Proceedings of Geosynthetics Mining Solutions, 2014
September 8–11, 2014, Vancouver, Canada
Published by InfoMine, © 2014 InfoMine, ISBN: 978-0-9917905-5-5

Geosynthetics risk-based design in mining

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Abstract

Geosynthetics used in mining applications are subjected to harsh environments, yet in some cases are supposed to last forever. It is likely that geosynthetics will, sooner or later, fail due to harsh conditions, chemical/UV degradation, or re-polymerization under stress. In the short term, the probability of failure is dictated, as for any geostructure, by the variability of geo-materials parameters, variability of loading, duration of required performance, and site-specific conditions. The short-term design problem can be thought of as a "standard" geotechnical exercise, where standard risk-based decision-making (RBDM) approaches may be beneficial. On the basis of available knowledge, it is difficult to determine the long-term probability of failure of the geosynthetics and the structures incorporating them. The only thing we know is that it is likely they will, sooner or later fail; similarly to any other material, the longer the life span of the proposed structure, the higher the likelihood of geosynthetics failure. Thus the challenge is to design robust structures that, if and when the geosynthetics fail, result in consequences that are tolerable and do not lead to unacceptable environmental impacts. This paper explores these issues by way of two procedural example studies involving the use of geosynthetics in mine facilities.

Geosynthetics used in mining applications are subjected to harsh environments and in some cases are supposed to "last forever." Logsdon (2013) states that if one considers the various phases of mining, the scientific basis for understanding closure risk, and established engineering practice, it seems reasonable to suggest that the total planning period for management of mine wastes should be in the range of 200 to 500 years, and such considerations should include a semi-quantitative assessment of whether or not major changes in performance are likely to occur between approximately 500 and 1,000 years. Thus he proposes that the design-basis events that would yield off-site impacts or major rebuilding for a mine waste structure should have a probability of occurrence of less than ten percent during the proposed 200-year period of performance. This means that the design basis for critical structures that would limit consequences to off-site-only impacts should be, following the same author, a 2,500-year recurrence event ($p = 4*10^{-4}$).

There is presently no industry standard for long-term performance of closed mine facilities, or established regulatory criteria for any geostructure we know. One exception is the extensive analysis of long-term periods of performance for mining residues managed in terms of the US Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978, which requires that control of tailings "shall be effective for up to 1,000 years to the extent reasonably achievable and, in any case, for at least 200 years" (EPA, 1983). The UMTRCA time frames were established to consider periods over which climatological and geomorphic processes could, in the views prevalent at the time of the promulgation of UMTRCA, reasonably be predicted, given the existing knowledge of earth science and engineering at those times.

The topic has been recently revisited in an update review of the performance of engineered barriers for waste management (NRC, 2007). The conclusion is that up to twenty years of field observations indicate that engineered waste-containment systems designed, constructed, and maintained appropriately meet or exceed their intended performance. NRC cautions however that the demonstrated period of performance for such systems remains only a few decades, and thus on-going maintenance is required (Mitchell, 2008).

Likelihood of failure of geosynthetics and related structures

Geosynthetics and in particular geomembranes have a proven performance track record, but are vulnerable to punctures (initial defects or defects that occur later on) and other "environmental" factors. The scale of mining operations such as heap leach pads is significant, and is often orders of magnitude larger than other dumping sites (urban waste, for example). The height of mine structures can reach 200 m, resulting in enormous normal stresses (up to 3,500 kPa). Sideslope may be as steep as 1.4H:1V (approximately 36°). The combination of high normal stresses, over-stressing in the vicinity of pipes, large angular rock in overliners and the subgrade, high temperatures, and aggressive leaching solutions pushes liner materials beyond the limits applicable in other fields.

Punctures serve as open pathways for loss of pregnant leach solution (PLS) in heap leach pads. Various authors estimate liner leakage rates ranging from 5 to 10,000 L/ha/day. Although it may be considered that these leakage rates are small, it is obvious that over years of service, or post closure, the volumes of released contaminants become significant, even if a cover is in place and fully functional. In these cases it is improper to use the term "probability of failure," because we are facing an "original inherent defect" which may evolve, resulting in releases that could lead to significant and increasing risks.

In the following sections we examine the short- and long-term implications of these vulnerabilities, inherent defects, and "unknown" probabilities of failure.

