

Landfill drainage layers: Part 3 of 4

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Previous GFR articles have described the methodology for designing a geocomposite for use in a landfill leachate collection system (LCS). (See Part 1 of this series—January/February 2005 for a complete GFR bibliography of geocomposite-related articles since 1998.) This article updates the magazine's series regarding this aspect of designing with geocomposites by expanding the documented design methodology to account for the different stages of a landfill life during operations and post-closure.

Also, the article will review the basic design equation for head buildup, which for geocomposites is often referred to as the "Giroud Equation." It will be seen that a key input parameter to this equation, which is the leachate impingement rate, typically decreases over the landfill life. At the same time, the reduction factors typically increase over the landfill life due to aging, creep, chemical precipitation and the like. These two considerations tend to offset each other. A logical design can take these factors into account so that an overly conservative design does not result. The proposed design concept is illustrated through the use of a design example.

Background on "design" transmissivity

The calculation procedure for the design of geocomposites used in leachate collection systems can be performed using Giroud's method (Giroud et al. 2000). The "design" transmissivity (θ_{design})—also referred to in the literature as "required" transmissivity (θ_{required})—of relatively low-thickness layers such as with geonets and geocomposites can be calculated as:

Equation 1

$$\theta_{\text{design}} = \frac{q_i \cdot L}{\sin \beta}$$

where θ_{design} = calculated design transmissivity for geocomposites (m^3/s per m width); q_i = liquid impingement rate (m/s); L = horizontal length of slope (m); and β = slope angle (degrees). Leachate impingement into the leachate collection layer is buffered to lesser and greater degrees due to the thickness of overlying waste and soil material. A commonly used computer model that is available for performing water balance analyses is the HELP Model (Schroeder, et al. 1994). Landfill leachate collection system (LCS) impingement rates depend on the operational stage of a landfill, which can be conveniently broken down as follows: (i) initial operation stage; (ii) active operation stage; and (iii) post-closure stage. Early in the landfill operation, surface water control may not be well established, and relatively thin layers of soil and waste may allow for a relatively large portion of the surface water to infiltrate into the LCS. As filling progresses, the use of protective soil and surface grading can reduce the amount of infiltration into the waste; thus, decreasing the LCS flow rate. In the post-closure period, the application of the final cover system greatly reduces the amount of infiltration into the waste, and thus greatly reduces the amount of leachate entering the LCS.

It is possible to model the landfill leachate generation in several operational stages (as few as three and as many as six) with varying geometry, waste thickness, cover slopes and cover materials. Separate HELP analyses can be performed for each operational stage modeled. An example of what a designer might consider when modeling a landfill broken into four stages is presented below (Bachus, et. al 2004):

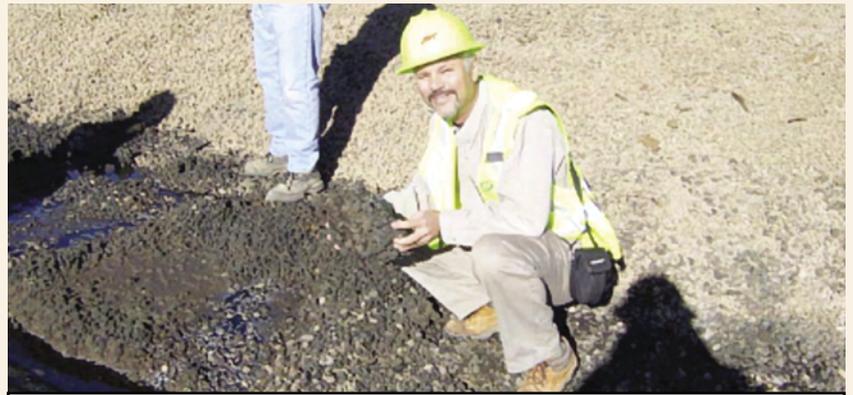


Photo 1. Author Richard Thiel holding 35 mm rounded gravel cemented by leachate chemical precipitation.

