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COMMON PRACTICE AND INNOVATIONS IN TALINGS DAMS USING GEOSYNTHETIC TUBES

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ABSTRACT

This paper demonstrates innovative concepts for building tailings dam embankments with the help of geotextile dewatering tubes and introduces the corresponding stability considerations. Geotextiles tubes were originally developed for the purpose of dewatering of sewage and sediments. In combination with carefully selected flocculation aids almost every type of sludge can be dewatered, stored safely and the required storage volumes reduced. Another focus of this paper is a new development combining the advantages of geosynthetic mattresses and geotextile tubes intended for the use in protection and sealing as ballast layers on tailings dam embankments.

1. INTRODUCTION

With special regard to the high risks arising from the treatment of inert as well as contaminated mine residues the long-term functionality of a basin and its embankments is of a high importance.

Over many decades the reinforcing and/or separation functions of geosynthetics have been deployed successfully for capping tailings ponds. Geosynthetics are also used for strengthening and/or increasing the height of dam walls built from low-shear strength material. Most types of geosynthetics can be used for the purpose of separating, filtering, draining, reinforcing, protecting and sealing for tailings dams.

This paper presents early concepts for using geosynthetic tubes in the construction of tailings dams. A combination of dewatering and consolidation of tailings and the consequent increase of the storage capacity of the tailings pond is the principal motivation in applying geosynthetic tubes in tailings dams. The principles of the dewatering processes, the dimensioning for dewatering purposes as well as the methodologies for tailings dams construction using geosynthetic dewatering tubes are introduced.

Besides the new construction methods using geotextile dewatering tubes the use of protection/ballast layers in tailings dam slopes is discussed on the basis of the current research and first experience with geosynthetic double layer mats in South Africa.

2. GEOSYNTHETIC DEWATERING TUBES

Geosynthetic dewatering tubes were originally developed for the purpose of dewatering of sewage and sediments. In combination with carefully selected flocculation aids almost every type of sludge can be dewatered, stored safely and the required storage volumes reduced. The tubes are manufactured from special filter fabrics. Single units of this fabric are sewn together and this way large tubes can be assembled. Dewatering tubes with volumes ranging from 15m³ up to more than 1500m³ have been assembled and used beneficially in recent projects. This dewatering methodology extends the range of different dewatering possibilities. The dried solid content is enhanced and an increase in the overall safety factor can be achieved. The principles on which dewatering by the means of geosynthetic tubes is based are given in detail in Sylwasschy & Wilke (2014). Additionally in Wilke & Breytenbach (2016) a case study can be found illustrating a large dewatering project. The single tubes can be stacked on top of each other (see Figure 1) and thereby increase the storage capacity of the area. This experience in installing the tubes in several layers has led to the initial idea of using geosynthetic dewatering tubes for tailings dam embankment construction.

Figure 1. Complete dewatering field showing with fifth tube layer, Wilke & Breytenbach (2015)

2.1 Dewatering Process

The dewatering process using geosynthetic tubes can be described in terms of typical filtration mechanisms since gravimetric cake filtration supported by cross flow filtration takes place. The latter results from the geometric shape of the tube. The geosynthetic thus works as a permeable separator and the volume of the sludge is decreased while water drains through the fabric.

Solid particles are retained in the tube and the solid concentration of the residual dewatered material increases. A natural filter cake is formed on the inner side of the fabric after an initial startup phase. The dewatering process is performed cyclically in several successive filling and dewatering phases. Static drainage starts as soon as the filling process is initiated. As can be seen in Figure 2 the filling volume is restricted by the maximum containment capacity of the geotextile tubes that depends on the tensile strength of the tube and its seams (see Section 2.2). When the given maximum design height is achieved the filing is stopped in order to achieve the dewatering to a required degree. After dewatering and consolidation refilling can be commenced. Following the filling and refilling phase the tubes will take an elliptically shape.

2.2 Dewatering tube dimensioning

The dimensioning of dewatering tubes combines two different design considerations. These are the tensile strength and the filter properties that are required for the tailings that is to be contained.