Short-term risk assessment

In the short term, the probability of failure p_f is dictated by the variability of geo-materials, and the variability of loading, as for any other geostructure. The short-term design problem can be thought of as a "standard" geotechnical design, where a risk-based decision-making (RBDM) approach may be beneficial.

Within the framework of a specific and detailed analysis for a site-specific RBDM, probabilistic geomechanical methods should be used to define the p_f of a particular structure (Oboni et al., 1984; Oboni and Oboni, 2013; Oboni et al., 2011).

In this paper, the p_f of geostructures is estimated using what may be called the "SLM" method, where the acronym is derived from the names of the authors of the paper in which the approach is described, that is, Silva, Lambe, and Marr (Silva et al., 2008; Oboni and Oboni, 2013). The SLM approach involves semi-empirical relationships between the probability of failure p_f and the classic factor of safety (FoS). Although no specific studies have been carried out on geosynthetic-reinforced structures at this time, and because this paper is generic, we assume SLM methods can be applied to the selected procedural examples' structures that include geosynthetics.

The first step in applying SLM is to define the "Category" (I to IV) of the structure under consideration. The SLM methodology sequentially examines the *aspects* of the Design (D1 Investigation, D2 Testing, D3 Analyses and Documentation) and Construction "CO," as well as Operations and Monitoring "OM" of embankments and slopes to determine the Category for a structure.

Each aspect is described by various detailed specifications. The less stringent the specifications, the lower the quality of the considered structure. Thus, SLM defines four categories ranging from I (Best) to IV (Poor). Experience shows that structures with high failure consequences are generally designed, built, and operated in such a way that they fall in Category I. Of course, if a structure has received little or no engineering it will fall in Category IV. Accordingly SLM's Category I describes OM as "complete performance program including comparison between predicted and measured; no malfunctions; continuous maintenance;" whereas a Category IV will have "occasional inspection, no field measures." We will assume in this paper that Category I OM applies to Production Phase (undergoing full monitoring and maintenance), and Category IV OM to Closure Phase with "abandonment" (no monitoring, no repairs, no maintenance, the structure gradually decays to a "non-engineered" equivalent status).

Figure 1 shows the FoS-p_f relationship for the four categories.

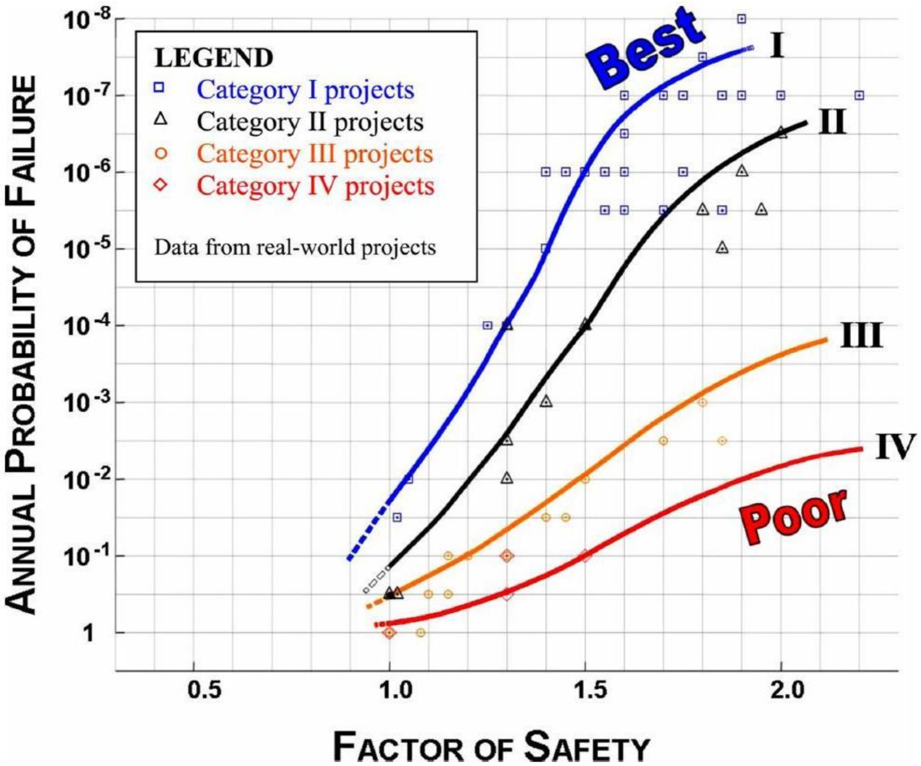

Figure 1: Annual probability of failure vs. factor of safety following SLM methodology (Silva et al., 2008)
Note: p_f scale is logarithmic, FoS scale decimal

