

Heap leach pads—The importance of proper testing, interpretation, and analysis of soil liner geomembrane interfaces

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Abstract

The design of heap leach pads involves a variety of components. One of the main components for these structures is the leach pad liner system, where a low-permeability soil is normally used in combination with a geomembrane to reduce seepage losses. Although this combination of materials has been shown to effectively reduce rates of infiltration, the soil liner-geomembrane interface presents a challenge to designers since it incorporates a “weak layer” into the system, which has negative effects on the physical stability of the structure.

Usually, the effects produced by the soil liner-geomembrane interface govern the stability of the heap leach pads; therefore, it is critical to characterize its behavior by (a) proper sampling and testing—for example, taking into account the design loads that will be imposed by the heap; (b) proper interpretation—for example, taking into account the nonlinear behavior of the interface; and (c) proper application of the results to the analysis—for example, assessing the use of post-peak and large displacement values. Lastly, verifications must be carried out during construction to ensure that the assumptions made during the design are implemented on site.

Although there are papers that discuss these issues individually, the intention of this paper is to present from the designer perspective the key variables to consider at each stage (sampling, testing, interpretation, analysis, and verification during construction). The approach will take into consideration an interface-testing database with more than 10 years of test results, and the experience gained in the interpretation and analysis of these results for heap leach pad projects developed in Peru.

Oversimplification of decisions related to testing, interpretation, and analysis of the soil liner-geomembrane interface can lead to potential economic, environmental, and safety impacts to the project, as well as an increase of the risk levels of the structure. Therefore, the implications of identification and discussion of the variables at each of these stages are important not only to designers, but also to other parties such as clients, manufacturers, and construction companies.

Introduction

The evaluation of geosynthetic/soil system failures has shown that a main contributing factor is often a lack of communication between the participating parties (Dixon, 2010). The participating parties on the soil liner-geomembrane cycle are: designers, clients (including their respective areas like procurement, operations, etc.), geomembrane manufacturers, and construction companies. Usually, their actions are not coordinated and one party can make individual decisions related to the soil liner-geomembrane cycle that may have significant impacts on the final results. Therefore, it is necessary to take an integral approach where the designer has a principal role during all the stages related to the soil liner-geomembrane cycle including sampling, testing, interpretation, analysis, and verification during construction. During construction, if different conditions from what were considered during previous stages are encountered, it is necessary to reinitiate the soil liner-geomembrane cycle, as shown in Figure 1.

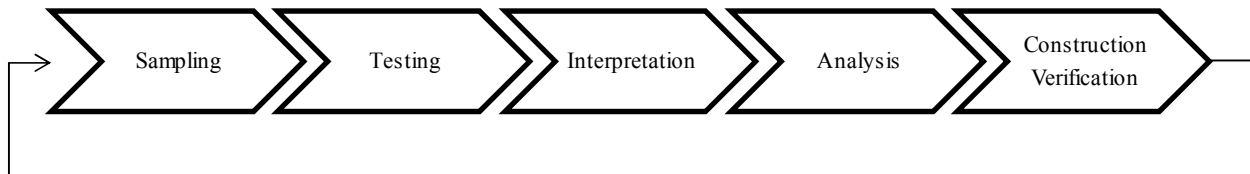


Figure 1: Soil liner-geomembrane interface cycle and stages

Key variables during the stages

The following section identifies and describes the key variables affecting results on soil-liner geomembrane interfaces observed during each of the stages shown on Figure 1.

Sampling and testing

Sample representativeness

This variable may seem obvious but is often overlooked, affecting the final results. The starting point for the soil liner-geomembrane cycle is to have a representative sample of what will be placed in the field. The engineer must ensure that the sample will best represent the expected field conditions.

For the soil liner, the sample should be obtained after the quarry study has been finalized and should be as close as possible to the fine bound of the specification. A common mistake is to test materials that are near the coarse bound of the specification, obtaining much higher resistance for the interface (examples are shown in the following sections), which affects the results of the stability analysis. To make sure that a representative sample is tested, laboratory manufacturing of soils is not recommended.