Pressure kPa (psf)	Creep Reduction Factor (RF _{CR})
48 (1000)	1.1
240 (5000)	1.2
478 (10,000)	1.3
718 (15,000)	1.6

Table 1. Creep reduction factors (RF_{CR}) for one manufacturer's biplanar geonet product line (Narejo and Allen 2004).

- *Initial operation stage*—Model leachate flow into the LCS based on a “fluff” layer of waste being placed in the landfill cell. A typical waste thickness might be on the order of 10 ft. The slope might be fairly flat (~2%) with a 6 inch daily cover layer.
- *Active operation stage I*—Model leachate flow into the LCS based on the landfill at a representative point in time in the landfill’s developmental phasing plan. The waste thickness might be on the order of half of the final thickness of the waste. The slope might be fairly flat, with an intermediate cover.
- *Active operation stage II*—Model leachate flow into the LCS based on the landfill at final grades with an intermediate cover in place and fair vegetation.
- *Post-closure stage*—Model leachate flow into the LCS based on the final closure conditions. The landfill will be at final grades with a permanent cover in place. Often this condition is modeled in HELP as simply the amount of infiltration through the final cover system.

Allowable and specified transmissivity

The next step in the design process is to define an allowable transmissivity (θ_{allow}), which is related to the design transmissivity (θ_{design}), by multiplying the design transmissivity by an overall factor of safety, FS_D .

Equation 2

$$\theta_{allow} = \theta_{design} \cdot FS_D$$

The overall drainage factor of safety should be applied to take into account possible uncertainties in the selection and determination of the design parameters. Recommended values of FS_D are typically between 2.0 and 3.0 or greater (Giroud, et al. 2000). For bottom liner LCS systems, a lower FS would be acceptable in the early stages of the project, but a higher FS may be desirable for long-term conditions. The authors will demonstrate that taking into account the various stages of landfill development and leachate generation can work to the advantage of many designs accounting for appropriate factors of safety.

Finally, the *specified* (also referred to as *maximum* or *ultimate* in the literature) transmissivity (θ_{spec}), which is the value that appears in the specifications, is obtained by multiplying the allowable transmissivity by appropriate *reduction factors*. These reduction factors take into account environmental factors such as biological clogging, chemical clogging and long-term creep of the geocomposite drainage layer that will decrease the in-place capacity of the geocomposite over time. The magnitude of each reduction factor (which should be equal to or greater than 1) should reflect a correction that provides a best estimate of the anticipated reduction. The reduction factors should not be inflated to a larger value to account for uncertainty, since this is accounted for in the overall factor of safety, FS . The

