DESIGN CONSIDERATIONS FOR THE USE OF GEOMEMBRANES FOR PHOSPHATE TAILING IMPOUNDMENTS

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Abstract

In the interest of ensuring the protection of the environment and public health as well as the conservation of water, geomembranes are increasingly being used in the construction of mill tailings impoundments to prevent contaminant migration into surface and groundwater and to maximize water reclaim. The recuperation of water is especially important in phosphate processing as these projects generally have a strong negative water balance. Metals associated with the phosphate ore and radioactive materials often concentrated in phosphogypsum residues, in addition to the extremely pH of the process liquids, have promulgated increasingly stringent standards regarding the containment level of tailings and residue storage facilities (TSF and RSF) around the world. In the United States, the state of practice for phosphogypsum tailings incorporates a geomembrane liner in conjunction with either an underlying compacted clay liner (CCL) or an overlying compacted gypsum layer [4]. Additionally, many phosphate-producing regions, including Morocco and Australia, are arid and thus water supply a concern. The authors of this paper have quantified liquid migration through a geomembrane liner system using natural clay barriers as a benchmark and statistical data on frequency and size of defects in geomembrane liners. An estimate of water savings per hectare of tailings impoundment is presented with the use of a geomembrane as a function of hydraulic head. A summary of the causes of tailings dam failures is also presented along with how a geomembrane liner may reduce this risk. This paper also provides an overview of design, construction quality assurance and leak location concepts, challenges and innovations specific to constructing a geomembrane-lined tailings impoundment.

Keywords: leakage, geomembrane, tailings, clay, design, construction quality assurance, stability, phosphate, gypsum, tailings, TSF, RSF

Introduction

The reasons for employing geomembranes for containment facilities are all based on the reduction of leakage and the resulting reduction in "failure" risk that comes with better containment; with the definition of "failure" including structural failure, environmental contamination and inadequate water supply. Whether for the protection of surface and groundwater or the optimized water reclaim, geomembranes are often the most cost-effective way to drastically reduce leakage from containment facilities, especially when cost is considered from a risk-based net present value (NPV), or risked NPV, approach. In fact, no modern large-scale leach pads use soil-only liners and this is often driven as much by economics as environmental factors [1], as the value of the solution itself lost through clay liners can pay for the extra cost of constructing with a geomembrane as well as the cost of proper construction quality assurance (CQA) [5].

The most common types of geomembrane typically used in the mining industry are high density polyethylene (HDPE), linear low density polyethylene (LLDPE) and polyvinyl chloride (PVC). These products are listed in order of increasing flexibility and decreasing strength. The thicknesses of the both types of polyethylene (PE) liners typically run from 1.0 to 2.0 mm, while PVC is typically 0.50 to 1.0 mm thick [1]. Geomembrane installations can be a single layer of geomembrane on prepared subgrade, two layers of geomembrane for addition protection, reduced head on the secondary liner and the added benefit of leak detection capabilities, or it can be a geomembrane over a low-permeability soil layer, referred to as a composite lining system.

The performance of the final, installed geomembrane product is not only a function of the design but also the quality control measures taken up until the beginning of the geomembrane service life. Geomembranes are produced using strict manufacturing quality assurance (MQA) programs, starting with the resin that the sheets are made out of and continuing until the rolls have arrived on site. The installation of the material is guided by CQA practices such as making sure that each welding machine has been set up correctly and trial welds have been performed, each weld is logged, each panel that is placed can be tracked through a system of panel numbers, each seam is tested for leaks through air pressure and vacuum box testing, and that the seam strengths produced in the field meet design specifications. CQA is not required by regulation in most countries, but statistics show a significantly greater number of holes per hectare and a higher rate of system failure when a CQA program is not in place [2]. An additional level of quality control would be to perform a geoelectric leak detection survey on the installed geomembrane. A leak detection survey can check 100% of the lined area for leaks present both before and after any cover soil placement (often a thin layer of gypsum in the case of phosphogypsum residues). This method uses electricity to pinpoint sources of current flow resulting from holes through the geomembrane.