To ensure a representative sample of the geomembrane, the engineer must verify that the geomembrane being tested is the same geomembrane that will be used during construction (the practice of

requesting a typical sample from the manufacturer should be avoided). Sometimes, the supplier has not been determined, or there is a need to provide alternatives; in these cases, samples must be tested for each different manufacturer and type of geomembrane, as there are significant variations on interface values for different products and manufacturers (examples are shown in the following sections).

A tendency among some of the parties involved in the soil liner-geomembrane cycle (i.e., procurement departments, some designers, and manufacturers) is to consider the geomembrane for heap leach pad applications as a commodity, assuming that its performance can be reduced to compliance with certain standards (such as GM13 and GM17). As indicated by Ossa (2010), these standards are not regarded as they should be. Originally, they were conceived as a generic specification for standard applications, indicating that additional tests, or more restrictive values for test indicated, may be necessary for a particular application (which is the case with heap leach pads). However, some parties invoke their use to avoid performance testing such as interface testing, or to avoid testing each type of geomembrane/manufacturer. The design engineer must explain to all parties the importance of a representative sample and the potential impacts on the results, stating the need for additional interface testing.

Sample extraction

This variable is included since obtaining samples from existing platforms for soil liner-geomembrane testing (a different condition that could be required) may require additional attention. In this case, the methods of construction and loading may modify the mechanical behavior of interfaces and the extracted sample may not represent the most critical condition. Therefore, it is important to plan the sample extraction carefully, reviewing the CQA information to locate the most representative location and considering safety recommendations while developing the plan.

Soil liner and geomembrane properties

Based on the testing performed at the Knight Piésold laboratory and as indicated by other authors, there can be significant differences in the interface values when there is a variation in soil properties such as gradation, plasticity density, or moisture content. Shear strength generally decreases with increasing moisture content and with decreasing soil density; therefore, interface shear strengths should be determined using a moisture content and density that are representative of field conditions. If a large range of moisture contents and densities are possible in the field, then the interface strength corresponding to the average and maximum moisture contents and the average and minimum densities should be determined (Gilbert, 2008).

Figure 2 shows examples obtained from the Knight Piésold testing database for (above) variation on fines content (mesh # 200); and (below) plasticity of materials. In both cases, the materials were obtained

from the same quarry used by the client and the rest of the variables remained fixed for testing. Thus, the importance of a good understanding of the soil liner quarry, which should be gained through testing the same material from the quarry to be used during construction, testing a material that represents the fine bound of the specification, and supervising the materials using quality control and assurance (QC/QA) during construction.

