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Slope stability considerations for lined landfills

The kick-off session of the 15th GRI Conference in Houston focused on the use of peak vs. residual strengths in design. While touching on testing and applications in retaining walls, the session provided one of the best open debates on the difficulties facing the designer in predicting the stability of a lined landfill in service. The author actively participated in this discussion and felt that many of the key points presented in this session would be of significant benefit to all designers. Key points in this article have been taken from papers by Gilbert (2001) and Thiel (2001). Readers are encouraged to obtain these articles and read them in their entirety. This article presents the highlights of discussions and recommendations made that morning on implementing conservative slope stability evaluations. The discussion is focused on slope failures that occur within the containment system. This neglects site subgrade stability considerations that are similar in nature but more related to unknown site conditions.

Factors influencing slope stability

The stability of an operational lined landfill is influenced by:

- the shear strengths of the veneer liner and lateral drainage systems that form the containment bowel beneath the waste,
- the density and shear strength of the waste itself, and
- additional forces that may be acting on or within the landfill.

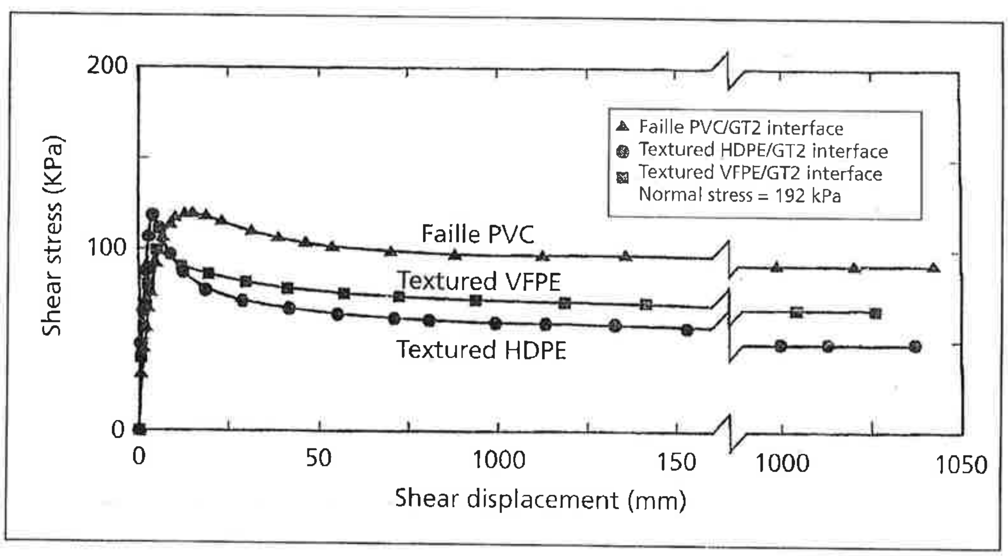
A summary of each of these factors is as follows:

Material shear strengths

In general, the uncontrolled movement of waste within a landfill will be the result of sliding along the interface of the veneer liner and drainage systems that make up the containment system and through the waste. Thus, the shear strengths of interest are the interface shear strengths between adjacent veneer layers and the internal shear strength of the waste.

The interface shear strengths of the veneer layers may display high peak strength at small strains and then significantly reduced shear strength at large strains. This is commonly referred to as a brittle failure. A good example of an interface exhibiting brittle interface shear strength is that between a nonwoven geotextile and a textured geomembrane. A typical interface shear strength vs. strain response for a nonwoven geotextile and a textured geomembrane is shown on **Figure 1**. The nearly constant interface strength at large strain is referred to as the residual

Figure 1: Comparison of failure envelopes for faille PVC, smooth VFPE, and textured HDPE geomembrane/GT2 geotextile surfaces (from Stark and Richardson 2000).



strength of the interface. It is generally felt that such large strains are beyond the capacity of 12-in. direct-shear machines commonly used in ASTM D 5321 and D 6423 testing. The lower interface strength that develops at large strain in these tests is referred to as post-peak strength to differentiate it from true residual strength.

Conversely, the interface shear strength of the veneer layer may increase to the peak strength and then remain constant with strain. This is referred to as a ductile failure. Municipal solid waste (MSW) is thought to exhibit ductile failure and geosynthetic interfaces such as nonwoven geotextile on a smooth PVC liner also have ductile failures (Stark and Richardson 2000). A comparison of brittle and ductile interface failures is presented in **Figure 1**.

