# Designer's Forum

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# GCL design series—Part 1: GCL performance as a fluid barrier

Over the past 18 months, GSE in conjunction with industry design and academic professionals have developed the industry's first comprehensive GCL design guidance document, the *GSE GundSeal Design Manual* (Thiel et al. 2001). Although the manufacturer of one particular type of GCL product sponsored the manual, it features design methodologies and procedures for evaluating all types of GCLs in a wide range of composite liner applications. It presents state-of-the-practice design principles related to hydraulic performance evaluation, slope stability analyses, construction and durability issues in utilizing GCLs in bottom liner systems, caps, ponds, and secondary containment lining applications.

An overview of the fundamental design issues presented in the manual is summarized in this three-part *GFR* series, with implications for making a design utilizing GCLs simpler, quicker and more effective. Part 1 presents an overview of the GCL design issues and GCL installation options, and discusses design principles related to hydraulic performance and leakage. Part 2 focuses on GCL slope stability, followed by Part 3 which expands on GCL installation and durability.

## Types of GCL composite lining systems

Conventional composite-liner applications in waste-containment industries require a geomembrane that overlays a low-permeability compacted clay liner. Alternately, GCLs are now commonly used as an alternative to replace all or part of the lining system.

Fabric-supported GCLs have a thin layer of bentonite (typically a sodium-based montmorillonite clay) carried between various combinations of woven and nonwoven needlepunched geotextiles. Products are available in a non-reinforced configuration (bentonite glued between the fabrics), or in a reinforced configuration (outer geotextiles are stitched or needlepunched together). To create a composite liner system, these types of GCLs are overlain by a continuous geomembrane, as depicted in **Figure 1**.

The geomembrane-supported GCL (GM-GCL) is comprised of a thin layer of bentonite mixed with a water-based adhesive that attaches it to a polyethylene geomembrane. This product has been used as a one-product composite liner in bottom liner and cap applications, effectively replacing both the geomembrane and compacted clay components of traditional prescriptive composite liners. There are two general design configurations for the GM-GCL product:

*Single composite mode*

In this installation, the bentonite side of the material is generally installed face down and the geomembrane side face up, to form a one-product composite (geomembrane-clay) liner. Normally, the overlaps are not mechanically joined, but are overlapped for self-sealing, as shown in **Figure 2**. It is also possible to weld the geomembrane components together utilizing conventional geomembrane welding techniques, including either dual-track hot-wedge welding or extrusion welding procedures (**Figure 3**).

*Encapsulated mode*

In this installation, a supplemental geomembrane is installed against the bentonite side of the material, as shown in **Figure 4**. In this application, the GM-GCL product is usually installed with the bentonite side face up and the geomembrane side facing against the subgrade, with a supplemental geomembrane installed over the bentonite surface. This configuration, however, can also be reversed so that the GM-GCL is deployed on top of a previously deployed geomembrane, with the bentonite side face down. Note that this configuration can also be used with fabric-encased GCLs by deploying the GCL between two geomembranes. The encapsulated design mode offers the following distinct perfor-