1. Leakage Analysis

1.1 Method and Assumptions

In order to quantify the leakage that can be avoided through the use of geomembranes, a simplified comparative analysis was performed. This analysis is meant to provide a comparison between lined and unlined tailings facilities located on sites with naturally occurring clay of varying thicknesses of 1, 3 and 10 meters with saturated flow conditions. The potential leakage was estimated for sites underlain by clay and compared to the potential leakage if a geomembrane is installed over those same clay thicknesses. The Giroud equation was used to calculate the leakage through a composite liner system [3]. Darcy's law (and the assumption of saturated steady-state flow) was used to calculate leakage through CCL and natural clay containment. Head depths of 1 through 20 meters were used in the analysis and the clay was assumed to have a hydraulic conductivity of 1 x 10^{-7} cm/sec. For the purposes of this analysis, the effects of slurry consolidation were not taken into consideration.

In order to calculate the leakage through a geomembrane or composite liner, the hole size and frequency must be estimated; these vary with the thickness of the geomembrane and the quality of the installation [2]. Theoretically, a geomembrane can be installed leak free if all measures are taken to control the quality, but due to site conditions and human error, this is essentially never the case for large-scale installations. For all practical purposes, even with the highest level of CQA, there will be some defects or leaks. To model this imperfection the leakage is estimated by three categories of liner installation; high quality, average quality and low quality. High quality represents an excellent liner installation and CQA program, along with a geoelectric leak detection survey. Average quality represents a liner installed with a CQA program of average quality. Low quality represents a liner installed with either a poor CQA program or the lack thereof. The hole frequencies and sizes for each tier of installation quality (as shown in Table 1) are based on published values and the authors' professional experience [2]. The holes were assumed to be circular, with average contact quality with the subgrade, and the geomembrane was assumed to be 1.5mm thick HDPE as this is the most commonly used geomembrane in mining applications.

Table 1. Hole Frequencies and Sizes

Installation Quality	Number of Holes per hectare	Average Hole Size (mm^2)
High Quality	2	1
Average Quality	10	5
Low Quality	20	10

1.3 Results and Discussion

The following tables show the results of the leakage rate calculations for a compacted clay liner (CCL) of 1 m thickness, natural clay containment of 3m and 10 m thicknesses, and geomembrane liners of various installation qualities (see Table 1). For simplicity, the permeability of the natural clay containment and CCL were assumed equal and both systems were assumed to be fully saturated.

Table 2. Leakage Rates for a 1-meter thick compacted clay liner

	LEAKAGE RATES (LITRES PER HECTARE PER DAY)				Percent Reduction in Leakage (clay leakage - geomembrane leakage)/ clay leakage		
head (m)	geomembrane high quality	geomembrane average quality	geomembrane low quality	clay only (1m)			
1	6.3	36.8	78.9	864	99%	96%	91%
5	35.4	208.1	446.1	4,320	99%	95%	90%
10	85.6	502.6	1,077.4	8,640	99%	94%	88%
15	150.6	884.3	1,895.6	12,960	99%	93%	85%
20	229.8	1,349.8	2,893.5	17,280	99%	92%	83%

Table 3. Leakage Rates for 3 meters of natural clay containment

	LEAKAGE RATES (LITRES PER HECTARE PER DAY)				Percent Reduction in Leakage (clay leakage - geomembrane leakage)/ clay leakage		
head (m)	geomembrane high quality	geomembrane average quality	geomembrane low quality	clay only (3m)			
1	5.9	34.6	74.2	288	98%	88%	74%
5	28.2	165.6	354.9	1,440	98%	89%	75%
10	59.5	349.2	748.5	2,880	98%	88%	74%
15	95.3	559.4	1,199.1	4,320	98%	87%	72%
20	135.6	796.6	1,707.7	5,760	98%	86%	70%