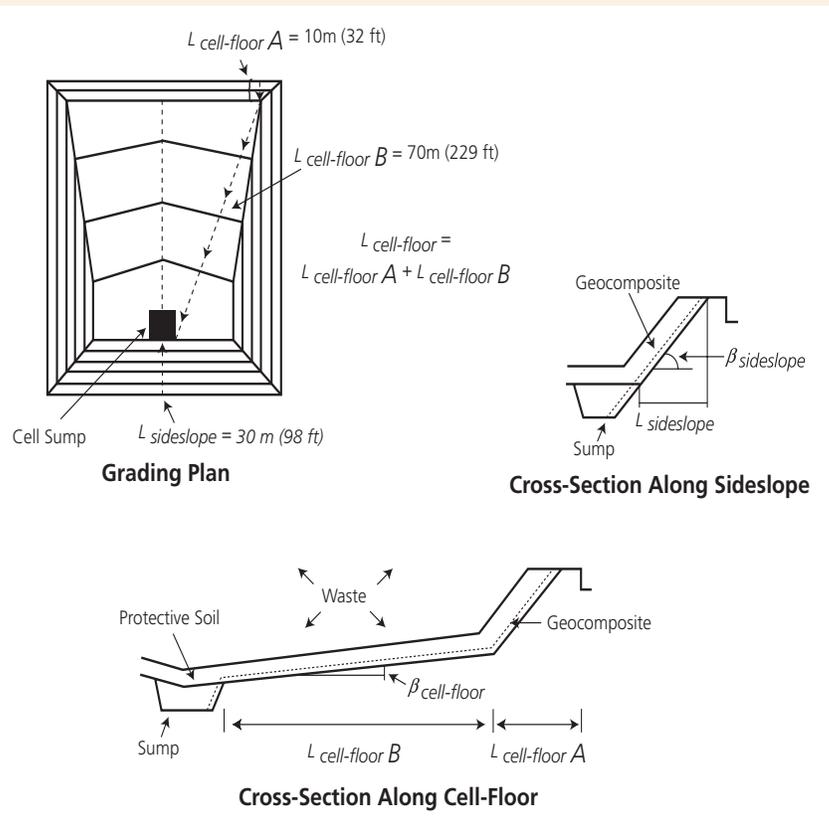


Figure 1. Simplified schematic of design geometry for example problem.

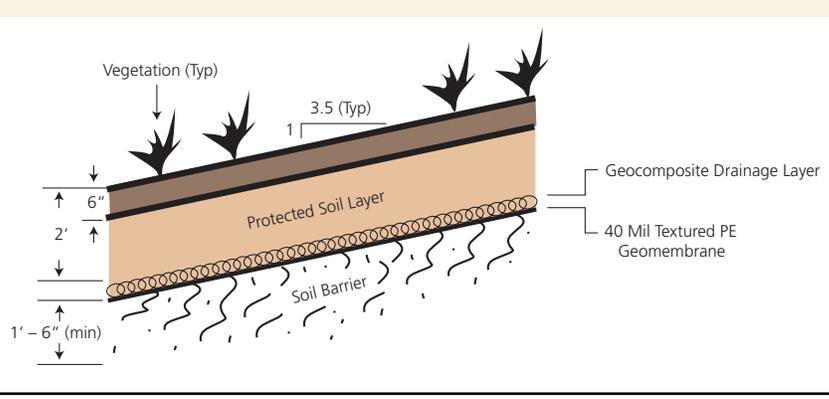


Figure 2. Design of final cover system.

specified transmissivity is shown in Equation 3 (see also, test standard GRI-GC8 [2001]):

Equation 3

$$\theta_{spec} = \theta_{allow} \cdot RF_{CR} \cdot RF_{CC} \cdot RF_{BC}$$

where:

θ_{spec} = specified value of transmissivity for geocomposites or geonet (m^2/s), as tested in accordance with GRI-GC8 and ASTM D4716;

θ_{allow} = minimum allowable transmissivity of geocomposites or geonet (m^2/s);

RF_{CR} = partial reduction factor for long-term creep (dimensionless);

RF_{CC} = partial reduction factor for chemical clogging (dimensionless); and

RF_{BC} = partial reduction factor for biological clogging (dimensionless).

Additional reduction factors, such as for particulate clogging, can be incorporated by the designer if deemed applicable to a given situation. The specified transmissivity (θ_{spec}) in Equation 3 should be compared with the 100-hour transmissivity value obtained from a laboratory test. The 100-hour transmissivity test value should be equal to or higher than the specified value of θ_{spec} . A description of typical values of reduction factors for bottom liner LCSs is given in the following paragraphs.