By using the SLM methodology, we can estimate the p_f of an "excellent" geostructure (FoS = 1.3 to 1.5; $p_f = 10^{-4}$ to 10^{-6}) in Class I. Class I structures that are well-engineered, also generally involve serious QA/QC. Should inspections be only occasional, or measurements/monitoring not performed, or defects not repaired, then the probability can be estimated at 10^{-3} and even higher. This means that even without any "exceptional, unforeseeable" future event, by simple neglect, a geostructure can reach a probability of failure exceeding the criteria suggested by Logsdon (2013).

Long-term risk assessment

It is probable that geosynthetics, like any other material, will fail sooner or later due to harsh conditions, or chemical/UV degradation, or re-polymerization under stress, or any combination of such factors.

On the basis of available knowledge and diverse physico-chemical operational environments it is difficult to determine the probability of these failures in the longer term. The only thing we know is that sooner or later the geosynthetics will fail. The longer the lifespan of the proposed structure, the higher the likelihood that the geosynthetics will fail. Furthermore, if the life of the structure extends into the post-production phase, we can expect a gradual reduction of monitoring, repair, and maintenance.

In the long(er) term the real challenge is to design robust structures so that if and when the geosynthetics fail, the consequences will be tolerable and the environment will remain protected. Here too RBDM offers good guidance, but the approach is different.

In case of partial fulfillment of a Category's qualifications, the original SLM paper suggests that one interpolates values (see Figure 1) after defining weights for the specifications/Categories. Thus a stepped increase of the probability of failure is suggested if one of the *aspects* is gradually worsened for a geo-structure belonging to a specific Category.

Thus it is possible to simulate long-term complete abandonment: p_f could actually reach the value of the lower Category IV (and even higher). For example, if we look at the case of OM standards phased release from Category I (operational life) down to IV (long-term closure with abandonment), the probability of failure will increase each time the OM standard attains a lower category. Interestingly, for initial FoS in the 1.3 to 1.5 range, the difference between Category I (we are assuming that the geo-structure under examination is initially an "excellent" structure) and Category II varies respectively between 1.5 and 2 orders of magnitude: for FoS = 1.5, $p_{fCatI} = 10^{-6}$, with possible increase to 10^{-4} and higher if the same structure falls into total neglect, defects are not repaired, etc.

To put these annual probabilities in perspective: $p_f = 10^{-4}$ means that over a portfolio of, say, one hundred structures, one would be expected to fail over a period of one hundred years on average, if maintained at the standard of Category II. If the system was to degrade further and reached, for example, $p_f = 10^{-2}$, then, within those one hundred structures, one would fail each year on average.

The big questions

The question this paper asks with respect to geosynthetics inclusions in mining geostructures are simple, but difficult to answer:

1. Given there is a definite likelihood that the geosynthetics will, sooner or later, fail due to the harsh loading conditions, evolution of initial defects, punctures, chemical/UV degradation and re-polymerization under stress (Athanassopoulos and Smith, 2013; Narejo, 2013) and considering that on the basis of available knowledge it is difficult to determine the probability of these failures in the longer term, is it really economical and safe to include geosynthetics in a long-term design?
2. How much will it really cost to perpetually maintain a closed facility that incorporates geosynthetics?

Two procedural examples follow and are developed in the attempt to explore these issues. We will show that we can do much better than we were able to do forty years ago, when UMTRCA was initiated.

Procedural example 1—A geogrid reinforced retaining wall

A large retaining wall is required to hold up a mine's ore stockpile pad. The pad is where ore from the mine is dumped and stored pending introduction to the crusher and subsequent milling processes. The retaining wall is built of reinforced earth. A geogrid is placed between engineered layers of soil. The front face of geogrid is shotcreted to make it look good and give additional stability.