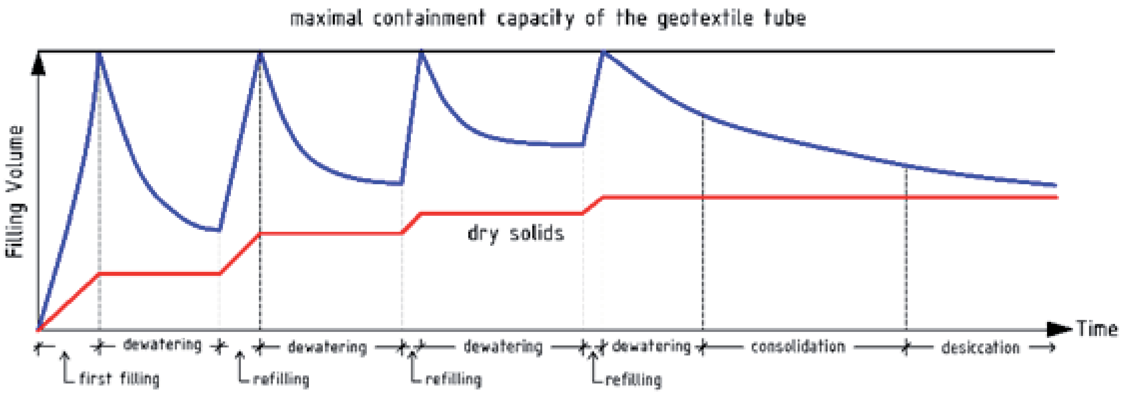

Figure 2. Schematic diagram of the dewatering sequence with geotextile tubes, Wilke & Breytenbach (2016)

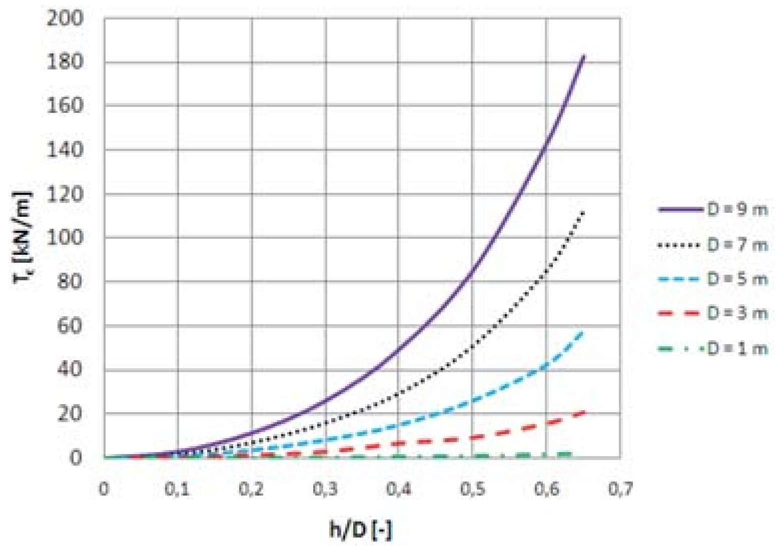

Figure 3. Tensile strength as a function on filling ratio, Wilke & Hangen (2011)

The required tensile strength is estimated using the linear membrane theory and depending on the circumference, the maximum filling height and maximum pumping pressure (Leshchinsky et al. 1995) is determined. In practice computerized software like GeoCoPS or SOFTWIN can be used for the computation of the required tensile strength of the fabric. Specific reduction factors for geosynthetic products can be applied using the aforementioned software to account for the loss of strength due to creep (RF_{CR}), installation damage (RF_{ID}), weathering (RF_{W}) and chemical and biological effects (RF_{CH}). These factor and are described in detail in ISO TR 20432:2007.

