier system under the buttress.

A protection geotextile has been specified to prevent damage by the buttress material (D_{max} 24mm) with a unit weight of 1 500 g/m^2 in polyester continuous filament. According to Hornsey [6], this compares to a 2 200 g/m^2 polypropylene geotextile. Furthermore, a testpad has been constructed to check both damage to the liner as well as any strain in the geomembrane as illustrated in figure 4. Results from the testing confirmed that the maximum strain in the geomembrane with a load of 500kPa (full height of the buttress) results in a strain of 1.5% calculated using the Tognon et al. method [7] as illustrated in figure 5, which is below the value of 3% for which geomembrane would exhibit stress cracking potentials.

Fig. 4. Testpad under construction to monitor damage and strain in the geomembrane.

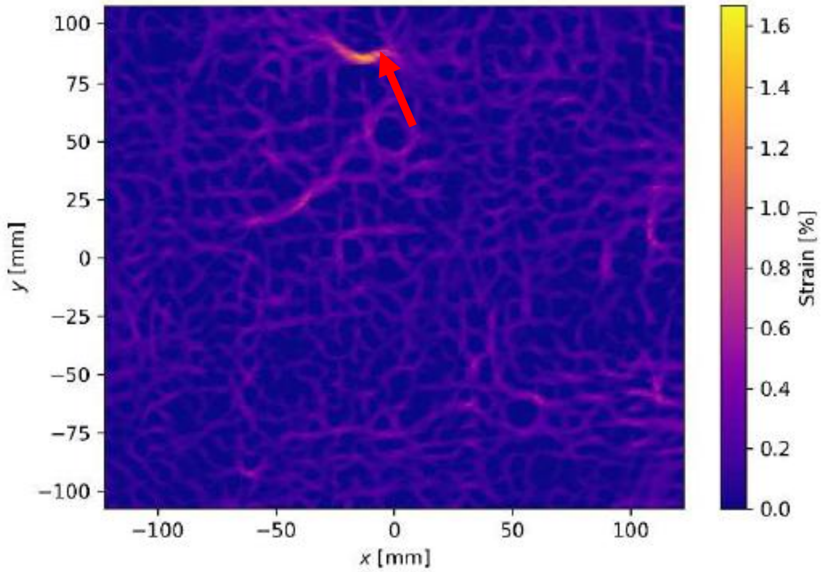


Fig. 5. Result of the testpad according to Tognon et al method.

3.2.1 Shear interface testing

The presence of a barrier system generally implies that the weakest failure plane is function of the weakest shear interface within the barrier system. As mentioned above, no testings were made available for the previous phases, therefore a literature value was used for the shear interface for the dormant dam and the active dam as different barrier systems were used. For the buttress, the dominant shear interface is between the residual soil and the GCL.

Testing in accordance with ASTM D5321 reported a ductile failure therefore the shear resistance at 10mm displacement was considered and the shear stress function in figure 6 was considered, with the cautious assumption of a 0 kPa adhesion.

The shear interface value below the existing TSF considered a Mohr-Coulomb failure criterion with literature value based on the existing information. Table 1 provides the values used in the stability analysis and the shear interface considered for peak and residual conditions.

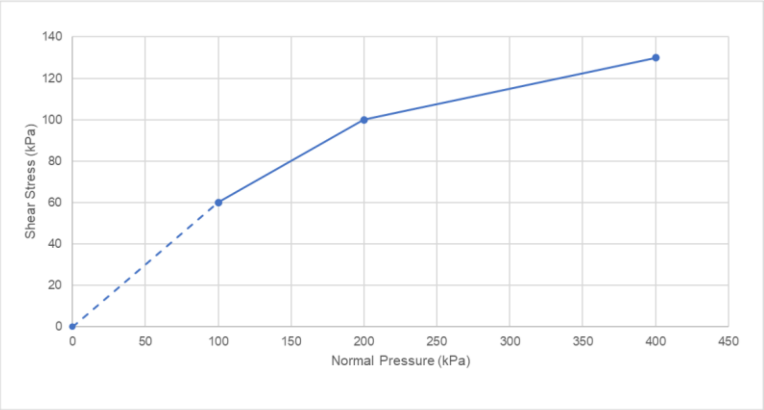


Fig. 6. Shear interface function between GCL and residual soil.