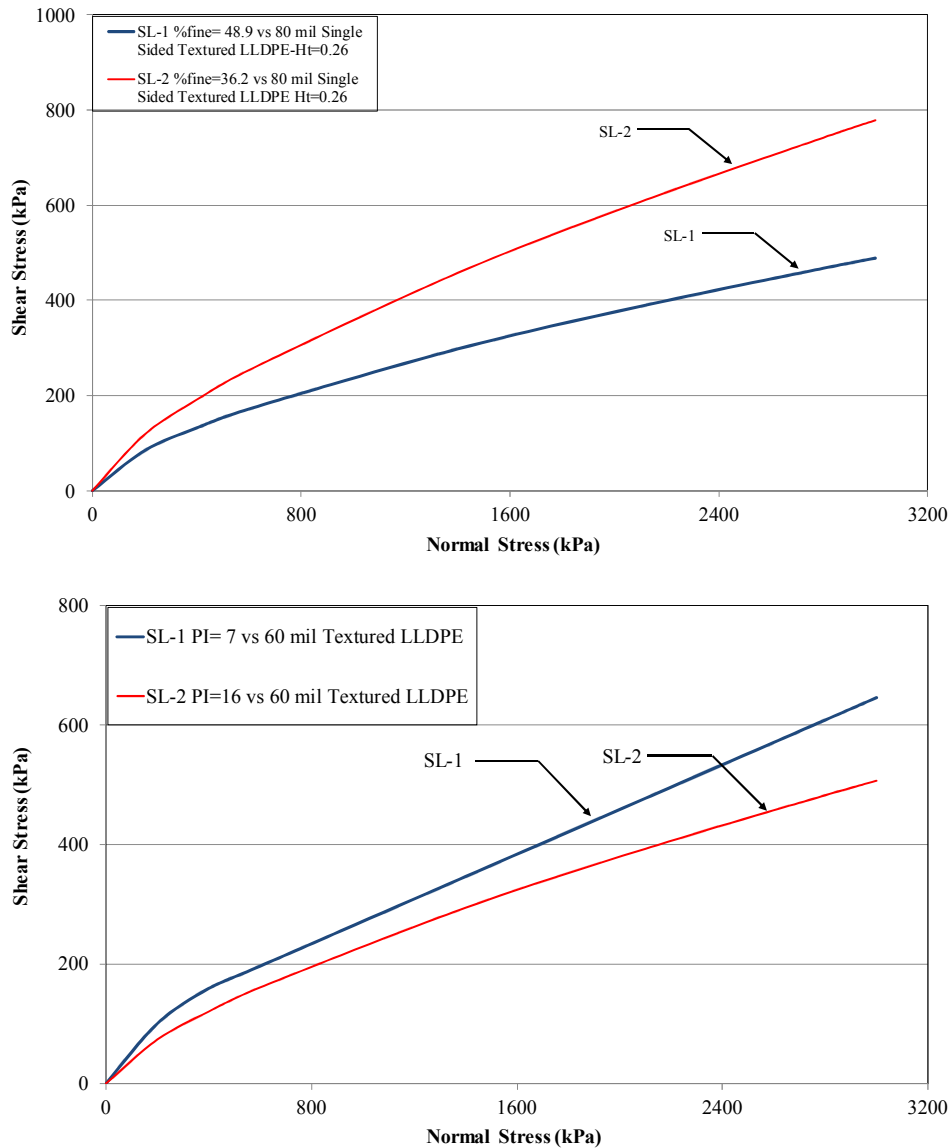
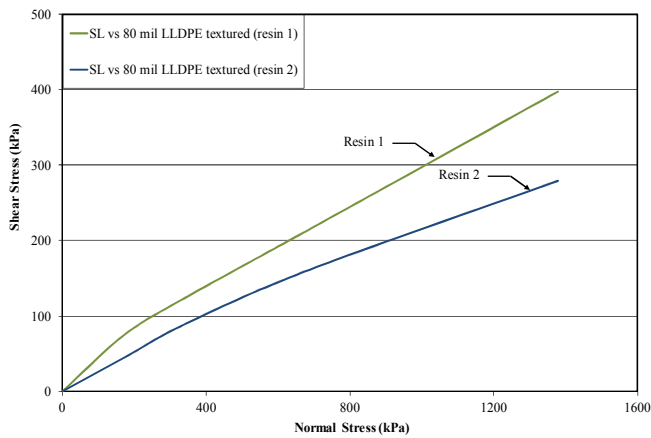


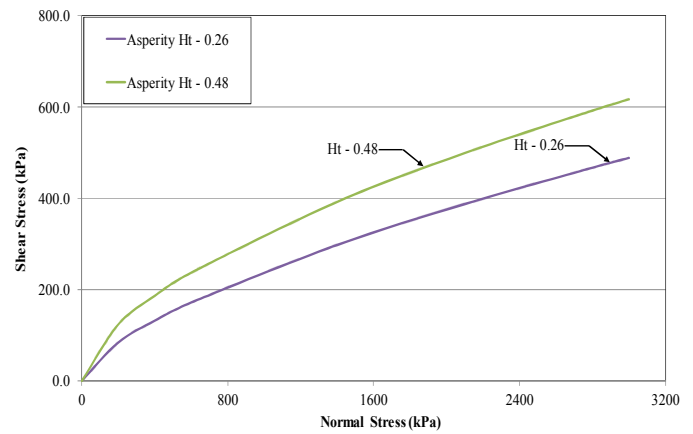
Figure 2: (above) Variation for fines content (below) Variation for plasticity material

For the geomembrane, there are also significant variations of the interface results when using different types of geomembranes, different resins, different manufacturers, or different types of textures. It is important to consider that geosynthetic products are proprietary and subject to change, exhibiting inherent variability in their properties.