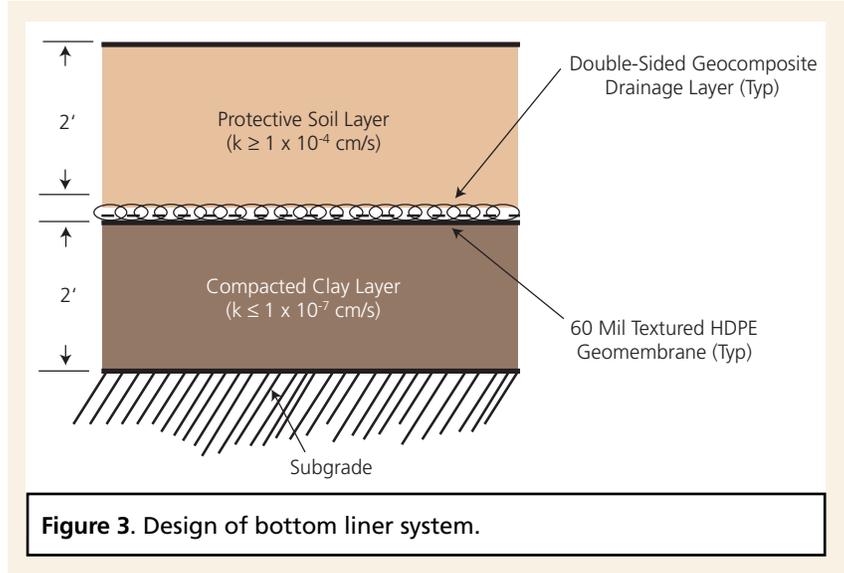


Figure 3. Design of bottom liner system.

Chemical clogging reduction factor, RF_{CC}

The designer should evaluate the soils she anticipates using in the protective layer of the liner system and the materials anticipated in the overlying waste, in order to judge the risk of chemical clogging. GRI-GC8 recommends using values in the range of 1.5 to 2.0 for chemical clogging in the leachate collection system. A greater reduction factor might be appropriate for “bioreactor” landfills based on observations of significant leachate collection gravel clogging (Figure 1). The design example presented in this paper illustrates how a properly designed system can accommodate such a large reduction.

Biological clogging reduction factor, RF_{BC}

The biological clogging reduction factor accounts for the reduction of flow in the geonet due to the growth of biological organisms such as fungi or algae, or root penetration through the overlying soil. GRI-GC8 recommends using values in the range of 1.1 to 1.3 for biological clogging in the leachate collection system. In the authors’ experience, and as suggested in other field literature (e.g., Rowe et al. 1997), the reduction factor for biological clogging in leachate collection systems can either be maintained fairly low or be lumped in with the reduction factor for chemical precipitation.

Creep reduction factors, RF_{CR}

Performance transmissivity tests are typically conducted for up to 100 hours, as required by GRI test procedure GC8. The decrease in transmissivity with time asymptotically approaches a stable value within 100 hours, and usually much sooner than that, indicating that much of the initial compression (and geotextile intrusion) has already taken place. The reduction factor for creep, RF_{CR} , accounts for the decrease in transmissivity beyond the

Stage	Description	Peak LCS in-flow— q_i
I	Initial operation—10 ft. (3 m) waste	0.571 in./day = 1.68×10^{-5} cm/s
II	Active operation—80 ft. (24 m) waste	0.064 in./day = 1.88×10^{-6} cm/s
III	Intermediate cover—140 ft. (43 m) waste	0.030 in./day = 8.80×10^{-7} cm/s
IV	Post closure—140 ft. (43 m) waste	1.09×10^{-5} in./day = 3.20×10^{-10} cm/s

Table 2. HELP analysis results for LCS design example.

first 100 hours experienced in the transmissivity test. The quality of the geonet core, including its structure, thickness, mass and density can have a significant influence on creep reduction factors. **Table 1** presents creep reduction factors for one manufacturer's biplanar geonet. Products from other manufacturers can have creep factors different from those given here.

Creep reduction factors should be selected on the basis of the expected normal stress in the LCS if one is to follow the staged design concept presented in this paper. A much lower creep reduction factor should be used at the initial stage of landfill operation as overlying waste thickness is small. A conservative value of creep reduction factors may be 2 for the final (closure) stage of landfill liner systems with overburden stresses up to 15,000 pounds per square foot (psf).

LCS geocomposite design example

The purpose of this design example is to demonstrate how the different stages of a landfill life can be taken into account when designing a geocomposite for a leachate collection system. The particular case of a "bioreactor" landfill, which is especially aggressive on drainage systems, is used. The design process involves the following steps:

- Step 1. Choose appropriate values for site specific design parameters (geometry and soil properties).
- Step 2. Establish design input flow rate (i.e., impingement rate, q_i) for each stage of landfill life.
- Step 3. Solve for the needed design transmissivity, θ_{design} , at different stages of the landfill life.
- Step 4. Establish a specified transmissivity, θ_{spec} , for each of the stages by selecting an appropriate global factor of safety and appropriate reduction factors. For this design example, several specified transmissivities would be calculated, one for each stage of the landfill life. The maximum required transmissivity would be specified in the contract documents.
- Step 5. Develop specifications describing laboratory testing conditions and acceptance criteria.