Special attention should be paid to the fact that the required tensile strength increases exponential with increasing filling height illustrated in Figure 3. The vertical axis shows the required tensile strength τ_c whereas the filling ratio h/D is shown on the horizontal axis. The filling ratio is the actual filling h divided by the diameter of the tube D. Since the storage capacity increases significantly as the filling height increases it is important to optimise this in relation to the tensile strength.

Classical design criteria cannot be adopted for the filtration consideration. The filter behaviour is therefore based on trials and/or experience of the filter performance relating to the relationships between the type of sludge, geotextile and flocculent used. A detailed overview can be found in Wilke & Hangen (2011) with references to Giroud (2005), Cantré (2008), Liao & Bathia (2008) and Adylik (2006). Furthermore information on the important role of flocculation and its impact on dewatering can be found in Satyamurthy & Bhatia (2009).

3. CONSTRUCTION OF TAILINGS DAMS

3.1 Common Practice

The methods used for construction and operation of tailings dams is closely linked to ore and tailings characteristics. Tailings may be raised by upstream, centreline or downstream methods or variations of both. The selection of the desired construction method is based on the setting, the risk and the economics of the project. Variables such as available embankment, discharge requirements, water storage requirements, seismic resistance, raising rate and relative costs (US Environmental Protection Agency 1994) all play a role. The tailings facility is usually established with astarter dam. This is built before the deposition commences and is sometimes designed much like a conventional water storage dam. If necessary the starter dam has draining and sealing elements. After the starter dam has been filled the tailings perimeter containment height is increased successively by using tailings or imported fill. More detailed information on the options for how this can be done are given in ICOLD Bulletin 74 (1994). The use of tailings for raising is sometimes limited due to the poor mechanical and hydraulically characteristic of the tailings.

3.2 Construction Methodologies using Geosynthetic Tubes

When considering construction of a typical downstream tailings dam embankments configuration through the utilization of geotextile dewatering tubes (see Figure 4) the following practical aspects need to be considered and dealt with:

3.2.1 Embankment Foot Print (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 area has to allow for drainage of the filtrate escaping the dewatering tubes and has to be erosion resistant. The dewatering footprint area has to be graded to slope perpendicular to the longitudinal axis of the tubes at a gradient of ≤ 0.1 % and to slope in the direction of the longitudinal axis of the tube at ≤ 1.0 %.

3.2.2 Filling of Geotextile Dewatering Tubes

Tailings is discharged into the dewatering tubes on the dewatering area by a manifold system. The flow can be directed in a controlled manner to every tube by use of valves and tube inlets.

3.2.3 Staged filling of Dewatering Tubes

In order to maintain timeous staged raising of the tailings dam embankments to allow for containment of tailings in the basin dewatering tubes have to be placed and filled in such a manner so as to mimic conventional downstream construction methodologies. Starter wall construction using dewatering tubes require the tubes to be placed longitudinally on the tailings dam embankment. This enables the relatively quick installation of the subsequent geomembrane barrier and geomembrane protection layers. As future tailings dam raises become required, the upstream dewatering tubes have to be installed in the same direction. 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.

3.3 Failure Mechanisms and Safety Considerations

Since tailings is usually polluted or contaminated failures can result in significant and sometime catastrophic environmental damage as well as loss of life. Therefore the long-term functionality and safety of tailings facilities is of highest priority and the principle aim of the tailings dam design. As mentioned in ICOLD Bulletin 74 a careful theoretical and experimental investigations of new design concepts and/or unconventional construction methods and materials is recommended. Thus the first safety observations are presented.