This is a perfect example to illustrate the application of SLM or similar methods for risk assessment of geostructures. The consequence of failure of the wall include bringing the mine to a halt for a long time—the consequences are extreme, whatever definition you adopt. At a preliminary level, given the particular nature of this failure, we could simplify the consequences and reduce them to the cost of business interruption (BI).

Of course, the gut feeling is that it is obviously cheaper to overdesign the retaining wall than to suffer its failure. The question is "by how much?" The reply is again simple, but not very simple: it depends on how deep the owner's pockets are, in other words on how much loss (actually risk) is tolerable to the owner. Numerous references exist on how to rationally develop tolerability thresholds, whether they are societal, i.e. tolerability thresholds applicable to public health and safety, or corporate, i.e. dealing mostly with physical losses deriving from accidents and mishaps. In Figure 2 we show the general shape of a corporate tolerability threshold (orange curve) as an example.

It is common to consider, for a critical facility, an initial FoS = 1.5, and today's criteria for excellence, i.e. CAT I ($p_{fCatI} = 10^{-6}$ as discussed above). Does this FoS, or a possible lower value, or a less stringent Category selection, imply an acceptable risk to the mine, given the potential BI it will take to repair or replace the wall?

If the designer selects a lower initial FoS, or a less stringent category, the p_f would be ten to one hundred times, or more, higher at the beginning of the structure's life. The reason for that dramatic difference lies in the significantly non-linear relationship, similar to exponentials, between FoS-p_f. The non-linearity is masked by the log-decimal scales SLM selected for displaying the relationships (Figure 1).

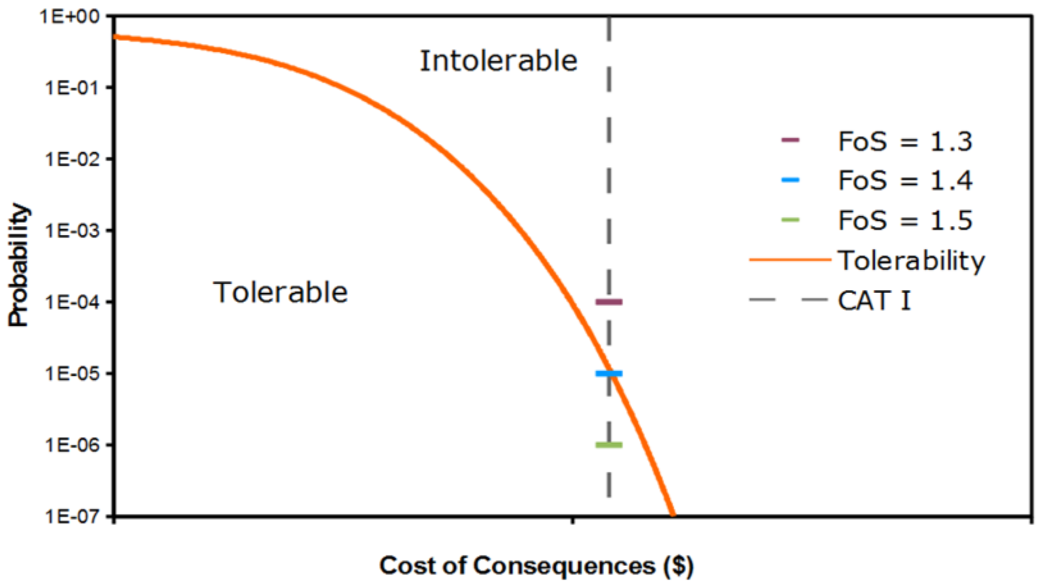

Figure 2: Introducing the concept of risk tolerability and comparing the risks of three alternatives of wall: same consequences, same "excellent" structures belonging to CAT I, but different initial selected FoS going from 1.3 to 1.5. A reduction of the FoS may push the risk to intolerable levels. The traditional FoS selection approach eludes this conclusion

As the procedural example mine is in a very high seismic environment, the design will most likely be based on the maximum credible earthquake (MCE). The probability that the MCE may hit during the life cycle can be evaluated (for example if the MCE is a 1/475 event, the probability it will hit in the next fifty years is roughly ten percent). For the MCE the FoS may be selected at a lower value than 1.5 (for economic reasons), say 1.3, leading to a higher probability of failure evaluated (Figure 1) at 10^{-4}. However, as the probability of MCE is 10%, the seismic risk will be evaluated with $10^{-4}*10^{-1} = 10^{-5}$ probability of failure.

