CURRENT INDUSTRY PERFORMANCE AND CONSTRUCTION ISSUES RELATED TO GCLs

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ABSTRACT

As the industry becomes more comfortable in using geosynthetic clay liners (GCLs) as liquid barriers, there remain several issues requiring the attention of designers, installers, regulators, and owners. Some observations and guidance are provided in this paper that are directed towards the design practitioner and field inspector. Specific issues are related to hydraulic conductivity vs. effective confining stress; long-term shear strength; contaminant transport relative to diffusion; construction issues related to handling, deployment, and covering; and construction quality assurance using electric surveys.

HYDRAULIC CONDUCTIVITY

The value of the hydraulic conductivity, *k*, of a bentonite is a predominant factor in controlling the leakage rate through GCLs. The hydraulic conductivity of sodium bentonite is affected by two principal variables: (1) the level of normal or compressive stress applied to the GCL, and (2) chemical alterations caused by different permeating liquids that change the hydraulic conductivity of the sodium bentonite.

Compressive stress is a significant variable that controls the behavior of bentonite. It decreases both hydraulic conductivity and the susceptibility of bentonite to chemical alterations. Increasing the compressive stress on a GCL decreases the void ratio (or porosity) within the bentonite layer, which lowers its hydraulic conductivity. This tendency toward decreased hydraulic conductivity in response to increased compressive stress is a basic characteristic of virtually all soils.

Figure 1 depicts the relationship between hydraulic conductivity and effective stress for several types of GCLs hydrated with tap water as reported by Daniel (Thiel et al., 2001). The differences in hydraulic conductivity between the various GCLs are minimal, excepting at lower compressive stresses in which internally reinforced and non-internally reinforced GCLs behave slightly different. GCLs with internal reinforcement (e.g. geotextile-encased, needlepunched GCLs) tend to have a slightly lower hydraulic conductivity under minimal confinement because as the bentonite hydrates and swells the reinforcing needlepunched fibers hold the encasing geotextiles together and thus provide additional confinement and compressive stress on the bentonite. At high normal stresses, the differences in hydraulic conductivity between the various commercial GCLs are subtle.