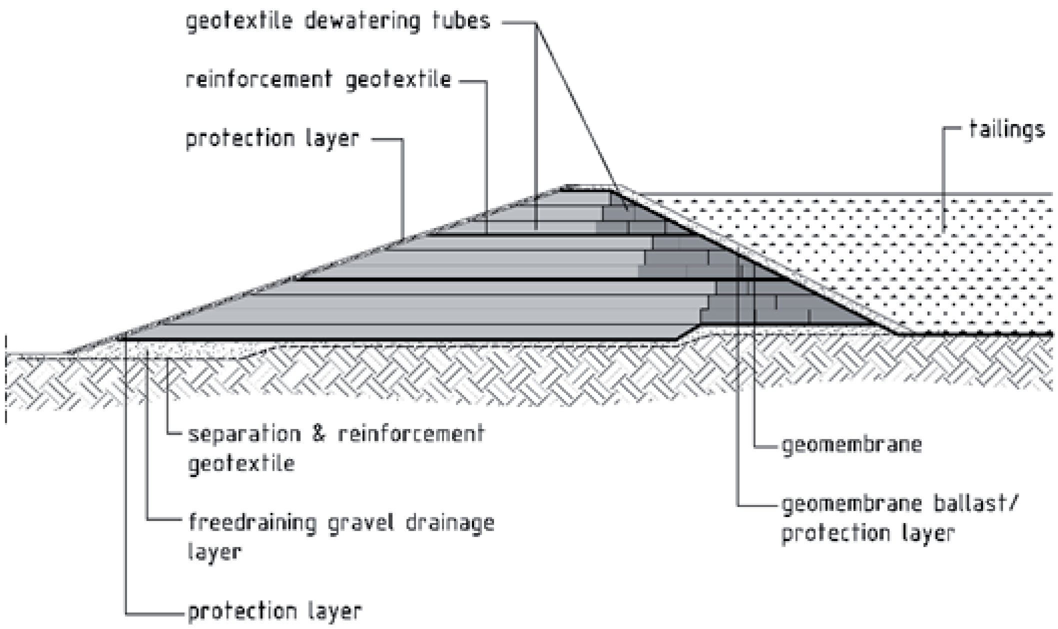

Figure 4. Construction Concept: Dewatering tube tailings dams

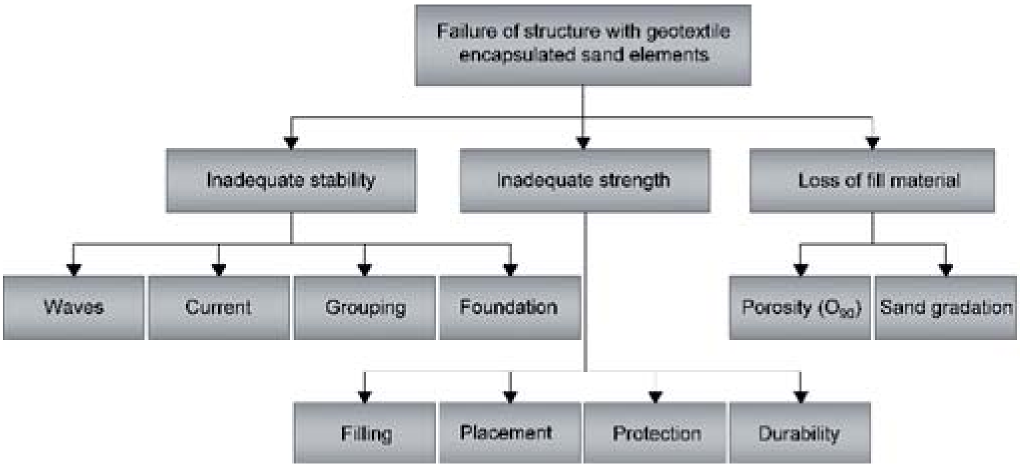

Figure 5. Fault Tree for a structure with geotextile-encapsulated sand elements (Bezuijnen & Vastenburg 2013)

The knowledge of all potential failure mechanisms is the basis of all safety considerations. The innovative construction methodology presented above has to fulfil all safety provisions that are compulsory for conventionally designed and constructed tailings dams. In accordance with US Environmental Protection Agency (1994) these provisions include slope failure from rotational sliding, foundation failure, overtopping, erosion, piping and overtopping.