With that p_f the risks would be barely acceptable, as shown in Figure 2, provided the structure is still CAT I, i.e. no prior damage has occurred. On the basis of that evaluation, the structure may be reinforced/repaired or not. If not repaired it would be "de-classed" to a Category II or lower OM. So, if a MCE occurs and the structure is damaged and not repaired, the rest of the life of the structure will be characterized by a $P_f = 5*10^{-2}$, possibly evolving due to degradation to values even larger than 0.5.

The following table summarizes possible changes of FoS and therefore p_f at various phases of the hypothetical structure's life, before and after a MCE.

Table 1: Possible changes of FoS

Phase	Category	Before MCE		At MCE	
		FoS	P_f	FoS	P_f
At construction	I	1.5	1x10^{-6}	1.3	1x10^{-3}
Internal damages to geogrids, malfunction go undetected	between I and II	1.3	1x10^{-3}	1.1	2x10^{-1}
Internal damages lead to detected deformation which are not considered "emergency"	between II and III	1.2	1x10^{-2}	1	5x10^{-1}
Internal damages lead to an "emergency" state	between II and III	1.1	0.08	Less than 1	Over 0.5

The "future history" in terms of FoS and p_f of the structure is then depicted in Figure 3, on the left in decimal, and on the right with a log-decimal scale. What these figures show is how the structure will spiral towards its decay if no major repairs are undertaken.

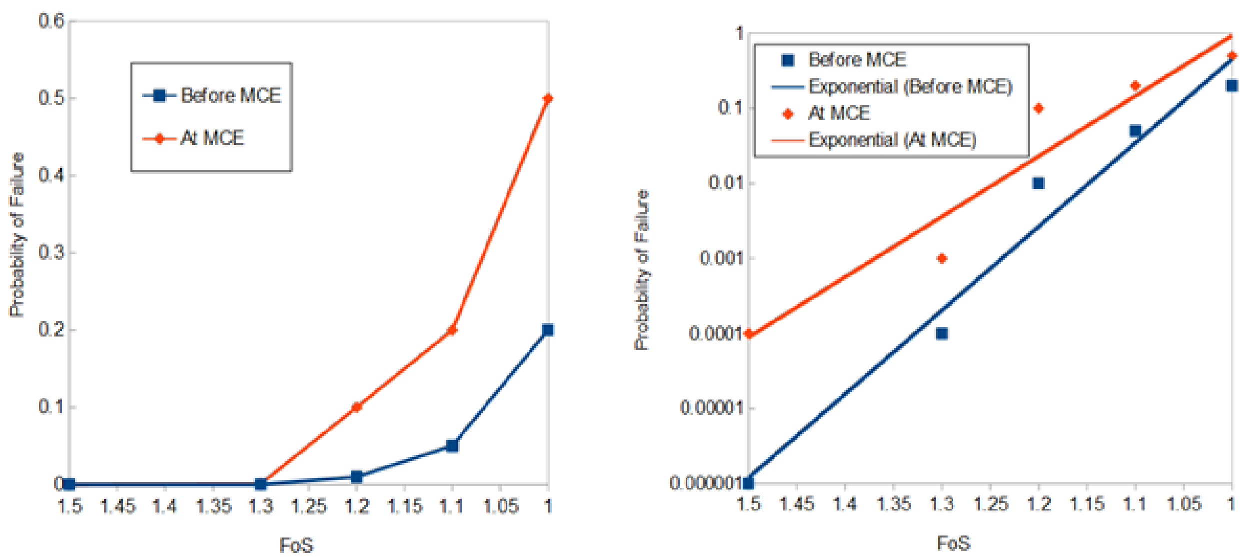

Figure 3: (Left) FoS vs. probability of failure during the life of the structure under normal aging and accelerated aging due to the occurrence of a MCE. As the FoS decreases the Pf increases dramatically (Right) The same graph as on the left, but the probability axis is in logarithmic scale

Then the engineer charged with formulating the closure plan asks: "What do I do with the wall at closure? Leave it to stand as a new topographic form? Tear it down and deal with the impossibility of disposing of all the geogrid? Or simply leave it to fail and slump to a geomorphographically stable form?"