Step 1—Establish input parameters

Several of the input parameters are derived from the geometry of the design. For this example, **Figure 1** shows a simplified design that will be used in selecting these geometric input parameters. **Figure 2** shows the schematic cross section of the liner and leachate collection system.

The inputs used in this example are presented below:

- Slope of cell floor = 4.5% = 2.57 degrees
- Drainage length on cell floor = 262 ft. (229 ft. + 33 ft. [70 m + 10 m])
- Side slope angle = 18.43 degrees (ΔS sideslope = 0.333)
- Drainage length on sideslope = 98 ft. (30 m)
- Unit weight of waste = 75 pcf (11.8 kN/m³) (typically ranges from 60 to 90 pcf)
- Thickness of waste = varies depending on operating stage

Cover soil properties (daily cover, interim cover, final cover):

Daily cover

- Permeability of daily cover = 5×10^{-3} cm/s (based on type of soil used for interim cover)
- Thickness of daily cover = 0.5 ft. (15 cm) (based on anticipated/required operating procedures)

Interim cover

- Permeability of interim cover = 1×10^{-4} cm/s (based on type of soil used for interim cover)
- Thickness of interim cover = 1 ft. (30 cm) (based on anticipated/required operating procedures)

Step 2—Establish design impingement rates

Select the impingement rates, q_i , to include in the various stages of operational life and for the final cover design. It is recommended that the designer model the impingement rate for key stages in the operating life of the landfill. The number of key stages will vary depending on site-specific landfill conditions such as: (i) interim staging and sequencing; (ii) runoff/run-on control practices; (iii) use of daily, interim and final cover materials; and (iv) thickness of waste and other overlying materials. For most sites it will likely take 3–6 stages to adequately define the operation stages.

For the leachate collector design example, it will be assumed that four stages will provide an adequate modeling of the landfill life. The results for the impingement rate for various operational stages for the design example have been obtained using HELP and are shown for each stage in **Table 2**. A more reliable indicator of stage impingement rates can generally be obtained from past operational records of the landfill itself or neighboring facilities. With over a decade of national lined landfill experience on file with most state regulators, good regional data on leachate generation rates is readily available.

Step 3—Solve for design transmissivity

Solve for θ_{design} for cell floor and side slope for each Stage (I–IV). For this example, the results of the θ_{design} solution are:

Stage IA (cell-floor)

$$\theta_{design} = \frac{1.68 \times 10^{-7} \text{ m/sec} \times 80 \text{ m}}{\sin 2.577^\circ} = 2.99 \times 10^{-4} \text{ m}^2/\text{sec}$$

Stage IB (side slope)

$$\theta_{design} = \frac{1.68 \times 10^{-7} \text{ m/sec} \times 30 \text{ m}}{\sin 18.435^\circ} = 1.59 \times 10^{-5} \text{ m}^2/\text{sec}$$

Results of similar calculations for other cases are summarized in **Table 3**.

Step 4—Establish specified transmissivity values

The specified transmissivity, θ_{spec} , is increased above the design transmissivity to account for uncertainties (in the form of an overall factor of safety) and the long-term reduction of the transmissivity of the geocomposite due to anticipated environmental factors (in the form of reduction factors).

