Utilizing geotextile tubes to extend the life of a Tailings Storage Facility

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ABSTRACT: As environmental legislation becomes more stringent, the required capital and operational investment for the construction and operation of mine Tailings Storage Facilities (TSF) is increasing significantly. The paper describes the system of geotextile tubes filled with tailings to create structural elements to enable the use of filled tubes to create extensions/rises for new and existing TSF's. Tubes can be placed as a new dam foundation or stacked on top of existing tailings dams, resulting in dam embankments comprising filled geotextile tubes, which leads to increased storage capacity for the mine operator and a subsequent expansion of the life of TSF's. Additionally, it is possible to use a broad range of tailings within the geotextile tube due to the potential to dewater the fills with flocculation agents, if required, during the filling process. The construction process is described and the required geotechnical stability aspects explored.

1 INTRODUCTION

1.1 *Environmental legislation*

Legislation (Waste Act 2008, National Norms and Standards 2013) in South Africa relating to the environmental requirements of mine waste storage has been updated (Waste Amendment Act 2014) with a more stringent requirement required from the mine owners and operators with respect to the treatment of their waste, including tailings. Consequently, higher amounts of capital and operational investment is likely to be required to deal with the deposition of mine tailings. A possible solution to reduce the mine investment is to incorporate encapsulated geotextile tubes to form the main structural body of the TSF dam/embankments. The financial benefits of including geotextile tubes is that even the finer fraction of the tailings could be used within the construction of the tailings dam which leads to a cost-effective use of a traditional waste product. There is also potential sustainability benefits due to the re-use of a former waste product, which substitute's coarser grained aggregates traditionally used to construct the tailing dam structures.

1.2 Geosynthetics

For several decades geosynthetics have been used successfully for mine related applications including the capping of sludge lagoons, geogrid reinforcing of retaining structures, including dam walls, reinforcement of access roads, and lining of TSF's and other impoundment facilities. In fact, almost all types of geosynthetics for the purposes of separation, filtration, drainage, reinforcement, protection, sealing and erosion protection can be applied within the wide application field of tailings dams.

This paper presents the first concepts of dewatering tailings using geotextile tubes. The dewatering processes, tube dimensioning and methodologies for stability analysis are introduced.

2 DEWATERING TUBE COMPONENTS

2.1 *Geotextile tubes*

Geosynthetic dewatering tubes were originally developed for the purpose of dewatering of sewage and various sludge sediments. The standard dimensions vary from small tubes with 30m³ storage volume up to 65m long tubes with a containment capacity of approximately 1,600m³ per tube. In combination with carefully selected flocculation agents almost every type of tailings/sludge can be dewatered within the geotextile tubes, including both organic and inorganic substances. Once filled, the dewatering tubes are elliptically shaped, stable long geotextile containment elements designed with a dewatering and storage function.

Normally the dewatering tubes are furnished with inlets, distributed along the longitudinal axis of the tube. The tube filling is undertaken through these nozzle inlets with the processed tailings slurry. Tubes can be installed in a single layer or stacked with multiple layers (Figure 1) to form a pyramidal type geometry (see Wilke et al 2015 for case study on stacked tubes).

Figure 1. Stacked dewatered geotextile tubes (5 tube layers high) after Wilke et al 2015.

2.2 *Flocculation*

The majority of the tailings is likely to be at the lower end of the grading curve i.e. clay and silt sized particles. Such particle sizes would take a long time to dewater within the geotextile tube, therefore additional flocculation agents are added to the tailings before they are pumped into the geotextile tubes to increase the speed of dewatering (the exception would be coarser tailings similar to a medium grained sand size which would have sufficient inter grain pore space to dewater under pumping pressure and self-weight).

There are several ways to agglomerate the finely suspended solids in order to increase the water release capacity and enhance the dewatering performance of the tailings (Wilke & Breytenbach 2015). Two basic bonding or agglomeration principles exist: coagulation and flocculation. Flocculation, which to date has been most commonly used in conjunction with geotextile dewatering tubes, will be briefly explained.

The flocculation is the step where destabilized colloidal particles are assembled into aggregates which can then be efficiently separated from water. Flocculants clarify water by combining with suspended solids, in such a way as to enable these particles to be quickly and easily separated from the water.

Flocculation agents can be produced from different raw materials including polyacrylamides, starch, chitin and minerals. Depending on the particle characteristics (size, charge, etc.) and the sludge properties (pH, concentration of suspended solids) an appropriate flocculation agent can be selected. This type of dewatering methodology extends the range of different dewatering possibilities and a potential high efficiency relating to the final dried solid content, the containment function and the overall safety factor.