Risks can be evaluated at each stage, using appropriate consequences and considering corporate/societal tolerability. Figure 3 shows the way, for the particular hypothetical structure under consideration, to evaluate p_f in the long run. To reply to the engineer's question, the task at hand, is to determine the consequences at closure (it is obviously not a business-interruption-only consequence, as earlier). These may be complex, including loss of life, environmental impact, and loss of roads. Techniques exist to combine different types of losses into one common metric and establish a tolerability expressed under a common metric.

Thus the two questions posed above can be answered as follows:

- Given there is a definite likelihood that the geosynthetics reinforced structure will, like any other structure, fail, risk-based design can lead to a well-balanced and rational solution.
- The impact of a possible MCE can be modeled and the evolution of the risks estimated.
- At closure, the structure will significantly increase its probability of failure; however the consequences will be different than during the service life; the post-closure risk can be estimated. Scenarios including demolition, disposal costs and related risks can also be modeled.
- Comparisons with other construction techniques will show if it is really economical and safe to include geosynthetics in a long-term design.
- Perpetual maintenance of the closed facility may require additional construction or reconstruction work, and make incur additional risks. The risk evaluation will allow rational and transparent RBDM.

Procedural example 2 – a heap leach pad

A typical heap leach pad is underlain by a geosynthetic liner and associated drains, which may be of geosynthetics or natural permeable materials. The liner is required to limit seepage from the base of the heap and to ensure that the seepage which contains the metals (gold, silver, copper, uranium, or nickel) being leached is directed to the drains and collection systems where the leachate is collected and sent to facilities to be processed.

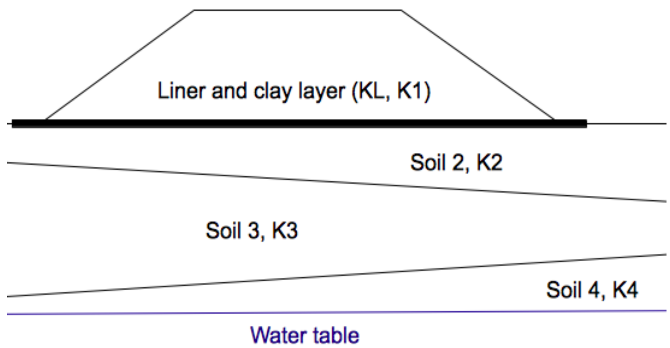

Figure 4: Simplified scheme of a heap leach pad structure

Figure 4 shows a schematic of a heap leach pad structure and the various layers underneath it. During operation of the heap leach pad, loss of fluid to the foundations is a loss of valuable materials, and a potential contaminant of the foundation soils and the groundwater beneath the facility. High-quality liners will leak; although leakage rates may be small, unless the liner is punctured at construction or during the service life. Service life is generally considered to be at least as long as the operational period of the pad.

At closure of the heap leach pad, the rocks of the heap may be washed, drained, or otherwise cleaned. During cleaning, contamination will most likely accelerate because the washing flows constitute a temporary flow increase. In theory, once this is done and a closure-cover is placed, the performance requirement of the geomembrane liner is significantly reduced: little water comes in through the cover; little water seeps and becomes contaminated; and contaminated seepage should reduce over time, because the fluid reserve is depleted.

However, we know that over of time, the cover will let more infiltration in; the seepage may be contaminated to some extent; the liner will degrade further; and groundwater impact may again become a concern.

Obviously this is not a case of geotechnical failure, strictly speaking, but a case of contaminated initial flows potentially significantly increasing to become higher contaminated flows, and potentially impacting the environment.

To analyze such situations, we recommend consideration of the global permeability of the liner. For example, consider that K_L varies stochastically around a minimum at construction (we could use for example the 5 L/ha/day quoted as the minimum by some authors) to 10,000 L/ha/day, or more, at the end of the design life. Then we would have a gradual increase of the permeability to K_1, to simulate total degradation of the liner itself (return to natural permeability of the clay strata underneath the liner which is, of course a stochastic variable itself) as shown in Figure 5.