An important concept, frequently missed by the novice, is that both peak and residual shear strengths can exist concurrently within the different interfaces of a liner system. Brittle interfaces that have high peak strengths may remain intact owing to slippage in an adjacent interface having a low peak strength. This concept is shown on **Figure 2**. For the liner system portrayed in **Figure 2**, large strain analyses would be performed using the peak shear strengths for the GCL internal shear strength and the textured geomembrane/GCL interface, and residual or post-peak strength for the GCL/drainage composite interface.

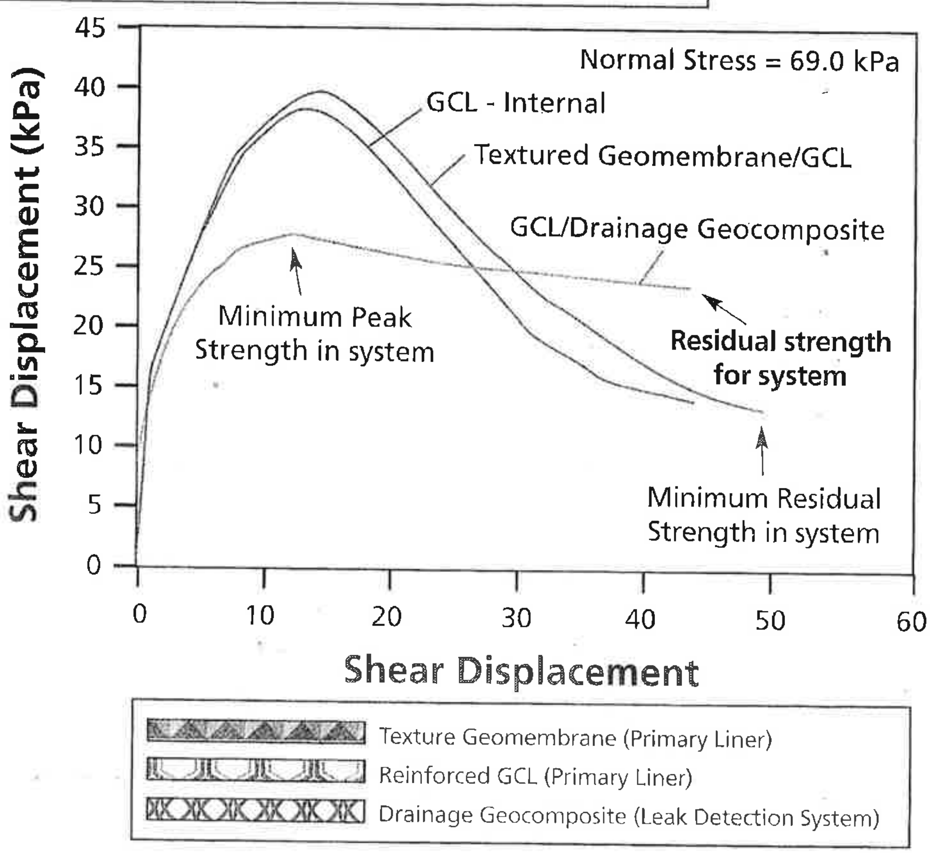
Hydrostatic forces

Since landfills are designed to contain liquids, the potential exists for large hydrostatic forces at critical interfaces. Historical data from operational landfills indicate that a majority have fully functional lateral drainage systems that do effectively limit the head acting on the veneer systems to less than 12 in. (30 cm) as required by law.

Two recent trends in operations may affect the satisfactory performance of the lateral drainage systems and lead to high hydrostatic pressures at the veneer systems. These two changes are as follows:

- The more recent movement to accept greater quantities of biosolids (waste water treatment sludge) has the potential to disrupt the uniform movement of leachate through the waste. The low-permeability and low-strength biosolids material must be effectively blended with the MSW waste to minimize this potential.

Figure 2: Example of residual strength for a system (from Gilbert 2001).



• Recirculation of leachate to promote accelerated degradation of the waste. This "bioreactor" concept is gaining in popularity faster than our technical knowledge of the impact of recirculation on internal drainage systems and waste strength. To put this in perspective, approximately 30 ft. (9.1 m) of liquid must be introduced for each 100 ft. (30.5 m) of waste to achieve the 60+% moisture contents required for accelerated degradation.