**Figure 1: Composite liner consisting of a primary geomembrane and a reinforced or unreinforced fabric-encased GCL.**

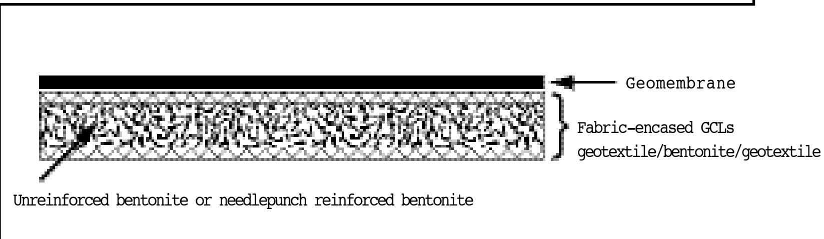
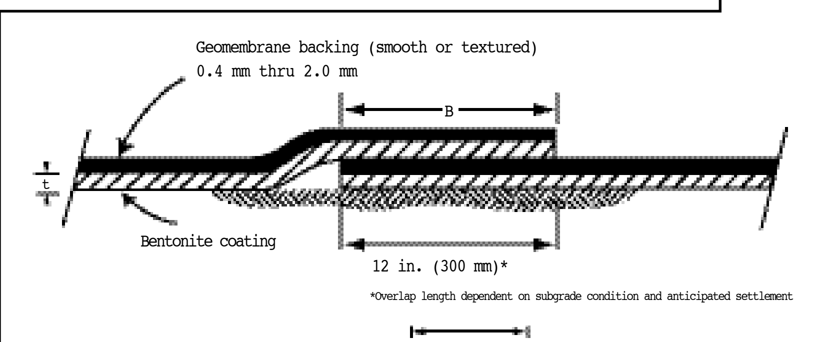



**Figure 2: Overlapped GM-GCL with shingle seams.**



mance advantages:

- improved fluid containment;
- improved bentonite durability during construction by preventing pre-hydration of the bentonite; and
- improved slope stability.

## Performance as a fluid barrier

The hydraulic performance of GCLs can be evaluated using standard accepted leakage models. Leakage through a composite liner may be caused by:

- defects in the primary geomembrane resulting primarily from installation damage;
- coincident defects in the upper and lower geomembranes in encapsulated GCL installations (geomembrane-clay-geomembrane); and
- seepage at overlapped seams when the geomembrane seams are not welded for the GM-GCL product.

The design equations and general approach for evaluating composite liner leakage, and environmental protection comparisons between the GM-GCL and an equivalent geomembrane-compacted clay composite liner are summarized below.

## Leakage modes

*Defects in composite-liner geomembranes*

Empirical modeling and field observations (Giroud and Badu-Tweneboah 1992; Giroud 1997) have resulted in the "Giroud equation" for estimating leakage through a hole in the geomembrane portion of a composite liner. The empirical equation takes the form of **Equation 1**. For hydraulic head ≥ 3 m, the empirical equation takes the form of **Equation (2)** (Thiel et al. 2001):

**Equation (1)**

$$Q_{GM} = C\,[1 + 0.1(h_w / t)^{0.95}]\, a^{0.1}\, h_w^{0.9}\, k_s^{0.74}$$

[For $h_w < 3$ m, and defect diameter $a \leq 5\text{x}10^{-4}$ m$^2$ (25 mm dia.)]

**Equation (2)**

$$Q_{GM} = C\,[1 + 0.1(h_w / t)^{0.95}]\, a^{0.1}\, h_w^{0.9375}\, k_s^{0.74}$$

[For $h_w \geq 3$ m, and defect diameter $a \leq 5\text{x}10^{-4}$ m$^2$ (25 mm dia.)]

where $Q_{GM}$ = rate of leakage through a defect (m$^3$/s), C = a constant related to the quality of the intimate contact between the geomembrane and its underlying clay liner, $h_w$ = head of liquid on top of the geomembrane (m), $t$ = thickness of the soil component of the composite liner (m), $a$ = area of defect in geomem-

Figure 3: Extrusion-welded GM-GCL seams.

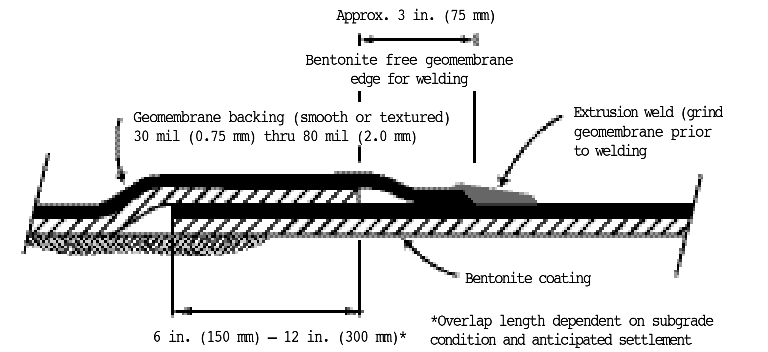



Figure 4: Encapsulated GM-GCL.