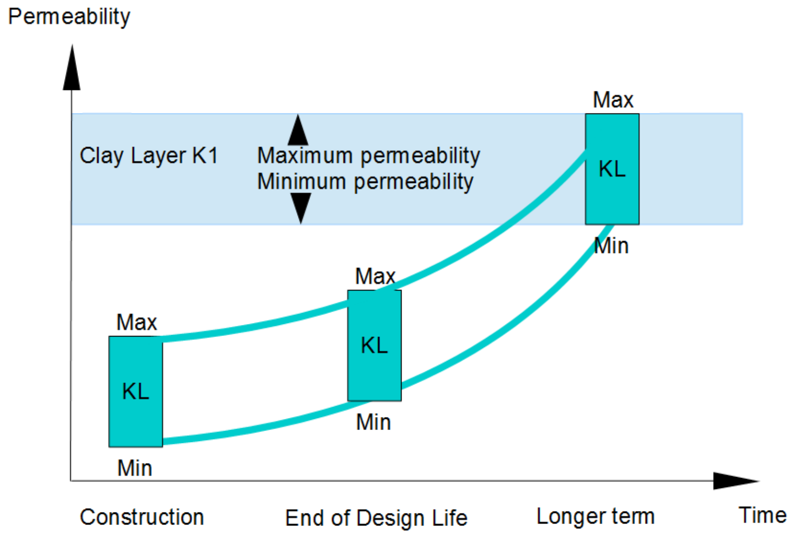

Figure 5: Evolution of the permeability of liner and clay layer. Clay layer permeability is assumed to be constant over time. In the very long term, the liner becomes ineffective, thus KL = K1

The stochastic variation around the selected values could be set by using a uniform distribution, as data would certainly not support more sophisticated assumptions at the preliminary design phase.

The same could be achieved for the permeability of the cover, K_C, and for the various flows during all phases of the pad life, including the washing phase, before cover construction. Rainfall, evaporation, and other environmental impacts could be simulated, including extreme future potential events due to climate change.

It would be possible to evaluate stochastically the flows to the foundation over the life cycle of the pad and, of course, the development of the related plume over the long term. If such analyses result in long-term trivial or insignificant impact to the groundwater, then all is well. However, if it is shown that there is a significant probability that contamination will reach alarming levels in some areas, the project proponents should be required to change the site; change the design; or refrain from operating the heap leach pad. Changing the design may include various mitigations, such as installing a low permeability sub-pad, a double liner, monitoring sensors, or leachate recollection systems.

Of course, the risks related to the pad could be evaluated by studying the consequences of the plume development. The consequence function should be sophisticated enough to cover the rules of Appendix D of the Mackenzie Valley Environmental Impact Review Board (MVEIRB) decision for the Giant Mine rehabilitation project and in particular:

> *The Board expects the risk assessment to use a unified metric showing consequence as a function of all health and safety, environmental, economic and financial direct and indirect effects. This will be done in a manner that allows transparent comparison of holistic risks with the selected tolerability threshold. Consequences will be expressed as ranges, to include uncertainties. (MVEIRB, 2013)*

At the end of the day, such a risk evaluation would support comparison of several solutions, their risk-benefits, and this could support decision making.

If the risks are shown to be intolerable and mitigating measures have to be included and foreseen for the long term, the procedure will show how much it will really cost to perpetually maintain the closed facility.

Conclusions

The demand for safe, secure, and cost-effective mine facilities makes it inevitable that the use of geosynthetics in mining will increase. The harsh environment of mines and the demand for long-term performance impose ever-increasing demands on geosynthetic manufacturers, installers, and designers. Amongst these demands is a clear assessment of the risks associated with the performance of the geosynthetics and of the structures into which they are incorporated. Such risk assessments must include consideration of the safety of the structures and the consequences of their failure, both during the life of the mine and in the long period associated with post-closure of the mine.

This paper has attempted to set out some of the many considerations and methods applicable to the assessment of the short- and long-term risks and consequences of using geosynthetics in mine facilities. The paper shows that short-term risks may be assessed using rational and transparent risk assessment methodologies. The paper shows that consideration of long-term risks requires a shift of thinking and the use of alternative design philosophies.

It is hoped that the ideas in this paper will stimulate discussion, advances in practices, and ultimately better engineering and decision making when using geosynthetics in mine structures.

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