3 DIMENSIONING OF GEOTEXTILE TUBES

The correct dimensioning of the geotextile dewatering tubes combines two different design aspects: the estimation of the required tensile strength of geotextile and selection based also on filter criteria.

3.1 *Required strength of tube*

The required tensile strength of the geotextile tube is estimated using the linear membrane theory and depends on the circumference, maximum filling height and maximum pumping pressure (Leshchinsky *et al*. 1995). To simply the calculation procedure and to add speed, computerized software including GeoCoPs (Adama) and SOFFTWIN (Palmerton) can be used for the estimation of the tensile strength in the tube fabric. Additionally, specific reduction factors for the geotextile tube can be applied to estimate the design/allowed strength. The reduction factors represent the loss of strength due to creep (RF_{CR}), installation damage (RF_{ID}), weathering (RF_{W}) and chemical and biological effects (RF_{CH}) related to the short term tensile strength of the fabric. Further information on the derivation of the required reduction factors are described in detail in ISO TR 20432:2007.

Special attention should be paid to the fact that the required tensile design strength increases exponentially with increasing filling height. During the tube dimensioning, a proper optimization of the theoretical diameter, maximum filling height, storage capacity of the tube and the required tensile design strength of the geotextile tube all have to be performed to ensure an optimal safe and stable design for the filling and dewatering operation.

3.2 *Required filter criteria*

With regard to the ideal filter behavior of the geotextile tube several classic design criteria can be applied. A detailed overview of filtration of natural filers and geotextile filters can be found in Giroud (2008).

4 CONSTRUCTION OF TAILINGS DAMS

4.1 *Traditional construction*

The construction of tailings dams is closely linked to mining operations and the characteristics of the tailings highly depends on the type and composition of the mined mineral. The tailings dam is raised in line with the mine waste storage requirements over the life of mine. The basic construction concepts for tailings dams are the upstream, downstream, or centre-line methods. The selection of the most favourable construction method is based on the tailings, embankment fill or discharge requirements, water storage suitability, seismic resistance, raising rate and relative costs (U.S. EPA 1994). All construction techniques are linked by the construction of a starter dam/dyke.

This generally is built before the mining process starts and therefore is built similar to conventional water storage dams. If necessary, the starter dam has to be equipped with draining and sealing functions. During the mine operation tailings are discharged and the tailings dam height is increased successively by using local or imported fill materials. More detailed information is given in ICOLD Bulletin 74 (1994). The use of fine tailings in the dam body is not accepted (sand sized tailings are allowed) due to their poor mechanical and hydraulic characteristics especially in seismic areas, although their use naturally represents a high potential for cost reduction and extension of storage capacity.

4.2 Construction Methodologies using Geosynthetic Tubes

When considering construction of a typical downstream Tailings Dam embankment using geotextile dewatered tubes, the following practical aspects need to be considered:

4.2.1 *Dam embankment footprint (dewatering area)*

Traditionally geotextile dewatering tubes are placed on a prepared area capable of bearing loads expected to be imposed by the filled dewatering tubes. The footprint should be capable of bearing the expected loads. Additionally, the dewatering area has to allow for sufficient drainage capacity of the dispersed water. Normally the dewatering pad consists of a containment bund, a flexible membrane liner and a gravel drainage layer.

The set-up of the dewatering field can be adapted to specific project requirements. Nevertheless, some points always have to be taken into account:

- The lining system design has to be adjusted to the degree of contamination of the sludge.
- The area on which the dewatering tubes will be placed has to be erosion-resistant. Otherwise the effluent water may erode the surface. This is particularly relevant for downstream dams of existing TSF’s and also for the upstream face.
- The area has to be horizontally levelled (slope perpendicular to the longitudinal axis of the tubes ≤ 0.1 %; slope in direction of the longitudinal axis of the tube ≤ 1.0 %).

4.2.2 *Filling of Geotextile Dewatering Tubes*

Tailings are transported into the dewatering tubes on the dewatering area by a manifold system. The inclusion of the flocculation agent is introduced via a mobile dosing unit (Figure 2) which can easily be positioned at a convenient location on or adjacent to the TSF. The dosing unit has an inlet pipe and an oulet pipe and the flow of tailings can be controlled via buffer tanks if necessary. A computerized dosing unit accurately controls the required inflow of the flocculent agent into the tailings stream. Additionally, the flow can be diverted in a controlled manner to every tube by use of several valves and tube inlets. Careful consideration has to be given to the tailings water retention characteristics and grading.