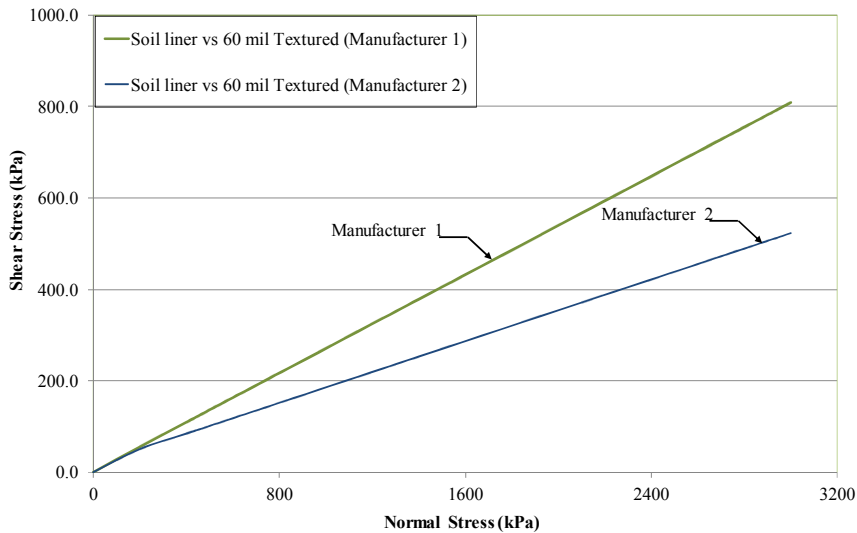
Figure 3 shows examples obtained from the Knight Piésold testing database for the following cases (a) Variation on the formulation of the geomembrane, changing the resin type, where the rest of the variables are fixed (same manufacturer, type of textured, soil, etc.); (b) different types of textures, following the same project specification; and (c) different manufacturers following the same project specification. Thus, testing each type of geomembrane and verification of geomembrane properties and materials during the design and construction verifies that the material that was offered and tested is the same material used during construction. For this purpose it is important to request and attach to each test the geomembrane certificate produced by the manufacturer, showing the lot and properties of the tested material to allow traceability and future comparison of values.



(a)



(b)



(c)

Figure 3: (a) Variation on the formulation of the geomembrane, (b) Different types of textures, (c) Different manufacturers

Finally, a proper report of the material properties (soil and geomembrane) must be produced and attached to the interface test to allow a thorough interpretation and analysis of the tested data. This report should also include the geomembrane manufacturer's certificate and all tests run to characterize the material properties.

Tests conditions

Most of the test conditions are described on the ASTM 5321 "Standard Test Method for Determining the Shear Strength of Soil-Geosynthetic and Geosynthetic-Geosynthetic Interfaces by Direct Shear." However, special attention should be given by the design engineer to the following points for heap leach pads:

- Normal stress loading: The height of the heap at the critical failure surface should be considered to determine the normal stresses to apply during testing. Excessive extrapolation of results is not recommended as there is nonlinear behavior of the interface with higher loads, which is difficult to predict with extrapolation. In projects where there are enough historical data and knowledge of the material, some predictions can be made on the shape of the interface stress-strain curves with higher loads, but testing is always recommended.
- Number of tests (points): The number of points for the test should be enough to characterize adequately the entire range of normal stresses on the heap (see previous point). Additionally, due to the variability of results, described by Dixon (2010), it is recommended to run several points at each normal stress. Recommendations for number of points at each normal stress are provided in standards (such as the BS6906, BS12957-1 and GDA E 3-8) and also by authors such as Dixon, but the design engineer's judgment is always required.
- Shear rate: It depends on several factors, but in general, the shear rate should be such that shear-generated pore water pressures are dissipated (in accordance with ASTM D 5321). As indicated by Gilbert (2008), faster shear rates will produce meaningless results because the pore water pressures and their effect on the measured strength are unknown. Consolidation data for the soil (when applicable) are necessary to determine the required rate of shear.
- Hydration: It is important to direct the sequence of hydration and consolidation at the laboratory and it is generally more conservative to hydrate the sample under low normal loads before consolidating (Thiel, 2001). In almost all situations for heap leach pads, field conditions during shear will correspond to drained conditions (Gilbert, 2008).

The cost of performing a correct test, which sometimes requires additional time and a sufficient number of tests (points), is justified compared to the potential consequences and costs of changes during construction and loading, not to mention repairs or failures.