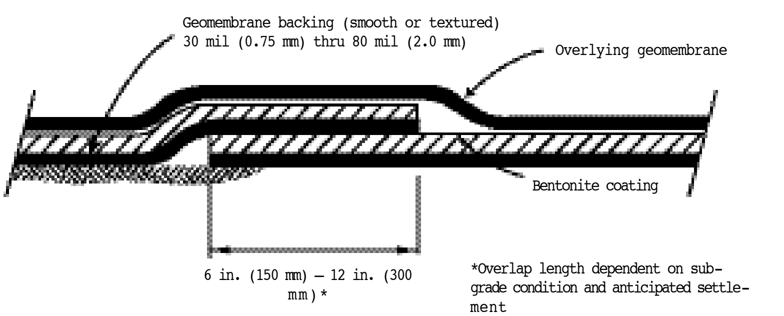
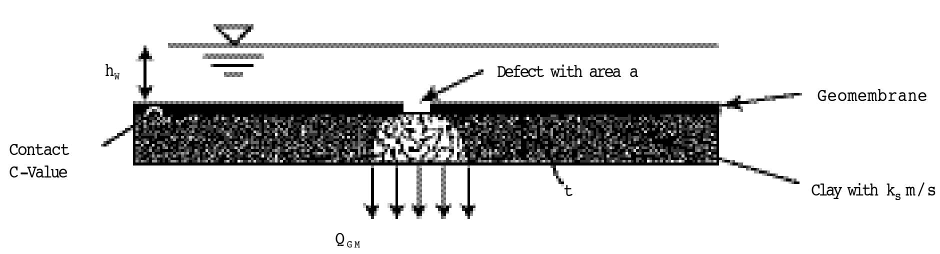



Figure 5: Drawing illustrating the factors taken into account by the "Giroud equation" for estimating leakage through a hole in the geomembrane part of a composite liner.



brane ($m^2$), and $k_s$ = hydraulic conductivity of the underlying clay liner (m/s) (see **Figure 5**).

The basis for **Equation (1)** is referenced in the U.S. EPA Technical Manual (1993), and is incorporated into the latest versions of the HELP computer model (U.S. EPA 1994) used for predicting landfill leachate generation and leakage.

*Defects in encapsulated bentonite system*

For an encapsulated design (**Figure 4**), the size of the defect in the lower geomembrane would control leakage, and leakage would occur when an event caused coincident defects in the upper and lower geomembranes. In this case, Darcy's law controls the advective flow rate through a defect of a given size. The leakage equation would take the following form:

**Equation (3)**

$$Q_{enc} = k_S\, i\, a = k_s\, [(h_w + t) / t]\, a$$

where $Q_{enc}$ = leakage ($m^3/s$), $k_s$ = hydraulic conductivity of the bentonite, $i$ = hydraulic gradient [(liquid head $h_w + t$) / $t$, where $t$ = bentonite (m/s) thickness], and $a$ = area of coincident defects through an encapsulated liner system ($m^2$) (see **Figure 6**).

*Seepage at overlapped (unwelded) GM-GCL seams*

In the case of overlapped GM-GCL seams (**Figure 2**), liquid will seep directly into and possibly through the overlaps. Therefore, the seepage rate through overlapped GM-GCL seams must be quantified in a leakage evaluation.

Due to the weight of its bentonite coating, an installed GM-GCL lays flat on the subgrade. This virtually eliminates wrinkles and results in excellent contact between overlapped panels at their seam areas. For a typical overlap distance of 300 mm, it would take more than 5 years before seepage would begin through the GM-GCL overlap with a fluid buildup of up to 300 mm. Steady-state leakage would most likely take several more years to develop as documented by Dr. David Daniel in Thiel el al. (2001). This seam performance is based on data provided by the large-scale tank tests reported by Estornell and Daniel (1992) and the Cincinnati U.S. EPA GCL test plot "P" exhumed after 4.5 years of performance.