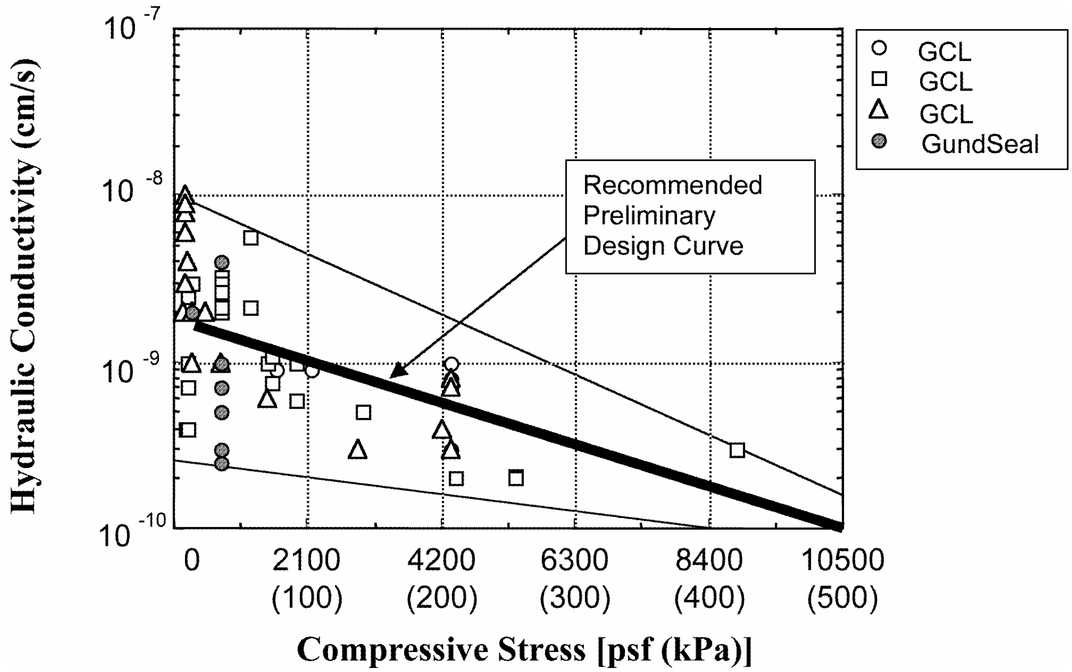

Figure 1. Hydraulic Conductivity of GCLs as a Function of Effective Confining Stress (Thiel et al., 2001).

Data supporting the work performed by Daniel has recently been completed by Thiel and Criley (2002) using three types of actual landfill leachates. GCL samples were prehydrated with tap water and subsequently permeated with the leachates. The three types of leachates tested included: (1) municipal solid waste (MSW) landfill leachate, (2) ash landfill leachate containing incinerated MSW, and (3) pulp-and-paper waste landfill leachate. The data are summarized in Figure 2.