The dewatering tubes comprise of single elements and must be considered as such in the assessment of equilibrium. A guideline for structures built with single geotextile-encapsulated sand elements like 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 in this guideline. The dimensioning of the dewatering tube in terms of both the required tensile strength in the textile and the loss of material have already been described in section 2.2 and therefore the equilibrium analysis should consider the tube acting as a discrete element The stability analysis of the groups of elements should be based on test fields or laboratory tests in order to build on the first stacking experience (see Figure 1) and the understanding of interaction behaviour of the single tailings tubes.

The geotextile surrounding the tailings can be considered as a reinforcing element within the tailings dam embankment. Therefore a tailings dam built with geosynthetic tubes can also be classified as a geotechnical structure that has been reinforced with geosynthetics. A large number of national guidelines for such structures are available all over the world. For instance in Germany the “Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcements” (EBGEO 2010) was published in 2010 and deals with different geotechnical applications, whereas regulations for structures built with tubes are not mentioned. Nevertheless the provisions for geosynthetic reinforcements can be transferred to the construction methodology described above. In accordance with EBGEO (2010) geosynthetic reinforcements applied to a slope or an embankment have to be analysed with regard to 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

Recommended design procedures are given in EBGEO (2010) or other guidelines dealing with geosynthetic reinforcements.

3.3.1 Analytical Methods

The required geotechnical limit state analysis determining the safety against failure of the structure is already a settled science. This section elaborates on different concepts of analysing tailings dams built with geosynthetic dewatering tubes and defines some of the uncertainties which have to be clarified in future.

The consideration of geosynthetic tubes in conventional analytical slope stability software is currently limited. One option for accounting for the beneficial effect of tubes can be by increasing shear strength parameters while another would be to account for the tensile design strength of the fabric.

Xu & Sun (2008) introduced an apparent cohesion arising from small geosynthetic bags using Equation 1. This formula was developed and numerically proven for bags measuring several decimetres.

$$c = \frac{T}{\sqrt{K_p}} \cdot \left(\frac{K_p}{H} - \frac{1}{B}\right) \qquad \text{Eq. 1}$$

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

The use of this approach for large dewatering tubes has not been proven yet. As can be seen in Figure 6 the back calculated “apparent” cohesion for three different tensile strengths was estimated considering a friction angle φ = 20° and a tube height H = 2.0 m for a range of tube widths from B = 1.0 to B = 15.0 m. This calculation shows that the apparent cohesion does not increase significantly for widths of greater than about 6 m .

The above approach was compared to performing slope stability analysis using GGU-Stability software by Civil Serve. The example embankment has a height of H = 10 m and a slope inclination of 1:2. The tailings crest width L_w is 5.0 m. The friction angle of the tailings was φ' = 20° The tensile strength of the dewatering tubes (H = 2.0 m, B = 10.0 m) has, for both machine and cross machine direction, been assumed to be T = 40 kN/m. This coverts in accordance with Equation.1 and Figure 6 to an equivalent of c = 26 kN/m². The stability analysis is based on a global safety factor without taking into account partial safety factors. The computed factors of safety (FOS) for the two methods are presented in Table 1. The apparent cohesion approach produces the highest factor of safety while the tensile design strength approach is more conservative.

Another important state of equilibrium to consider is the degree of dissipation of pore pressures and 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 et al. (2016b). The importance of the degree of dissipation of pore pressures and the impact on local stability requires further analysis that is beyond the scope of this paper since this will depend on a number of variables including the filling and construction schedule and the rate of rise of the facility. For low rates of rise undrained conditions may therefore only exist in the upper dewatering tubes and therefore may be neglected.