Leakage per unit length due to seepage along a saturated GM-GCL overlap would be calculated in accordance with Darcy's law as follows:

**Equation (4)**

$$Q_{olap} = k_s\, (h_w/B)\, t$$

where $Q_{olap}$ = flow rate per unit length ($m^3/s\bullet m$), $k_s$ = hydraulic conductivity of the bentonite (m/s), $h_w$ = hydraulic head on top of the liner (m), $B$ = width of overlap (m), and $t$ = thickness of the bentonite (m) (see **Figure 7**).

To determine leakage due to seepage at overlap seams, the total linear length of seam for a given project must be calculated. The general length of overlap seams ($S$) in an installation area ($A$) is:

**Equation (5)**

$$S = A\, (1/L + 1/W)$$

where $L$ = average length of panels less overlap (typically 51.2 m), $W$ = average width of panels less overlap (typically 5.0 m). Applying **Equation (5)** to a typical GM-GCL installation thus results in approximately 2200 m of overlap seam per hectare of lined area. The actual length of overlap seam would increase slightly if the complexity of the installation increased due to structures, for example, or irregularities. Total leakage at overlapped seams is subsequently determined by multiplying $Q_{olap}$ by the length of seam $S$ for a given lined area $A$.

**Figure 6: Drawing illustrating the factors taken into account by the equation, derived from Darcy's law, for estimating leakage through a hole in an encapsulated bentonite system.**

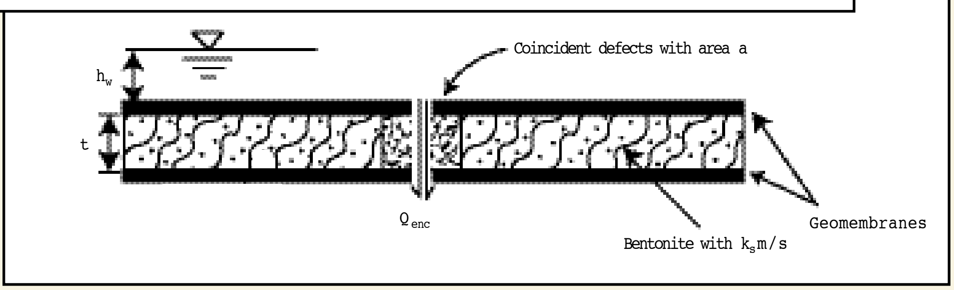
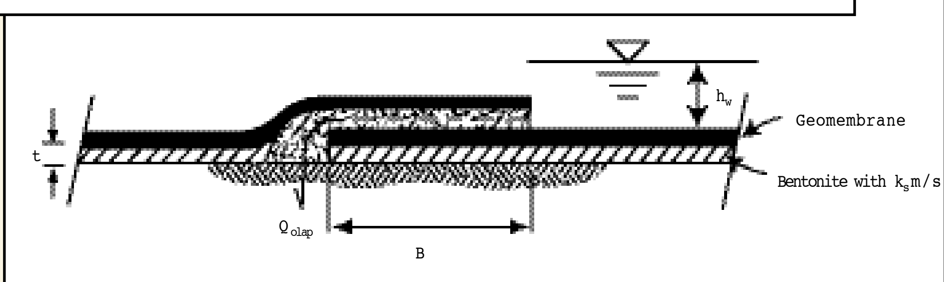



**Figure 7: Drawing illustrating the factors taken into account by the equation, derived from Darcy's law, for estimating seepage at overlapped (unwelded) GM-GCL seams.**




## Factors affecting leakage

*Intimate contact "C-Value"*

The Giroud equation contains the factor C which accounts for the degree of intimate contact between the geomembrane and adjacent clay. In Thiel et al. (2001), Dr. J.P. Giroud evaluates the contact C-factor between the bentonite component of a GM-GCL and an adjacent geomembrane by analyzing the approaches developed and expounded by Rowe (1998), Foose et al. (2001), and Harpur et al. (1993). Using the results published in those references, Giroud recommends a conservative value of C = 0.01 for contact between the bentonite component of the GM-GCL and its geomembrane. The second author uses a value of C = 0.05 for fabric-encased GCLs (NWNP side against a geomembrane) to represent "excellent" contact conditions.