Equipment

There are several types of equipment. The most common is the direct shear apparatus; other types include ring shear apparatus, tilting table, or an apparatus with a combination of these methods. As stated by Dixon (2010), the design of direct shear apparatus is the main reason for the observed large variability of measured interface strengths; therefore it is important that the design engineer verifies the type of equipment to be used by the proposed laboratory and its applicability to the project.

The standardized size of the shear box has minimum plane dimensions, which are the greater of 300 mm by 300 mm, 15 times the d_{85} of the coarser soil used in the test, or a minimum of 5 times maximum opening size (in plan) of the geosynthetic tested (not applicable for geomembranes). Smaller shear box sizes of 200 mm by 200 mm and 150 mm by 150 mm are used when conducting very high normal stress interface testing. In these cases, it is important that the design engineer verifies their applicability (based on the soil to be tested) and the correlation of data produced between the 300 mm by 300 mm box and smaller devices, considering, for example, running tests with the same normal load but with different boxes.

The design engineer has to determine the configuration of setup for the equipment, deciding if is necessary to include the soils and other geosynthetics above and below the interface of interest. Doing so tends to give a more realistic representation of the field conditions. Using rigid sub/super stratum tends to give a more conservative result (Swan, 2013).

Interpretation and analysis

The stability assessment for heap leach pads requires careful interpretation and analysis of the stress-strain behavior of the soil liner-geomembrane interface. Although the international standards provide guidance on the methods that can be used to measure interface shear strength, the designer must use engineering judgment to interpret the test results and evaluate values to be used in design (Dixon, 2010).

Based on Knight Piésold's laboratory database results and in accordance with other authors, it should be mentioned that the majority of soil liner-geomembrane interfaces present a strain softening behavior for higher loads, where the shear strength reduces with displacements beyond the peak value (see Figure 4). The design engineer should also consider the nonlinear behavior of the interface while interpreting the results and whether minor extrapolation is required for higher loads (i.e., while selecting the function to represent the interface envelope on the software for analysis). It is important to note that

due to the limitations imposed by the direct shear apparatus used for testing we typically obtain large displacement strength instead of residual strength values.

Probably the most important decision for interpretation and analysis is whether to use peak or post-peak values for the analysis. The literature shows different approaches, which can lead to significantly different results. Smith (2008), presents a “summary of recommendations for use of peak or residual shear strength parameters,” which can be useful when selecting a criteria. In general, reduction in strength after the peak value is due to physical changes in the soil and geomembrane forming the interface, resulting from relative displacement between the materials (Thiel 2001).