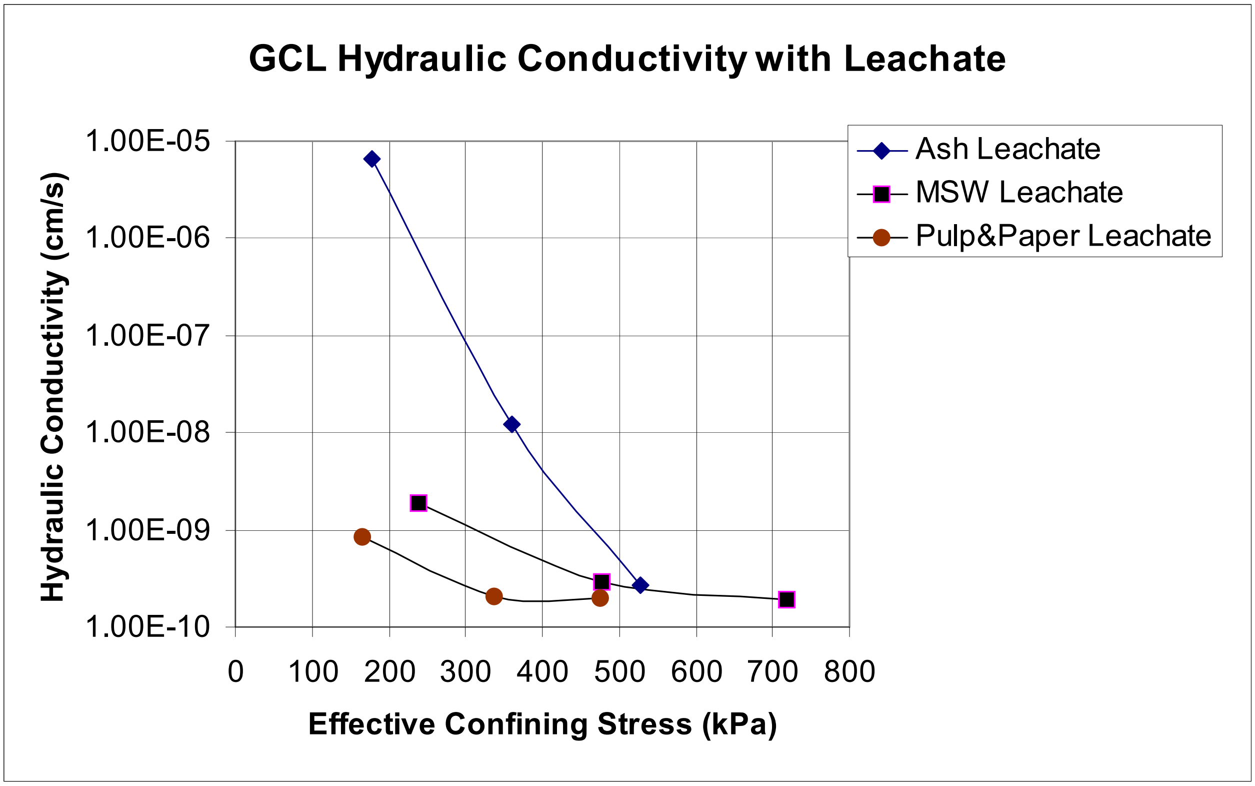

Figure 2. Hydraulic Conductivity of GCL vs Effective Confining Stress for Three Different Leachates.

The data presented in Figure 2 support the concept that the effective confining stress placed on a GCL is a very significant variable affecting the hydraulic performance of sodium bentonite. Even for very aggressive incinerator ash leachate there is little difference in hydraulic conductivity compared to other leachates, or even water, above 500 kPa effective confining stress. This information bodes well for using GCLs in bottom liner applications, although the data is still relatively short-term.

CONTAMINANT DIFFUSION THROUGH GCLs

In the US, contaminant transport through liner systems in waste containment facilities has traditionally been evaluated solely as advective flow, commonly referred to as 'leakage' in every-day terminology. Advective leakage is typically estimated using flow models such as Darcy's law through saturated soils, or the 'Giroud' equation through geomembrane defects in composite liners (geomembrane-clay or geomembrane-GCL). Over the past decade, contaminant transport through barrier systems by diffusion has become recognized as a potentially significant pathway for contaminant transport.

Diffusion results from contaminant transport through intact liner systems (geosynthetic or soil), and is independent of hydraulic gradient or gravity. The driving force for diffusion results from a difference in chemical potential above and below the barrier system and is modeled using Fick's first and second laws for diffusion through materials and Henry's law for partitioning between material interfaces. (See Foose et al. (2002) or Rowe et al. (1995) for a more detailed description of diffusion.) Two generalizations regarding contaminant transport by diffusion through composite liners include:

- It is not a significant issue with metals, salts, or other polar compounds because these contaminants are not readily sorbed by geomembranes. The predominant pathway for contaminant transport for these constituents is through defects in the geomembrane.
- Diffusion of volatile organic compounds (VOCs) through composite liners may be 10,000 to 1 million times greater than advection because VOCs are readily sorbed by geomembranes (i.e. a liner system could have over 10,000 geomembrane defects per acre and leakage of VOCs through holes would still be less than by diffusion.)

What the primary author has learned in struggling with this issue is that in regards to diffusion there are two kinds of soils: saturated and unsaturated. Diffusion of VOCs in unsaturated soils can be on the order of 10,000 times greater than in saturated soils because the VOCs diffuse in both the vapor-phase and aqueous-phase rather than solely in the aqueous-phase.

So how does this issue affect GCLs? From the standpoint of diffusion, a GCL generally represents a 6 mm layer of saturated soil. From the standpoint of equivalency of a GCL to a compacted soil liner system, a 6 mm layer of saturated soil in a GCL is significantly thinner than a typical compacted clay liner (generally 600 mm or thicker). Thus a GCL without an attenuation layer does not compare favorably with traditional compacted clay liner with regard to diffusion of VOCs.

When evaluating the performance of GCLs and comparing them to other liner systems, it is the complete hydrogeologic setting between the top of the liner and the groundwater which really counts when evaluating contaminant transport. That is, any saturated soil (where the soils are at least 85% degree of saturation) below the liner system might perform nearly as well as a compacted clay liner in regard to diffusion. Rowe (1998) discussed the issue of equivalency in detail and demonstrated how this can be assessed in terms of contaminant impact.

The take-home message is that when comparing GCL-based liner systems to compacted-clay liner systems for bottom liners where diffusion is being investigated, it is important to take a critical look at the entire soil profile between the liner system and the groundwater. A performance-based evaluation of alternative liner systems with respect to groundwater impacts might be more appropriate than equivalency-based comparisons between different liner systems.