*Hydraulic conductivity*

The hydraulic conductivity $k_s$ of sodium bentonite in GCLs is affected by the level of normal stress applied to the GCL, and chemical alterations caused by different permeating liquids that may increase the hydraulic conductivity of sodium bentonite. Guidance to selecting the appropriate hydraulic conductivity value(s) for a project-specific GCL application and liquid is presented in Chapter 2 of Thiel et al. (2001) as compiled by Dr. David Daniel.

*Project-specific design assumptions*

• Liquid head buildup, $h_w$ — The buildup may vary from less than 25 mm for cap applications, up to 300 mm for regulated allowable buildup above bottom liners, and elevated liquid head for secondary containment leakage events and impoundment applications.

• Defect area, $a$, and frequency of defects per unit area—Industry average standards for estimating defects in an installed geomembrane assume that approximately two to ten 100 mm$^2$ holes per ha exist after a geomembrane is deployed and covered with soil. The number and size of these defects can be reduced through more thorough CQA procedures, such as the use of an electric defect-detection survey after the overlying soil has been placed. The quality of installation and the assumed size and frequency of geomembrane defects should be evaluated on a project-specific basis.

• Clay liner thickness, $t$ —The thickness of compacted clay liners is generally given by prescriptive requirements. The thickness of the GCL bentonite layer is based on the mass loading of bentonite (standard 3700 g/m$^2$ at 0% moisture) at the design normal load. The thickness of the hydrated bentonite component of the GM-GCL as a function of effective compressive stress ranges from 8.5 mm to 3 mm for a normal load range from 10 kPa to 1000 kPa, respectively (Thiel et al. 2001).

## Leakage rate comparisons

In evaluating hydraulic performance, each liner system is analyzed by utilizing the project-specific design criteria outlined above and applying the applicable leakage equations. The total potential leakage for the composite liner system is calculated by combining the leakage through the assumed frequency of geomembrane defects with the leakage at the overlapped seams, if the geomembrane seams are not welded. The methodology for deriving a design leakage rate for composite liners is presented in Thiel et al. (2001) with examples demonstrating various design assumptions and performance criteria in each design chapter for bottom liners, caps, ponds, and secondary containment applications.

**Figure 8** (p.20) presents an example of leakage rate comparison between the various GM-GCL seam configurations (overlapped seams, welded seams, and encapsulated bentonite alternatives) and a prescriptive U.S. EPA Subtitle D geomembrane-compacted clay composite liner for a typical landfill bottom liner application (Erickson and Thiel 2002). For the calculations in this comparison, the design assumptions were: liquid head $h_w$ = 300 mm; bentonite thickness $t_{bent}$ = 5 mm; assumed area of defects $a$ = 0.0001 m$^2$; defects per hectare $n$ = 10; and overlap distance $B$ = 300 mm. Design assumptions for the prescriptive compacted clay liner included thickness $t_{ccl}$ = 600 mm and hydraulic conductivity $k_{ccl}$ = 1 x 10$^{-9}$ m/s.

As shown in **Figure 8**, the simple-overlap design with the one-product composite liner will environmentally out-perform a prescriptive Subtitle D liner (geomembrane over 600 mm compacted clay layer) even when its bentonite's hydraulic conductivity is increased to $k_{bent}$ = 1 x 10$^{-9}$ m/s. The environmental performance of the encapsulated GM-GCL design is exceptional, with estimated leakage rates between 100 and 100,000 times lower than the prescriptive geomembrane-compacted clay liner (showing as nearly zero leakage on the graphical scale in **Figure 8**), depending on the hydraulic conductivity of the bentonite.