Table 1. Results of comparison between different approaches

Approach	**Angle of friction φ**	**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

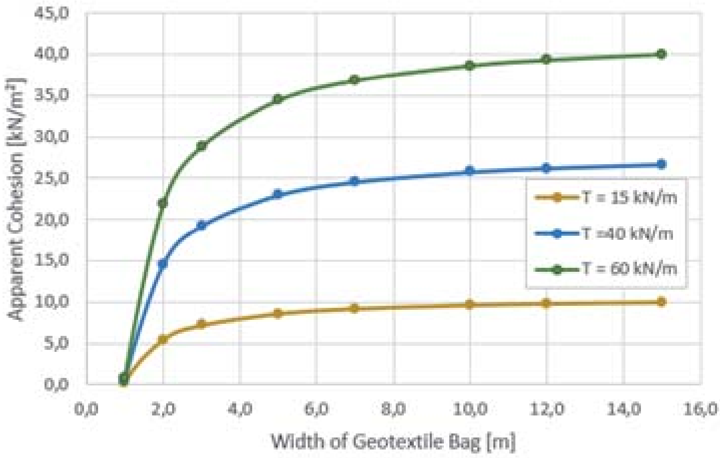

Figure 6. Apparent cohesion calculated using Eq. 1 depending on width of geotextile bags, H = 2,0 m. φ' = 20°

Besides in-slope stability, potential failure due to sliding on the dam base and along inter-tube surfaces must be considered. The possible slip surfaces can be between tube fabric and tailings or between two dewatering tubes ie. fabric on fabric. Therefore the interface frictional behaviour should be established from shear box tests.

4. THE USE OF GEOMEMBRANE PROTECTION/BALLAST LAYERS IN TAILINGS DAMS

4.1 Current Research

As a result of a large volume of research and practical experience, the placement of ballast layers on top of a primary geomembrane barrier has become common practice.

Field research presented by Msiza & Shamrock (2014) clearly shows a reduction in the mechanical and performance properties of exposed geomembranes. Through eliminating UV and thermal exposure of geomembranes, the depletion of anti-oxidants from geomembranes is slowed significantly, thereby extending the expected service life of the geomembrane (Rowe et al, 2013).

4.2 Geosynthetic Protection/Ballast Layer Alternative

The geosynthetic protection/ballast is a geotextile containment system manufactured utilizing weaving technology, which provides a tubular system interconnected into a single integrated mattress configuration (see Figure 7). Weaving technology enables customization of tube dimensions to suit project requirements. Various raw materials can be considered depending on the project requirements. Through the utilization of a geosynthetic protection/ballast layer it is possible to:

- Eliminate heavy construction equipment on top of primary geomembranes
- Eliminate greatest threat to liner integrity
- Enhance site safety significantly through reduction of construction traffic
- Increase storage space due to utilization of waste (e.g. tailings) inside the protection tubes
- Protect your environmental investment safely and efficiently

Figure 7. Installation of geosynthetic protection/ballast layer placed on top of primary geomembrane

5. OUTLOOK AND CONCLUSION

In this paper early concepts about the utilization of geosynthetic dewatering tubes in tailings dams have been presented. This innovative methodology enables the increase of the storage capacity in the pond by using tailings as embankment fill material in tailings dams. The transport and installation of imported granular fill materials is reduced significantly by the deployment of this methodology.

The principles of the dewatering process and the dimensioning of dewatering tubes with regard to the required tensile strength and filtration prperties of the fabric was demonstrated. In recent dewatering projects stacking of tubes has been carried out successfully (Wilke & Breytenbach 2016).

Practical experience with the construction of the main components of a tailings dam built with geosynthetic dewatering tubes with particular reference to the downstream raising method was introduced in the paper.

In order to mitigate the possibility of failure design should consider the main failure modes. The lack of design guidelines specifically developed for dewatering tubes can be compensated for by combination of existing guidelines dealing with the design of tailings dams, encapsulated sand containers (Bezuijnen & Vastenburg 2013) and geosynthetics in retaining structures or slopes (EBGEO 2010 or other national guidelines).

In future stability analysis (analytical or numerical), fields trials or laboratory tests should be used to study the behaviour of stacked dewatering tubes. Verification of the analytical models is essential in order to improve on the reliability of the stability analysis of tailings dams built with dewatering tubes.

Geomembrane protection/ballast layers for upstream tailings dams slope protection can deliver significant benefits and could improve the durability of tailings dams in the long term.

6. ACKNOWLEDGMENTS

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