Finally, it is important in the authors' opinion to put any new issue such as diffusion in perspective. Significant points include:

- The quantity of VOCs that actually diffuse through a liner system may be very small and will decrease as the source concentration decreases. Long-term steady state analyses in this regard are unrealistically conservative. That is, the assumed boundary conditions related to contaminant concentration at the source and contaminant build-up at the receiving end can have a large influence on an analytical model.

- Theory vs. practice with regard to evaluating diffusion through *composite liners* is relatively new and there is a scarcity of corroborating laboratory and field data for *composite liner systems*.

- Other attenuation factors, such as sorption, biodegradation, and abiotic degradation (e.g. hydrolysis), are probably very significant.

LONG-TERM SHEAR STRENGTH

At the 14th annual GRI conference in 2001, the primary author presented a discussion on utilizing peak vs. residual shear strength in landfill <u>bottom liner</u> designs (Thiel, 2001). (Cover systems are mentioned separately at the end of this section.) The key questions posed included:

- *Should a designer use peak or residual shear strength(s), something in between, or a combination of peak and residual strengths when evaluating a landfill design?*

- *To what extent does the design practitioner understand mobilized shear stresses?*

- *Should the choice whether to use peak or residual shear strengths be applied to the entire lining system, or should slopes and base liners be treated differently?*

- *Is there a preferred design approach?*

- *What factors of safety are appropriate for design?*

In that paper, discussion included the issue of progressive failure as it relates to strain-softening (or "brittle") interfaces. The interface and internal shear strengths of reinforced GCLs certainly fall into the category of strain-softening materials given that the residual strength of the GCL is significantly lower than material peak strength. The difference in peak and residual strength is largely dependent on the strength and mass of the reinforcing fibers.

Several mechanisms that could result in progressive failure were identified for strain-softening materials, including:

1. The non-uniform and lack of a thorough understanding of the distribution of shear stresses.
2. Unexpected or sudden increases in pore pressures.
3. Seismic events.
4. Construction-induced deformations.
5. Waste and/or foundation settlement resulting in downdrag.
6. Geosynthetic material aging and creep.

Specific engineering approaches should be used to address each of these potential trigger mechanisms. Very often, however, several or all of these issues are not specifically addressed and are therefore not explicitly incorporated into the global factor of safety (*FS*). Whether a designer knowingly or unknowingly adjusts his or her *FS* to address each of these issues is variable as there is currently no well-defined state-of-the-practice for evaluating and accommodating these issues, perhaps with the exception of seismic loading. In all cases, the selection of long-term shear strengths is project-specific and the responsibility of the designer.

Progressive failure can occur if the most overstressed component of the liner system fails due to any of the six reasons listed above. The load that was carried by the now-failed material or interface would subsequently be redistributed to the remainder of the structure. With time, the additional load placed on the remaining components of the lining system may cause an additional component failure within the lining system. This transference of shear stresses as materials/interfaces fail would occur until total system failure or long-term equilibrium is reached. The more highly strain-softening (or brittle) the failing interface is, the more potentially sudden and catastrophic the ultimate failure would be.

Long-term slope stability with GCLs can be achieved by way of the reinforcing fibers in fabric-encased needlepunched reinforced GCLs or, alternately, by encapsulation of bentonite between two geomembranes to preserve the dry shear strength of the bentonite. In regard to geomembrane supported GCLs and the encapsulated bentonite design methodology, a detailed discussion is presented by Thiel et al. (2001).

Specific to fabric-encased GCLs, over the past year the most significant technical publications regarding the long-term shear strength of reinforced GCLs were presented at the GCL specialty conference International Symposium in Nuremberg, Germany in April, 2002. Of particular note was the session titled Durability and Lifetime where three papers discussed aging and polymer degradation of the reinforcing fibers in GCLs (Thies et al., 2002; Hsuan and Koerner, 2002; and Thomas, 2002). These papers suggest that even in buried, low-oxygen environments, the service life of the geotextile polypropylene fibers under tension will most probably range from less than 100 years up to perhaps 300 years, depending on the resin additive package. This issue may affect not only reinforced GCLs but potentially all geotextile products where long-term durability relative to slope stability is a concern.