The hydraulic analysis and design methodology presented above can be adapted to all design applications in order to evaluate the environmental performance and equivalency of a GM-GCL composite liner to conventional geomembrane-compacted clay composite liner systems for a project-specific set of design parameters.

## Summary

Whether a GCL is used in a bottom liner or cover, as a single-composite liner or with a separate geomembrane, three fundamental design issues should be considered for GCL applications, including: performance as a fluid barrier; slope stability; and installation and durability. Part 1 of this series on GCL design guidance focused on the general approach and design equations required for evaluating GCL hydraulic performance based on standard accepted leakage models.

The three potential modes of leakage through a geomembrane-clay composite liner and leakage analyses were presented, including (1) leakage through geomembrane defects, (2) geomembrane defects in encapsulated bentonite (geomembrane-bentonite-geomembrane) liners, and (3) seepage at overlapped (unwelded) GM-GCL seams. These leakage mechanisms, combined with project-specific design factors (including intimate contact, hydraulic conductivity, liquid head, frequency and size of geomembrane defects, and clay liner thickness) provide the basis for evaluating global project leakage.

Finally, a methodology for comparing potential lining system leakage rates through a geomembrane-compacted clay composite liner vs. a GM-GCL composite liner was presented. This leakage analysis allows the design practitioner to effectively evaluate environmental performance and equivalency of a GM-GCL compared to conventional compacted clay-geomembrane composite liners for a given set of design parameters.

The subsequent parts of this GCL design guidance series will focus on GCL slope stability (Part 2) and installation and durability (Part 3).

### References

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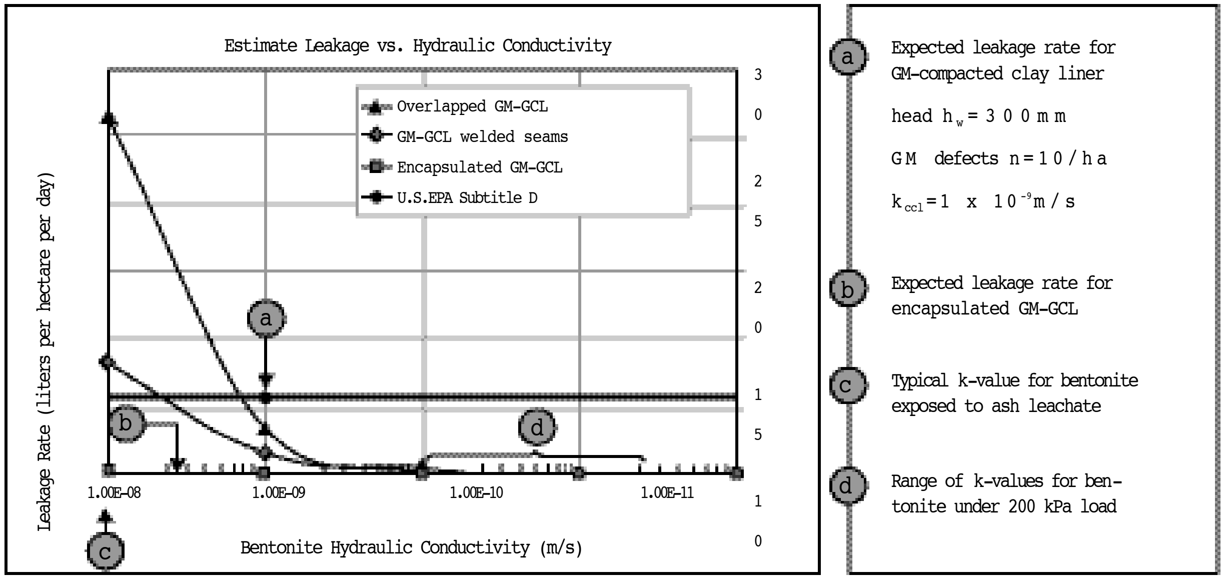
Figure 8: Comparison of hydraulic performance of example composite bottom liner systems with (a) GM-GCL alternative liners and (b) U.S. EPA Subtitle D composite bottom liners.

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