Figure 2. Example of mobile dosing unit for addition of flocculation agent into tailings flow (Courtesy of Clariant)

4.2.3 Staged filling of Dewatering Tubes

Practically, dewatering by means of geotextile tubes comprises a cyclical process, schematically shown in Figure 3.

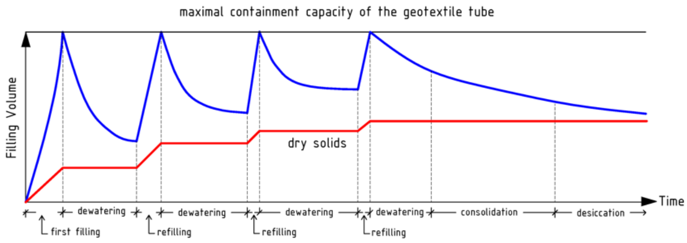

Figure 3. Dewatering cycle by use of geosynthetic tubes (adapted and modified from Lawson (2008).

During the first filling cycle the dewatering tube is filled to the given maximum initial design height (as determined by the design), and the filling is stopped. The static drainage of the sludge by gravitation commences as soon as the filling process is halted and following a degree of dewatering the tube can be refilled again. During this cycle the water within the sludge is extracted, therefore the volume is reduced and the solids concentration of the residual dewatered material increases.

The principal process is repeated until the tube is completely filled. Subsequent consolidation and further desiccation occurs. Wilke & Cantré (2016) provide further information on the geotechnical characteristics of the dewatered soils within geotextile tubes following a consolidation period of up to 6 months

In order to maintain efficient staged construction of the tailings dam embankments and to allow for optimum utilization of tailings storage facilities, the dewatering tubes have to be placed and filled in such a manner so as to mimic regular downstream or upstream construction methodologies. Starter dam construction using dewatering tubes requires the tubes to be placed in the direction of the tailings dam embankment. By doing so this will enable the relatively fast installation of the subsequent geomembrane barrier and geomembrane protection layers. As future tailings dam raises become required, the dewatering tubes have to be installed in the same directional manner (Figure 4).

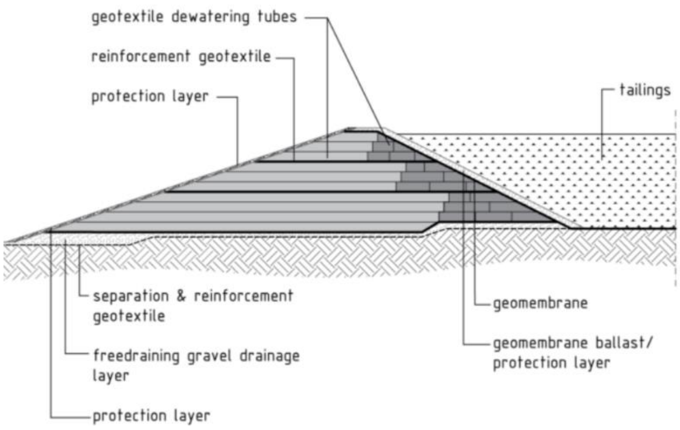

Figure 4. Concept layout of a downstream starter dam using geotextile tubes and geotextile reinforcement (if required to ensure stability)

When considering the equal loading of the base of the tailings dam footprint it can be considered to place the geotextile dewatering tubes which do not form part of the starter walls perpendicular to the embankment direction, this will also provide greater embankment stability.

5 STABILITY AND SAFETY CONSIDERATIONS

The failure of tailings dams can result in huge environmental damage as well as loss of life. Therefore the long-term functionality and safety of TSFs are of the highest concern and aim of the tailings dam design. As detailed within ICOLD Bulletin 74 (1989), a careful theoretical and experimental investigation of new design concepts and/or unconventional construction methods and materials are greatly recommended. Thus the first safety observations are presented.

The knowledge of all potential failure mechanisms is the base of all safety considerations. The innovative construction methodology presented has to fulfil all safety provisions compulsory for conventionally designed and constructed TSFs. In accordance with U.S. EPA technical report EPA 530-R-94-038 (1994) checks are required including slope failure from rotational sliding, foundation failure, erosion, piping and overtopping.

A guideline for structures built with single geotextile-encapsulated sand elements including geotextile bags, mattresses, tubes or containers was developed by Bezuijnen & Vastenburg (2013). The fault tree shown in Figure 5 comprises all potential failure mechanisms for those systems described.