Case	Description	q_i (cm/sec)	θ_{design} (m ² /sec)	σ_{100} (psf)	RF _{cc}	RF _{bc}	FS _d	RF _{cr}	θ_{spec} (m ² /sec)	θ_{100} (m ² /sec)	Ratio $\theta_{100}/\theta_{req}$	Acceptable
IA	Initial Operation	1.68E-05	2.99E-04	750 psf	1.2	1.1	2.0	1.10	8.7E-04	9.0E-04	1.0	Yes
IB	Initial Operation	1.68E-05	1.59E-05	750 psf	1.2	1.1	2.0	1.10	4.6E-05	5.0E-04	11	Yes
IIA	Active Operation	1.88E-06	3.34E-05	6,000 psf	1.5	1.2	3.0	1.25	2.2E-04	4.0E-04	1.8	Yes
IIB	Active Operation	1.88E-06	1.78E-06	6,000 psf	1.5	1.2	3.0	1.25	1.2E-05	3.0E-04	25	Yes
IIIA	Intermediate Cover	8.80E-07	1.56E-05	10,000 psf	2.0	1.3	4.0	1.30	2.1E-04	2.0E-04	0.95	No
IIIB	Intermediate Cover	8.80E-07	8.35E-07	10,000 psf	2.0	1.3	4.0	1.30	1.1E-05	1.5E-04	13	Yes
IVA	Post-Closure	3.20E-10	5.69E-09	10,500 psf	4.0	1.3	5.0	1.40	2.1E-07	2.0E-04	966	Yes
IVB	Post-Closure	3.20E-10	3.04E-10	10,500 psf	4.0	1.3	5.0	1.40	1.1E-08	1.5E-04	13,565	Yes

Table 3. Results of calculations for the design example.

- FS_D = The global factor of safety is a somewhat arbitrary value selected by the designer based on the level of uncertainty and relative risk associated with failure. Typical values suggested for design with geocomposites range from 2.0 to 3.0 (Narejo and Richardson 2003). Given the higher levels of uncertainty associated with long-term performance of bioreactor systems, and the relative importance of having leachate collection systems that operate well into the future, somewhat higher factors of safety may be warranted for the different life stages. For this design example we have chosen values of $FS_D = 2.0, 3.0, 4.0$ and 5.0 for Stages I–IV, respectively, as shown in **Table 3**. These values reflect advancing degrees of uncertainty as time goes forward.
- RF_{CC} = The suggested range for the reduction factor for chemical clogging from GRI-GC8 is from 1.5 to 2.0 for most leachate collection systems based on the chemical makeup of leachate and the length of time exposure. While these values might be typical for “standard average” landfill conditions, a more rigorous and expansive interpretation might be appropriate over the lifetime of a “bioreactor” landfill. For a very short exposure time, as in Stage I, a low value would be appropriate. As exposure time increases, the recommended reduction factor would be increased. We have chosen values of 1.2, 1.5, 2.0, and 4.0 for Stages I–IV, respectively, as shown on **Table 3**. This suggests that up to half of the flow capacity could be lost due to biological clogging during the active life of the cell, and 75% of the flow capacity could be lost to chemical precipitation during the long-term post-closure period.
- RF_{BC} = The suggested range for the reduction factor for biological clogging from GRI-GC8 is from 1.1 to 1.3 for leachate collection systems. We believe this range is appropriate even for bioreactor landfills because the most serious clogging condition is probably from chemical precipitation rather than a biological mechanism.
- RF_{CR} = The creep reduction factor varies with stress and is product-specific. For this design example, **Table 1** provides data for a particular bi-planar product from one manufacturer.

Based on the selected reduction factors and global factors of safety, the specified transmissivities, θ_{spec} , can be calculated as follows:

Stage IA (floor)

$$\begin{aligned}\theta_{spec} &= \\ 2.99 \times 10^{-4} \text{ m}^2/\text{s} &\cdot 2 \cdot 1.2 \cdot 1.1 \cdot 1.1 \\ &= 8.6 \times 10^{-4} \text{ m}^2/\text{s}\end{aligned}$$

Stage IB (side slope)

$$\begin{aligned}\theta_{spec} &= \\ 1.59 \times 10^{-5} \text{ m}^2/\text{s} &\cdot 2 \cdot 1.2 \cdot 1.1 \cdot 1.1 \\ &= 4.6 \times 10^{-5} \text{ m}^2/\text{s}\end{aligned}$$

Results of similar computations for all stages of the design case are shown in **Table 3**.