These studies pose two questions:

- What is the reinforcing mechanism for needle-punched products, and how will it be affected if the geotextiles degrade over a very long period of time (again, for now, relative to bottom liners rather than covers)?

- What is the design lifetime of waste containment facilities that utilize reinforced GCLs relative to slope stability? The answer to this question may or may not be different than the design lifetime relative to the containment of contaminants. It is a difficult question, which should be answered in the context of societal values in conjunction with engineering judgment.

Regarding the first question, the authors do not believe it is simply the engagement of tensile forces in the reinforcing fibers that contribute to the apparent high peak internal shear strength at high normal loads for needlepunched reinforced GCLs. The shear strengths exhibited at high normal loads, even under fully hydrated conditions, are much greater than the sum of the bentonite shear strength and geotextile tensile strength. By some mechanism, which is not fully understood, the mass of needled fibers introduces an engagement of complex shear interfaces between the fibers and bentonite, and between the fibers themselves. Exactly how this complex interaction might be affected by long-term degradation is not at all clear at this time.

Regarding the second question, after landfill closure, slope stability may or may not be monitored closely. Most probably future landfills will receive minimal long-term attention according to current thinking, and the cost of rebuilding or remediating the site most likely will not be accrued. If the landfill was designed with brittle interfaces that degrade with time under nominal levels of shear stresses, the system may ultimately fail. In relation to a reinforced GCL, long-term stability and potential failure are dependent on the original factors of safety and how large of a drop occurs when the reinforcing fibers lose part or all of their strength. The more brittle the interface, the higher the risk of a sudden and catastrophic failure depending on how far below unity the factor of safety is with residual strength conditions. Again, it is a very complex question as to how long and by what mechanisms the shear strength might degrade.

Two general design approaches are discussed below related to peak vs. residual design assumptions with respect to reinforced GCLs.

One common design methodology focuses on the material or interface with the lowest peak strength. This echoes the adage that a chain is only as strong as its weakest link. In regard to the slope performance of reinforced GCLs for this design assumption, designers strive to transfer the weak interface to a location other than the internal reinforcing fibers of the GCL. Given that this methodology focuses on a weak interface separate from the internal portion of the GCL, it essentially assumes that the reinforcing fibers of the GCL will last into perpetuity when compared to some other interface that has a lower short-term peak strength. If relative movement does occur due to an earthquake, for example, then the residual shear strength of the material or interface with the lowest peak strength would govern. For many situations, particularly in a-seismic areas, it is an acceptable state-of-the-practice to design solely on peak shear strengths based on short-term direct shear performance testing with the objective of achieving a standard $FS \geq 1.5$. The authors would not fault a designer who followed these practices given that this state-of-the-practice is the legal basis upon which engineering professionals are judged.

If a project is constructed based on this design approach, and if the absence of the reinforcing fibers would result in a potentially sizeable or catastrophic failure (e.g. $FS < 1.0$), then perhaps there should be a defined design life with stipulations for future re-examinations of stability and potential allowances for future maintenance and re-construction costs. Alternately, an evaluation could be made using a cost-benefit and risk analysis approach associated with the impact of a sizeable slope failure as a result of a design assumption that relies on the long-term durability of the reinforcing fibers. Such an analysis could be an extension of the probabilistic method promoted by Duncan (2000), which could be modified to incorporate the fourth dimension of *time* into the model.