Table 4. Leakage Rates for 10 meters of natural clay containment

	LEAKAGE RATES (LITRES PER HECTARE PER DAY)				Percent Reduction in Leakage (clay leakage - geomembrane leakage)/ clay leakage		
head (m)	geomembrane high quality	geomembrane average quality	geomembrane low quality	clay only (10m)			
1	5.8	33.8	72.5	86	93%	61%	16%
5	25.5	149.8	321.1	432	94%	65%	26%
10	49.8	292.3	626.7	864	94%	66%	27%
15	74.8	439.1	941.2	1,296	94%	66%	27%
20	100.8	591.8	1,268.4	1,728	94%	66%	27%

The leakage analysis shows that the installation of a geomembrane significantly reduces the liquid losses through the bottom of a containment facility, especially when a thick layer of clay is not present under the site. This approach gives a rough idea of the potential water savings when a geomembrane is employed in a tailings impoundment design. An important note regarding geomembrane liners with "low quality" installations: data and in-house surveys suggest that over 30% of such systems experience a failure that requires either a substantial reconstruction or complete replacement (or abandonment) of the system and this is not reflected in the leakage figures reported in the preceding tables (the failure rate of systems with "average" or "high" is negligible).

2. Design Considerations

Designing with geomembranes is a specialized field within geotechnical engineering, which is typically based on the strength of soils. In addition to the consideration of the engineering properties of soils, a design must also consider the engineering properties of geomembranes and how the soil and geomembrane interact.

Anchor trenches are required to keep the geomembrane from slipping down slopes. For a tailings impoundment, an anchor trench would be installed in the starter embankment. As the embankments rise, a second phase of liner would be welded on to the lower geomembrane and it would be extended up over the new embankment.

Since water is prevented from migrating through the bottom liner by using a geomembrane, internal drainage within the tailings impoundment becomes an important component of the design. A drainage system along the floor of a lined tailings impoundment provides several geotechnical and water recovery benefits. By allowing water to drain from below the tailings, consolidation occurs more rapidly by having double-drainage. As the tailings consolidate, the density increases which also increases the shear strength, which improves stability. This increase in density also allows for a greater amount of tailings storage within the same impoundment volume.

A drainage system also helps maintain a low phreatic surface within the impoundment. Lowering the phreatic surface decreases the risk of liquefaction, which has been the cause of many tailings dam failures. It also decreases the potential for internal piping or erosion of tailings material used for dam construction. Seepage losses through the liner are also reduced by the lower phreatic surface. As an additional benefit, the drainage system also allows for faster water recovery from the impoundment for use in the processing plant, thereby reducing water makeup demand from alternative sources.

High quality containment systems reduce the risk of structural failure due to a number of favorable factors. The seepage in the embankment and foundation is significantly reduced (often by 2 orders of magnitude), thus improving the stability of the slopes and the risk of internal erosion (or "piping") failure; the latter, loss of fines by migration in seepage waters, is the cause of many dam failures including the well know cases of Los Frailes (Spain) and Omai (Guyana). A recent survey of tailings dam failures by the authors' firm considered 122 documented failures and found the following trigger modes: seepage alone was the primary cause in 14% of the failures, slope instability 30%, foundations 11%, and earthquakes 20%. Slope instability, foundation failures and earthquake response are all significantly and negatively affected by higher phreatic surfaces in the embankment and foundation. Thus, a total of 75% of these failures were directly related to seepage and all would have been significantly less likely - and most probably avoided - with a good quality liner system. A liner system also allows the dam to be more aggressively designed; using steeper slopes, less complicated (and less expensive) embankment fill and drainage systems and simpler construction methods, which can offset the cost of the liner. Taken in total, conventional tailings disposal presents one of the highest risks in mining and considering this in the design is well advised [7, 8].

Conclusions

If design concerns include environmental degradation, water conservation or reduction of risk, then employing a geomembrane in the design of a tailings or residue storage facility could significantly improve its performance. As illustrated by a quantitative comparative analysis of leakage rates, constructing a tailings impoundment with a geomembrane can reduce leakage by up to 99% in sites with thin clay layers and up to 94% in sites with up to ten meters of clay. In addition, the risk of failure is mitigated, substantially eliminating 75% of the cause of most tailings dam failures. Using average or high quality installation techniques further reduces the risk of failure of the geomembrane liner by at least 30%.

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