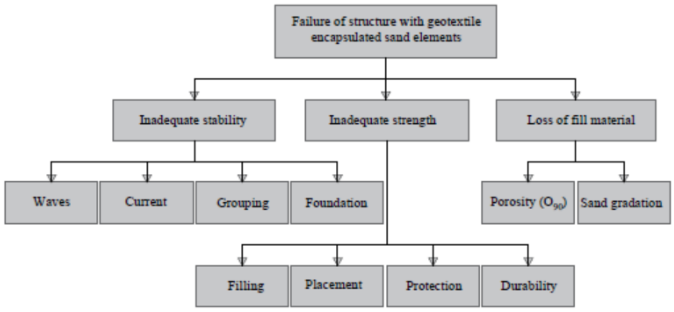

Figure 5. Fault Tree for a structure with geotextile-encapsulated sand elements (Bezuijnen & Vastenburg 2013)

5.1 *Inadequate stability*

5.1.1 *Waves and Currents*

The stability safety related to 'waves' and 'currents' (Figure 5) can be neglected for the tailings dam application.

5.1.2 *Grouping*

The analysis of the 'grouping' stability should be performed in test fields (Figure 1) and/or large scale laboratory tests, in order that the understanding of interaction behaviour between the individual tailings tubes can be expanded.

5.1.3 *Foundation/Overall stability*

The geotextile of the dewatering tube can be considered as a reinforcing element within the tailings dam embankment. Consequently, the tailings dam constructed with geotextile tubes can also be classified as geotechnical structure that is reinforced with geosynthetics. A large number of national guidelines for reinforced soil structures are available worldwide. In Germany, EBGEO (2011) deals with different geotechnical applications. However, regulations for structures built with geotextile tubes are not mentioned. Nevertheless, the provisions for geosynthetic reinforcement can be transferred to the construction methodology described above. In accordance with EBGEO, geosynthetic reinforcements applied to a slope or an embankment have to be analysed with regard to the following failure mechanisms:

- Rupture of geotextiles reinforcement
- Pull out of geotextile reinforcement
- Slope Stability
- Sliding on the embankment base
- Sliding along reinforcement layers
- Bearing failure
- Squeezing out of subsoil

Recommended design procedures to check the above failure mechanisms are included in greater detail in EBGEO or other National Guidelines (e.g. BS8006, SANS: 207). The required geotechnical ultimate limit state analysis determining the safety against failure of the structure conventionally are proven using analytical methods. The possibilities of considering geosynthetic tubes in a conventional analytical slope stability software are limited. The improving/contributing effect of geotubes can be implemented via apparent shear parameters and/or using their design tensile strength. Xu & Sun (2008) introduced an apparent cohesion arising in small geotextile bags using Eq. 1. This formula was developed and numerical proven for bags measuring several decimetres.

$$c = \frac{T}{\sqrt{K_p}} \cdot \left(\frac{K_p}{H} - \frac{1}{B}\right) \quad (1)$$

c	Apparent cohesion	[kN/m²]
T	Tensile design strength of soilbags	[kN/m]
K_p	Passive earth pressure coefficient, $K_p = (1+\sin\phi)/(1-\sin\phi)$	[-]
H	Height of single geotextile bag	[m]
B	Width of single geotextile bag	[m]

The possibility of transferring the apparent cohesion approach to large dewatering tubes has not been proven yet. The apparent cohesion for three different tensile strengths was estimated (Figure 6) with the width of geotextile tubes varying between B = 1.0m and B = 15.0 m. The results show shows that there is only a small increase in apparent cohesion between the narrow and wide width of the geotextile tube.

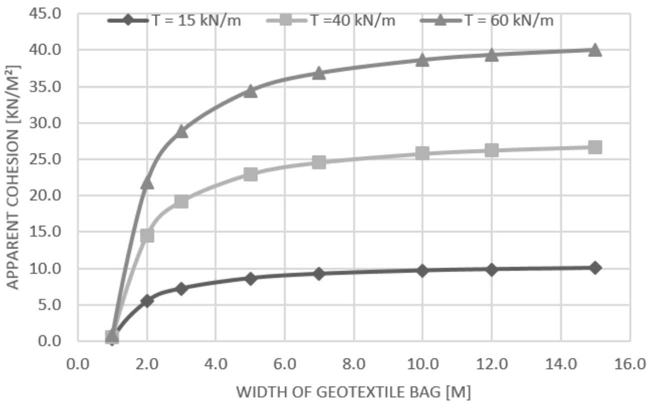

Figure 6. Apparent cohesion v width of geotextile container calculated using Eq. 1, H = 2,0 m. φ′ = 20°

Another method adopts slope stability analysis using commercial software (GGU Stability). An embankment of H = 10 m and slope inclination of 1:2 was modelled with a dam crest width of L_w = 5.0 m. and a friction angle of 20° was used for the tailings. A tensile strength of 40 kN/m was assumed for the dewatering tubes (H = 2.0 m, B = 10.0). This relates in accordance with Eq.1 and Figure 6 to c' = 26 kN/m².