A second design approach evaluates long-term stability utilizing the lowest potential residual shear strength of all interfaces in the lining system. This includes evaluation of the residual shear strength of hydrated reinforced GCLs which is essentially the residual shear strength of hydrated bentonite, albeit with some unknown fiber inclusions. The design constraint typically requires that, under residual strength conditions, the global factor of safety is greater than unity ($FS \geq 1.0$). Thus, this design assumes that although the reinforcing fibers of the GCL will fail or lose a significant portion of their strength, the system will maintain a long-term $FS \geq 1.0$ for the worst case residual condition. Therefore, the potential for a sudden and catastrophic failure is greatly minimized or eliminated. Clearly this approach adds one additional design constraint and is therefore generally more conservative. We say 'generally' more conservative, because often the goals of the second design approach are de-facto satisfied by the nature of the materials and project geometry, even if it was not the outright intent of the designers to achieve this goal.

Currently there is no industry consensus with regard to a state-of-the-practice design approach relating to the long-term (e.g. greater than 100 years) shear strength behavior of GCLs. We are, however, in a new era of civil and environmental engineering. Landfills are among the largest structures in the world (second only, perhaps, to heap leach pads, which also rely upon GCLs and other geosynthetic interfaces!). Society is expecting us to "put these structures to bed" so that they can rest in peace with little to no further regard for their condition. It is only appropriate that design practitioners within the geosynthetics industry raise such questions as these.

Finally, the preceding discussion was written with bottom liner systems in mind. The authors have a less critical view regarding cover systems where the shear stresses are less, the potential danger to safety and environmental impairment is less, and the opportunity for repair and maintenance is much greater. In this case, long-term creep-shear studies (Seibken et al, 1996; Trauger et al., 1996; and Bentofix, 2002) have indicated that using the peak shear strength of internally reinforced GCLs is a reasonable design approach.

HANDLING GCL ROLLS

The guiding principle for unloading and transporting materials on the jobsite is to follow the manufacturer's recommendations. This requires the use of either a stinger rod or spreader-axle-bar configuration in conjunction with a stout core pipe. Manufacturers explicitly direct against most other methods of handling GCL rolls. Generally, manufacturers do not condone moving and stacking rolls using the forks on a forklift.

Material unloading at the jobsite should be considered an important element of construction quality assurance (CQA). Oftentimes the geosynthetic rolls arrive to the jobsite well in advance of the trained Installer, and either the Owner or the General Contractor will unload the materials. In most cases, neither of these two parties is necessarily trained, equipped, or sensitive to the nuances of unloading geosynthetics, particularly GCLs. Usually they will resort to utilizing a forklift for off-loading rolls. The results are often that the outer wraps of the GCL become speared with holes, and the cores of the rolls are broken or crushed because the weight of the roll has been cantilevered over the ends of two forks. This type of damage to the rolls makes subsequent use of a stinger-bar and axle-spreader-bar for unwinding rolls more difficult.

This type of roll damage does not occur just with neophyte contractors. The primary author recently performed CQA with an experienced landfill General Contractor that has been constructing landfills in conjunction with geosynthetics installations for more than a dozen years. The Owner of the landfill (a major national firm) asked the

General Contractor to unload the materials in advance of the Installer arriving on site, with the results exactly as described above.

The key to success in regard to roll handling is to be prepared with the proper equipment before the delivery trucks arrive on site. Any exception to the manufacturer-prescribed methods of handling GCL rolls should only be done under full CQA supervision.

DRIVING OVER DEPLOYED MATERIAL

Installers and contractors invariably ask if they can drive directly on top of various deployed geosynthetics. In response to this issue, there are no absolute answers. However, general guidelines (such as ASTM D 6102, manufacturer's recommendations, and common sense) should be followed with the aim of preserving the integrity of the geosynthetics. For example, geosynthetics are not manufactured and designed to be driven over and yet under carefully controlled circumstances the deployed materials can be driven over by a fully loaded scraper without causing any damage. Should this practice ever be allowed in the specifications? Certainly not! And yet some lee-way could be given in this area of CQA.