Seismic forces

Federal law requires a seismic evaluation for landfills sited in a seismically "active" region. The current methodology for predicting potential seismic deformation is a psuedo-dynamic procedure that replaces the actual time-dependent seismic accelerations with a constant acceleration. The constant acceleration is obtained by first using USGS open file map 2120 to define the probabilistic bedrock acceleration beneath the site. The bedrock acceleration is "brought" to the ground surface using either empirical site amplification relationships or actual site amplification models. The constant seismic acceleration is then taken as one-half of the ground acceleration.

The seismic stability analysis is performed as an equivalent static analysis with the addition of a horizontal force equal to the mass of the material within the moving block multiplied by the constant seismic acceleration. If this analysis produces a factor of safety greater than 1.0, the seismic stability requirements are satisfied. For this seismic condition, the predicted displacements are small and peak interface strength values can be used in the analysis.

If the factor of safety is less than 1.0, then a displacement analysis must be performed.

The success of the displacement analysis is predicated on a reasonable solution for the potential large-strain failure surface that will develop during the seismic event. The displacement analysis must initially solve for the yield acceleration that produces a slope stability factor of safety of 1.0. The total seismic displacement is then determined either empirically based on the seismic acceleration and the earthquake magnitude or using a double-integration procedure if an actual design earthquake time-history is being used. Additional details regarding the seismic evaluation are presented in EPA/600/R-95/051.

The use of peak shear strengths is generally not appropriate for seismic displacement analyses if displacements greater than 1 in. are predicted. In general, a system residual or post-peak residual strength should be utilized in seismic evaluations.

Slope stability analysis techniques

Three analysis techniques can be used by an engineer to evaluate the stability of a lined landfill:

Two-dimensional (2-D) analysis

This is the everyday workhorse that is employed in the majority of actual designs. Using computer programs such as PCSTABL, the engineer can quickly evaluate the stability of a large number of circular and block failure surfaces. The accuracy of the method is limited by the ability of a 2-D "cut" through the landfill to define the minimal stability of the 3-D waste mass. Additionally, the 2-D analysis assumes that displacement is constant along the failure surface, so true strain distributions within the system are not known.

Three-dimensional (3-D) analysis

Soong et al. (1998) showed that a 3-D analysis more accurately predicted observed historic failures in landfills compared to 2-D evaluations. However, the 3-D analysis is more complex and therefore more subject to errors in application. Psuedo-3-D techniques using weighted averages of 2-D analyses are also available that offer the simplicity of 2-D evaluations with a more realistic evaluation of 3-D factors of safety. Like 2-D analyses, the 3-D methods assume that displacement is constant along the failure surface, so true strain distributions within the system are not known.

Finite element method (FEM)

By far the most complex of the analysis methods, the FEM requires estimating elastic properties of materials in addition to their shear strength at failure. This method provides a measure of the strain distribution along potential yield surfaces, but is not currently a realistic option for design. It is commonly used in evaluating long term strains in liner systems piggybacked over existing landfills.

The general recommendation for today's designer is to use the 2-D analysis with shear strengths adjusted for anticipated deformations. For instance, in deep-canyon facilities, it would be prudent to assume that sidewall shear strengths were at a residual level due to waste subsidence-related settlements. The shear strengths for the base of the liner would be maintained at peak strength values because of the limited differential movement anticipated. Note that both peak and residual (or post-peak) strengths may be used concurrently in the analysis. Obviously, engineering judgement remains a key factor in practical analysis.

Summary

Several concepts are presented in this paper that may be new to even experienced designers of lined landfills. These important concepts are as follows:

- Ensure that the stability of the liner system exceeds 1.0 when using the minimum system residual strength. Recall that the minimum system residual is defined as shown in **Figure 2**. This does not mean that the analysis is performed using residual strength values for all interfaces.

- If you cannot achieve a minimum stability of 1.0 when using the minimum system residual strength, then evaluate the risk associated with a system failure and determine if it is acceptable to the owner and regulatory community.
- Both peak and residual (or post-peak) strengths must be defined to adequately evaluate the stability of a liner system.
- Stability evaluations using 2-D stability analyses are adequate, assuming care is given in selecting the critical section(s) such that potential 3-D anomalies are accounted for.

Fortunately, the past decade has been remarkably free of major slope-stability problems in lined landfills given the novelty of the application

The author acknowledges and appreciates the contributions of Richard Thiel and Robert Gilbert to the concepts presented in this article. The reader is encouraged to obtain and review the references in their entirety; further discussion of these concepts is recommended. GFR

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