The stability analysis is based on the global safety concept without taking into account partial safety factors. The resulting factor of safety (FOS) is presented in Table 1. The apparent cohesion approach considers the friction angle and results in a higher factor of safety. In comparison the results using the tensile design strength approach appears more conservative.

Table 1. Results of comparison between different design approaches

Approach	Angle of friction	Cohesion c	Design Strength (single layer) T	Design strength (double layer) T	Factor of Safety
	[°]	[kN/m²]	[kN/m]	[kN/m]	[-]
Apparent cohesion	20.0	26.0	-	-	2.38
Tensile design strength	20.0	0.0	40	80	1.49

In further analysis the use of these approaches shall be determined with regard to their applicability for tailings dams. In this comparison drained shear parameters of the tailings have been taken into consideration. Another important point is the stability during the filling of the tubes. With regards to this, test results showing the development of the undrained (vane) shear strength are presented in Wilke (2016). The applicability of the undrained shear strength in the slope stability analysis has to be analysed in further detail as it depends on the filling and construction schedule. Due to the large period of construction time the undrained conditions may only dominate in the top dewatering tubes. The occurrence of pore water pressures in the tailings dam has to be known over the entire life span of the tailings dam structure.

In addition to the slope stability, failures due to sliding on the dam base and along individual geotextile tube surfaces have to be considered. The possible slip surfaces can be in between geotextile tube fabric and tailings or in between two adjacent geotextile dewatering tubes. In this regard the friction angle ϕ should be estimated for example from shear box tests. It is likely that the friction between two dewatering geotextile tubes is the critical slip surface within a tailings dam.

Figure 4 shows the addition of horizontal layers of geotextile reinforcement and these may be required if the safety against internal slope failure is not sufficient with the dewatered geotextile bags alone. The additional wrapping of the horizontal reinforcement around the geotextile tubes at the upstream and downstream edges also increases the anchorage. A higher strength horizontal geosynthetic reinforcement (high strength geogrid or geotextile) may be required at the base of the dam structure to control overall stability, sliding stability and/or foundation extrusion. The requirement of horizontal reinforcement is determined at the design stability stage. In addition to the ultimate limit state analysis discussed an estimation of the serviceability during both construction and service phase can be investigated with the help of numerical modelling. The stress distribution and deformations can be analysed as well as the interaction behaviour of all components. This type of modelling research is currently being undertaken and the results will soon be available and published.

5.2 *Inadequate strength*

The dimensioning of the dewatering tube in terms of both 'inadequate strength' in the tube geotextile in relation to 'filling' and 'placement' together with the 'loss of fill material' are components of the dewatering operation described/referenced in Section 4.

The 'protection' and 'durability' of the geotextiles tubes once they have been filled and are in place within the tailings dam are primarily related to issues of U.V. protection, vandalism and accidental impact forces. Typically, a thin veneer of cover soils will protect the tubes.

6 SUMMARY

In this paper concepts about the utilization of geotextile dewatering tubes to form the embankments of tailings dams have been presented. This innovative construction methodology enables the increase of the storage capacity in the pond by using the tailings as embankment fill material within the tailing dams. The use of dewatering geotextile tubes has a large potential to lower the transportation and installation of imported granular fill materials and the associated capital expenditure and carbon footprint. The principles of the dewatering process and the dimensioning of dewatering tubes with regard to the required tensile strength and filter stability of the fabric was demonstrated. In recent dewatering projects experience in the high stacking of dewatered geotextile tubes has successfully been undertaken (Wilke 2015). With regard to practical aspects the main components of a tailings dam built with geosynthetic dewatering tubes as well as the downstream construction method were also introduced. In order to avoid any performance failures of a tailings dam embankment constructed with dewatering geotextile tubes, a precise design considering the main failure modes is required. The current lack of design guidance can be compensated with a combination of existing guidelines dealing with tailings dams, encapsulated sand containers and geosynthetics in retaining structures. It is considered that methods of apparent cohesion and/or tensile strength design approaches, coupled with appropriate numerical modelling, will provide sufficient design robustness to prove the safety of such structures. The undertaking of further research, comprising further stability analysis (analytical and numerical), test fields and laboratory tests, will improve our knowledge of the behaviour and interaction of stacked dewatered geotextile tubes to form dam embankment structures. The knowledge of these subjects remain essential for the stability analysis of tailings dams built with dewatering geotextile tubes and new research will continue to be published through 2016.

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