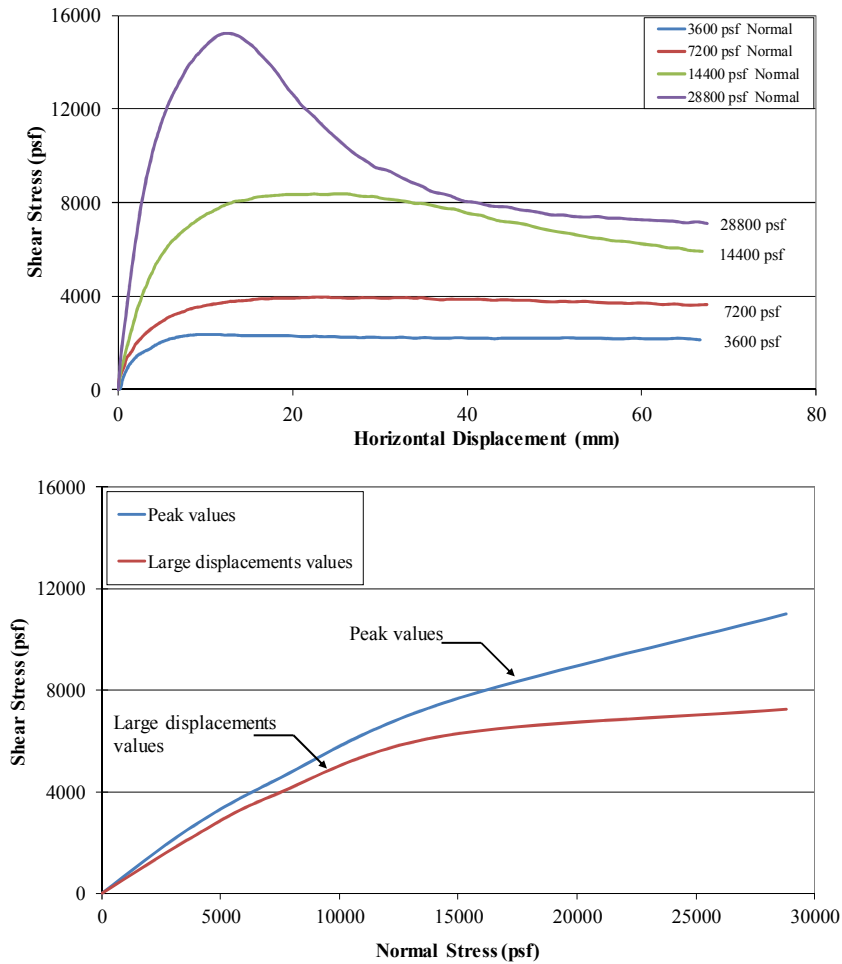


Figure 4: Typical stress versus strain curves with peak and large displacement values

Displacements on heap leach pads can be produced by different causes. The main causes for displacement sufficient to mobilize post peak values are:

- Construction of the Pad: During construction of the platform localized stresses are transmitted to the interface that can mobilize the values to a post-peak condition in various areas of the platform.
- Seismic: Seismic forces may cause differential movement or slipping at the interface layer. If displacements are expected, then large displacement values should be used for the analysis.
- Settlement of the ore on the foundation: The ore is deposited loose on the heap, so particle rearrangements are expected over time. This rearrangement of particles leads to settlement that can be in the order of several meters. The settlement produced next to the side slopes of the heap leach pad may produce down-drag forces that can mobilize post-peak values.
- Steep slopes: The material on steep slopes will compress while transmitting the driving load in the slope to the material located below, and slippage will occur along the interface (Gilbert and Byrne, 1996).
- Ore loading: Loading with heavy equipment close to the liner may produce concentrated efforts and mobilize post-peak values at the interfaces. This can be easily mitigated with an adequate loading plan.
- Others: Interfaces involving soils can have reduced strength with displacement as a result of the soil dilating during formation of the shear plane (Dixon, 2010).

Due to the issues listed above, the authors recommend the use of post-peak values for heap leach pad stability analysis as they represent a better approximation of the conditions expected on site.

Construction verification

The soil liner-geomembrane cycle has to include the construction phase, where the design engineer has to verify that the assumptions made in previous stages are being implemented on site. This requires the involvement of the engineer during the purchasing process, verifying the materials to be placed on site (soil liner and geomembrane) with QC/QA. If during the verification process new materials are encountered the soil liner-geomembrane cycle has to start again, taking representative samples of the materials, testing them following correct procedures, doing a proper interpretation and analysis, and finalizing with verification during construction.

This is the stage when the most deviations are produced as the design engineer is not involved in all processes. The most common processes where the engineer is not involved and in which deviations occur are the purchase process—when a different product may be acquired by the procurement department—and during construction, when modifications to the extension or locations of soil liner quarries may be carried out without the approval of the design engineer. To prevent these problems it is important to prepare a proper specification. Stark (2013) recommends specifying the minimum shear strength and

testing requirements, and prequalification testing and conformance requirements, including the design “stress-strain envelope” on the specifications.

Figure 5 shows an example of interface values reported during the construction phase (purchase of materials, where the interface value is below the design level) and corrections made (which imply reformulation of the geomembrane to be purchased) to be within acceptable levels.