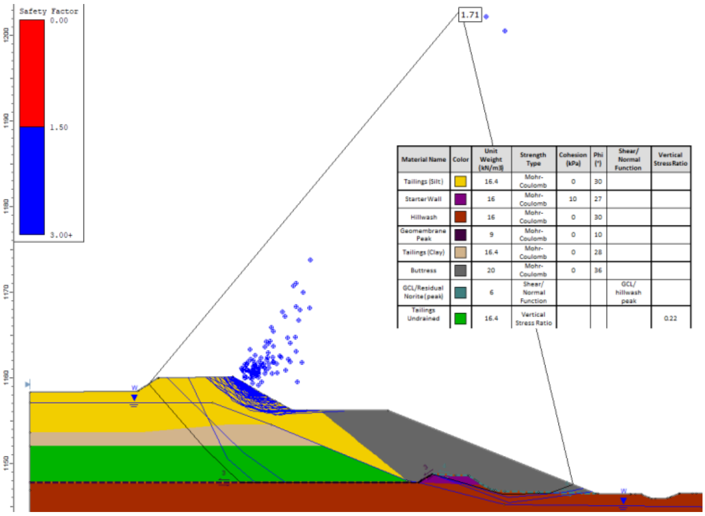
Table 1. Shear interface defined for stability analysis.

TSF	Shear Interface	Φ_{peak}' / Φ_{res}' (°)	a_{peak} / a_{res} (Kpa)
Dormant	Smooth HDPE / residual clay	11 / 6	0 / 0
Active	GCL / Clay	21 / 16	5 / 0

3.2.2 Stability Analysis

The stability analysis was updated considering a shear interface testing conducted between the shear – stress function rather than a Mohr-Coulomb in order to follow the results as well as the lowest shear resistance in the barrier system. From the CPT investigation and triaxial testing, strength ratio in peak and residual were obtained using Robertson method and from the dissipation of the CPT a pore pressure regime with a gradient of 5 Kpa/m was highlighted, however it was considered hydrostatic to allow for future operations. The buttress was designed to meet static drained, undrained peak and residual factor of safety.

To note that this facility was originally designed for static drained factor of safety of 1.3, whilst now the static drained required 1.5; yet the dictating factor of safety is residual with a target factor of safety of 1.1. Figure 4 illustrates a typical stability using RocScience Slide where the failure is through the barrier system as expected and different shear interface functions were used.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (°)	Shear/ Normal Function	Vertical Stress Ratio
Tailings (Silt)	🟨	16.4	Mohr-Coulomb	0	30		
Starter Wall	🟪	16	Mohr-Coulomb	10	27		
Hillwash	🟥	16	Mohr-Coulomb	0	30		
Geomembrane Peak	■	9	Mohr-Coulomb	0	10		
Tailings (Clay)	🟫	16.4	Mohr-Coulomb	0	28		
Buttress	⬛	20	Mohr-Coulomb	0	36		
GCL/Residual Norite (peak)	🟦	6	Shear/ Normal Function			GCL/ hillwash peak	
Tailings Undrained	🟩	16.4	Vertical Stress Ratio				0.22

Fig. 5. Typical stability result for static undrained peak condition (note the different barrier system configuration).

3.2.3 Drainage

The drainage was divided as well between the Class A barrier to cater for the infiltration by the TSF and the Class C by the buttress. HDPE pipes to assure long term durability have been considered with drilled holes designed to retain the D_{min} of the buttress material to ensure bridging would occur. Due to the importance of drainage in TSF, a factor of safety between 5 and 10 was used with slope of more than 1% to ensure no silting up within the pipe and allow for camera inspection and jet-rodding. A 250mm PN 17 PE 100 was specified. One drainage system will run within the toe wall above the Class A barrier and the other one will be at the hill of the buttress as the foundation is sloped inward at 2% to ensure no water is discharged outside the barrier system (a toe wall is included to formalise the barrier at the toe of the buttress).

4 Conclusions

The increase in surveillance and monitoring of tailings dam has increased in the past 5 years due to recent failures and the introduction of the Global Industry Standard for Tailings Management (GISTM) and related standards.

Existing TSF's under these new conditions are deemed not meeting stability requirements and required improvements which often lead to construction of buttresses. If the tailings classify as waste, the inclusion of a barrier system is often the caveat in the stability and it might have not been carefully considered during the original design.

The stability is dictated by the shear interface of the barrier system, being on the geomembrane or on the clay, today software technology allows to define point to point the shear interface as well as the shear resistance over stress, to account for multi-layered systems or brittle response (ductile would be conservative).

In this case study, the complexity of four different barrier systems present on the same facility, required careful consideration on how to tailor the barrier system around the stability component as the TSF was marginally stable and common solution such as excavation and running barrier system along the slopes were not satisfactory. Furthermore the different waste classification between the tailings and the buttress material allowed the use of different barrier system to improve the cost effectiveness of the solution and for a more efficient construction, over and above tailoring the design to an active facility with running deposition, active stormwater and surveillance and monitoring in place.

Environmental and geotechnical compliance need to be considered during operations as well as in rehabilitation and closure which will require considerations on the performance of the system in perpetuity and the final land use such as the performance of the drainage material, erosion of the slopes and the performance of the barrier system which is assumed to reach end of life when a non-infiltration capping is constructed.

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