The authors have found that the best compromise is to specify that the only equipment allowed on the geosynthetics are those pieces of equipment specifically approved in writing by the manufacturers, unless field demonstrations convince the engineer that other types of equipment will work. Sometimes field demonstration can override the manufacturer's recommendations.

Recently the primary author was involved with a project that disallowed front-end loaders to drive directly on the GCL while deploying geomembrane over the GCL. Due to high winds, the installer did not wish to hand-pull the geomembrane and desired to unroll the sheet using a piece of equipment while backing up. The GCL manufacturer subsequently approved a rubber-cleated track loader. Close inspection by the CQA representative revealed that the rubber-cleated equipment had caused more damage than the much heavier loader due to weight distribution when carrying a 2,000 kg geomembrane roll. This demonstrated the value of field observation.

The largest variables that affect the use of equipment directly on top of a deployed GCL are the moisture content of the bentonite and the type of GCL. Even with reinforced GCLs, if the bentonite becomes moist to the extent that it behaves like plastic putty, no mobile equipment should be permitted to driven on it. The bentonite will become displaced and the reinforcement may be damaged in the wheel paths. The drier the GCL, the less it will be influenced by equipment wheel loads. Reinforced GCLs will fare better with equipment traffic than unreinforced GCLs.

It is common that low ground pressure all-terrain-vehicles (ATVs) and 6-wheel gators are allowed to drive directly on top of dry fabric-encased GCLs. Although this equipment is commonly permitted on geomembrane-supported GCLs, it may be advantageous to utilize a 0.75 mm smooth geomembrane slip sheet between the vehicle and the bentonite if the bentonite side is facing up. Larger equipment, such as front-end loaders, may also be permitted on fabric-encased GCLs but only if the GCL is dry, the subgrade is suitable, and equipment turns are very gentle. Again, a field demonstration and close observation should be used whenever there is a question related to potential damage to the GCL.

ELECTRIC DEFECT DETECTION SURVEYS

When evaluating the equivalency between GCLs and compacted clay liners used in conjunction with geomembranes in composite bottom liner systems, the issue of the relative thinness of a GCL and its susceptibility to large through-liner construction damage should be evaluated. When the size of a defect is greater than approximately 20 mm it becomes difficult for sodium bentonite to swell into the defect and seal it from potential leakage. The potential for completely breaching through a GCL as a result of installation damage is much greater when compared to a thick compacted clay liner. Now there is a very cost-effective technology to completely address this issue.

Over the past two decades, technology has been developed to allow electrical defect-detection surveys to be conducted over large areas of soil-covered geomembrane with a high degree of sensitivity and accuracy. This would apply for GCL installations that have a separate welded geomembrane covering the bentonite. This technique is now commonly available from vendors in North America, Europe, Asia, and other geosynthetic containment markets, and generally costs less than $0.54/m^2 ($0.05/ft^2). Thus, it is also a cost effective CQA tool to locate defects in a soil-covered geomembrane lining system.

The primary author typically does not allow soil-spreading operations to occur directly over liner systems without having a CQA monitor present in front of the dozer blade 100% of the time to verify that the liner system is not damaged. This usually requires bringing on an additional CQA monitor during the soil-spreading phase, because other construction activities on a typical project require the attention of the lead CQA Officer. Using the electric leak detection technology allows reducing the requirement for 100% CQA supervision of the soil-spreading operation over liner systems, which in turn offsets part of the cost of performing the survey. In this case, the lead CQA Officer observes the soil-spreading operation from time to time to make spot checks for layer thicknesses or that no excess wrinkling is developing, and the concern for monitoring construction damage to the liner system is relegated to the electric survey.

This technology functions by impressing a voltage difference across the geomembrane liner. Given that the geomembrane is an electrical insulator, current can only flow through defects in the geomembrane. A digital data recorder is used to measure the differences in electrical potential on the cover material, and defects are isolated as anomalous readings in these measurements. More detailed information can be found in Darilek and Laine (1999) and Laine and Darilek (1993).