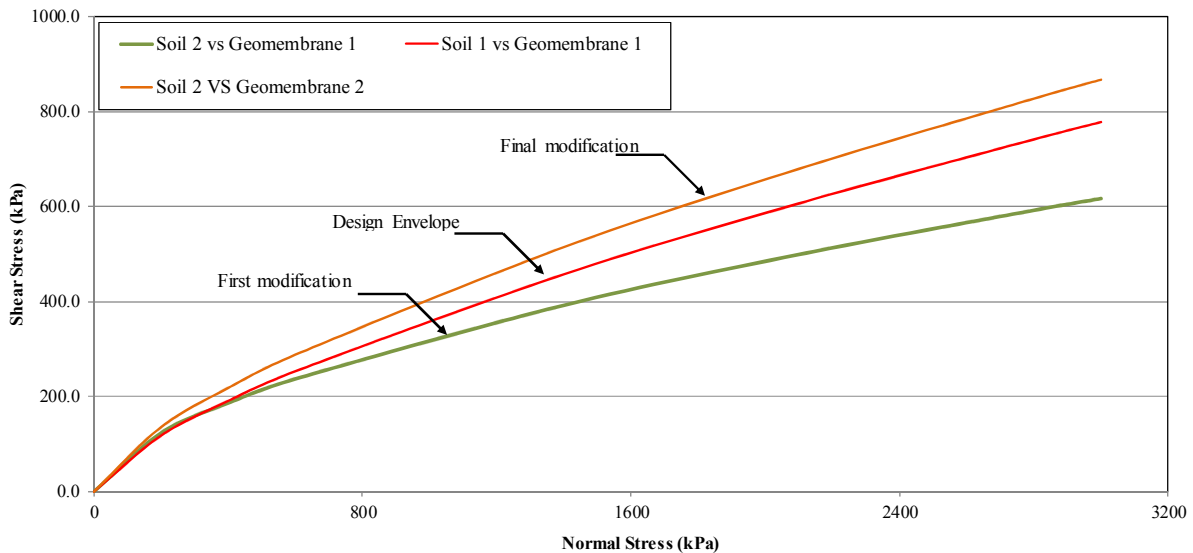


Figure 5: Comparison between design envelopes construction envelopes

Finally, in order to facilitate the review of the soil liner-geomembrane cycle, Table 1 presents a summary of the variables at different stages for soil liner geomembrane interfaces.

Conclusions

The importance of proper sampling, testing, interpretation, and analysis of soil liner-geomembrane interfaces is demonstrated by the significant variations of results presented in this paper if proper care is not taken at each stage. Oversimplification of decisions related to the soil liner-geomembrane interface cycle can lead to potential economic, environmental, and safety impacts to the project, as well as an increase of the risk levels of the structure.

It is necessary to take an integral approach where the designer has a principal role during all the stages related to the soil liner-geomembrane cycle, including sampling, testing, interpretation, analysis, and verification during construction. If different conditions from the ones considered during previous stages are encountered during construction, it is necessary to reinitiate the soil liner-geomembrane cycle.

The existence of national and international standards for testing cannot replace the required engineering judgment necessary for all the stages of the soil liner-geomembrane cycle. An improper

decision at any of the stages may make the final testing results meaningless and not applicable to the project.

Table 1: Variables at different stages for soil liner-geomembrane interfaces

Stage	Variable	Comments/Effects
Sampling	Sample representativeness	Soil: After quarry investigation, fine bound of specification Geomembrane: Same geomembrane to be used on site
	Sample extraction	New HLP, following typical recommendations for sampling Existing HLP, sample may not be the most critical
Testing	Soil material properties	Different results for different gradation, plasticity, density, moisture content Proper identification/reporting during testing
	Geomembrane properties	Different results for different types/manufacturers Proper identification, attaching manufacturer certificate Normal stress loading: Consider heap height (at failure)
	Test conditions	Number of tests (points): Enough to cover the normal stresses range and with several points at each normal stress
	Test equipment	Shear rate Hydration: Saturated/soaked/dry; drained or undrained Shear box sizes Maximum load capacity
Interpretation and analysis	Post peak behavior	Review of stress-strain curve Large displacement / Residual parameters Chosen displacement for interpretation Linear envelope may be used for low loads
	Failure envelope	Nonlinear envelope must be used for higher loads If extrapolation is required, represent non-linear behavior
Construction verification	Verification of materials and interfaces	Verification of the materials considered in the design, i.e., make QA of materials If new materials are encountered, the cycle must start again (sampling, testing, interpretation, analysis, and verification) Participation of design engineer in the purchasing of materials construction Proper specifications

It is important to prepare proper specification documents to prevent some of the problems that can arise during construction. The specifications should include direct references to interface shear strength

requirements and require additional interface testing for conditions different to the design (i.e., during the bidding process or when site modifications occur).

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