Step 5—Specification development

The specifications should clearly define the conditions of the laboratory testing and the criteria that define the product’s acceptability.

The required laboratory testing conditions include: (i) applied stress; (ii) hydraulic gradient; (iii) boundary conditions; and (iv) seating time.

(i) Applied stress—The applied stress used in testing should be equal to the maximum applied stress anticipated in field conditions.

For the design example:

$$\sigma_{100} = t_{waste} \cdot \gamma_{waste}$$

$$\begin{aligned}\text{Stage I: } \sigma_{100} &= 10 \text{ ft.} \cdot 75 \text{ pcf} \\ &= 750 \text{ psf (36 kPa)}\end{aligned}$$

$$\begin{aligned}\text{Stage II: } \sigma_{100} &= 80 \text{ ft.} \cdot 75 \text{ pcf} \\ &= 6000 \text{ psf (287 kPa)}\end{aligned}$$

$$\begin{aligned}\text{Stages III and IV: } \sigma_{100} &= 140 \text{ ft.} \cdot 75 \text{ pcf} \\ &= 10,500 \text{ psf (503 kPa)}\end{aligned}$$

(ii) Hydraulic gradient—The hydraulic gradient is equal to the sine of the slope angle in units of length/length.

For the design example:

Stages A (cell floor)

Slope angle = 2.57 deg.
—> Gradient = 0.045

Stages B (cell side slope)

Slope angle = 18.43 deg. _
—> Gradient = 0.32

(iii) Boundary conditions—The term “boundary conditions” refers to the makeup of the overlying and underlying materials during testing of the geocomposite. The testing procedure should follow the guidelines of GRI-GC8, which requires that the boundary conditions mimic field conditions. This means that site-specific materials shall be used wherever possible. This example assumes that the on-site soil anticipated to be used as protective soil between the waste and the geocomposite will be used above the geocomposite, and that a textured geomembrane will be used below the geocomposite. Both materials to be used in testing should be provided to the laboratory by the engineer or contractor.

(iv) Seating time—Seating time affects the amount of creep and intrusion that the geocomposite undergoes prior to transmissivity testing, which in turn affects the measured transmissivity of the product. The laboratory testing should follow the guidelines of GRI-GC8, which requires a seating time of at least 100 hours for testing the transmissivity of the geocomposite. A greater seating time is acceptable; however, this may incur greater testing expense and is usually not necessary. As required by GRI-GC8, a seating time of 100 hours is used in this design example.

An acceptable product should possess a creep reduction factor lower than that used in the design, and a 100-hour transmissivity value higher than the specified value (θ_{spec}) for each of the design stages as presented in **Table 3**.

Discussion of results, conclusions

This third part to the Designer’s Forum series demonstrates how the different stages of a landfill life can be taken into account when designing for a leachate collection system with geocomposites. **Table 3** summarizes the results for the design example. The following observations can be drawn from this exercise:

- For this design example, the critical stages in the design of the geocomposite appear to occur right at the beginning of cell operations, and towards the end of the active cell life. This is probably a typical situation for many landfills.
- If the most conservative parameters had been used for the reduction factors for all stages, even with a modest factor of safety of only 2.0, the selected geocomposite would have failed the criteria by a very large margin.
- The condition on the floor is typically more critical than on the side slope. This is because the smaller gradient on the floor requires more head build-up to pass a certain amount of flow.
- **Table 3** indicates that the sample product that was tested for this design passes all the criteria, except for the condition of Stage III of the landfill life on the floor. It only fails that stage just barely, however, and the designer could either re-visit the arbitrary factor of safety for that design stage (a FS_D value of 4.0 is fairly high, whereas a value of 3.8 would result in a passing criteria), or could require a thicker or more robust geocomposite product that has a higher transmissivity.

The most significant conclusion demonstrated by this exercise is that the use of unique reduction factors, and a unique factor of safety, for each stage of a landfill’s life can reduce the conservatism inherent in a single calculation. This design approach allows the critical points in a landfill’s life to be identified with regard to performance of the geocomposite, and focused laboratory testing can be performed to address those critical conditions.



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