An electrical leak detection survey can provide a high level of confidence in locating defects in a welded geomembrane that would be of significant concern. The survey is extremely practical in that it is utilized after the lining system has been exposed to essentially all potential mechanical damage (e.g. after the geomembrane and GCL liners have been deployed and covered with soil). The sensitivity of this technology depends on site specific factors such as:

1. The resistivity of the soils above and below the geomembrane.
2. Thickness of the soil overlying the geomembrane.
3. Spacing between measurements.
4. The expertise of the personnel performing the survey and interpreting the data.

The typical size of a geomembrane defect that can be detected under a 300-600 mm soil cover are holes greater than ranges between 1 mm to 10 mm, although much smaller defects are often located. Defects in a geomembrane of this size and smaller are mitigated by the healing and swelling properties of the bentonite in the underlying GCL. Defects larger than 10 mm, which are the defects of real concern, are easily located by an electrical detection survey and can subsequently be repaired prior to operations.

Based on the primary author's experience with electric defect detection surveys conducted on five recent projects, this CQA tool can alleviate most all concerns related to the relative thinness of GCLs and their susceptibility to large construction-related defects. Regarding the five projects referenced by the primary author, all involved geomembranes over GCLs (both fabric-encased and geomembrane-support GCLs), and the total lined area was approximately 13.2 ha. A total of 25 defects were located; two defects were large (each approaching 35 cm^2), several were long knife cuts, and many were barely visible pinholes.

Preparation for an electric leak location survey in a GCL installation usually involves installing a grounding wire at one or more locations in the lined area. The wire is installed between the GCL and the overlying geomembrane and carried out to the edge of the liner system. This is usually done by the CQ monitor in accordance with directions provided by the defect-detection firm. After the liner system is installed and covered with soil, the defect-detection firm is mobilized to the site. A typical survey for a 4 ha project requires approximately 5 days to perform. Usually the first two days are required for laying out the string-line grid, and performing a calibration. The primary author strongly recommends calibrating with an actual hole drilled into the geomembrane, and suggests that a 3 mm (1/8 inch) dia. hole be used. The calibration verifies that a) the overlying soil is moist enough to conduct electricity, b) the underlying GCL conducts electricity, and c) the size hole being calibrated can be detected at the maximum grid spacing proposed for the survey. The typical grid spacing used on the author's projects has been 0.9 m x 1.5 m. The survey involves the technician walking along the grid with sensing equipment and a data recorder. If the cover soil is a free-draining gravel, it is often necessary to have a water truck spray the gravel just in advance of the data gatherer to insure proper electrical conductivity. Fine gravels and sands typically hold plenty of capillary moisture to conduct a survey with no further wetting. After several grid lines have been walked, the data is downloaded into a personal computer in the field and evaluated by the technicians. Anomalies in the data are traced back in the field in real time following the coordinates of the grid system, and the technician pinpoints where the defect is located. Laborers (often the certifying engineer!) are then directed to remove the cover soil and expose the damaged geomembrane. When properly scheduled, the survey work can be accomplished without interruption to further construction activities. On larger projects, areas can be surveyed and signed off in stages.

Having experienced the cost and frustration of chasing sources of leakage through geomembranes into a secondary leak detection layer, the primary author is convinced that the added CQA cost to perform a post-installation electric defect detection survey is well worth the benefits derived from installations involving GCL-geomembrane composite liners deployed over leak detection systems.

CONCLUSIONS

Like any other geosynthetic material, GCLs are a technical product that requires the use of sound engineering principles and good workmanship in order to perform properly. Industry leaders need to uphold a high standard of design and installation to allow these products to be as successful as they are ingenious.

Society has many complex problems to solve. It is a credit to our industry that we have developed innovative products to help solve these problems. We also must acknowledge the limitations of these products, and wrap our arms around those limitations. These honest efforts will continue to squeeze out more innovations from all of us.

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