DESIGNER'S FORUM

Design considerations for surface impoundments

By Gregory N. Richardson and William G. Hase

THE GENESIS OF THIS COLUMN came last year, during the Sixth International Conference on Geosynthetics in Atlanta. At that time, the primary author had several discussions with Dr. J.P. Giroud of GeoSyntec Consultants, Boca Raton, Fla., regarding the book he is preparing—*Lessons Learned from Failures Associated with Geosynthetics*—the misuse of his equations for predicting leakage through liner systems, and fatal flaws we had observed others make in the design of surface impoundments. Giroud has slaved over the *Lessons Learned* manuscript for the past three years, so it is amazing that he still talks to those of us who have contributed and continues to have faith in our application of geosynthetics. Later last year, both authors had an opportunity to review many of Giroud's concerns during the repair of a small landfill-surface impoundment—thus, this column was born.

Geomembrane-lined surface impoundments are common fixtures at both landfills and mine processing areas. Using a geomembrane liner to limit liquid loss from such impoundments is obvious. At the same time, the use of a geomembrane to line impoundments requires the designer to address key differences between liquid containment and the more publicized containment of leachates that drain from solid wastes or mining ores. These key differences include:

- Heads that act on a geomembrane barrier in a surface impoundment are significantly larger than the 30 cm or smaller heads that commonly act on solid-waste-landfill liners.
- The head that acts on the surface-impoundment liner can vary dramatically in a very short time span.
- Common geomembranes, such as high-density polyethylene (HDPE), have densities less than that of water and will float in common leachates or effluents.
- The impoundment must be cleaned out periodically, which requires maintenance operations in close proximity to the geomembrane.
- The geomembrane barrier frequently is visible, or at least accessible, for maintenance.

Each of these key differences produces a design challenge or opportunity not common to solid-waste liner systems. This article will review these differences and provide common-sense design guidance for liquid-containment systems.

Evaluating impoundment leakage—composite liner

The liner system's ability to limit leakage from the impoundment is a fundamental design consideration. Leakage through geomembranes in solid-waste containment systems commonly is estimated with equations developed by Giroud for relatively small heads that act on the geomembrane. Designers commonly estimate the leakage through a circular defect in a geomembrane/compacted-clay liner (CCL) composite barrier by using the following equation (Bonaparte, et al. 1989):

$$Q = C_{qo}\, h^{0.9}\, a^{0.1}\, K^{0.74} \qquad \text{Equation 1,}$$

where:

C_{qo} represents a dimensionless parameter that quantifies the quality of contact between the geomembrane and the clay

h is the height of water standing on the geomembrane (m)

a is the area of the hole (m^2)

K is the permeability of the underlying clay (m/sec).

Giroud presented similar equations for square, infinitely long, and rectangular defects (Giroud, et al. 1997). For circular defects, he established C_{qo} values of 0.21 for poor contact and 1.15 for good contact.

Equation 1 is appropriate only when the head that acts on top of the liner is small in comparison to the thickness of the CCL. This typically is the case for landfill-liner designs where "peak" leachate heads of less than 30 cm occur over CCLs with a thickness of 60–90 cm. For the larger head ranges commonly encountered in surface impoundments, Giroud modified Equation 1, as follows (1997; Giroud, et al. 1998):

$$Q = C_{qo}\,[1 + 0.1(h/t_{um})^{0.95}]\, h^{0.9}\, a^{0.1}\, K^{0.74} \qquad \text{Equation 2,}$$

where t_{um} is the thickness of the CCL. *This is valid for heads of less than 3 m and when the clay-liner permeability is less than a value k_G,* which is dependent on the hole size and maximum design head. Values for k_G are given in **Table 1**.

Impoundments that use a composite-liner system must be designed to ensure the

TABLE 1. HYDRAULIC CONDUCTIVITY, K_G, FOR LIQUID THROUGH A CIRCULAR GEOMEMBRANE DEFECT UNDERLAID BY LOW-PERMEABILITY SOIL ON GEOMEMBRANE (GIROUD ET AL. 1997B)

Head of liquid on geomembrane h (m)	Geomembrane defect diameter, d (mm)						
	0.5	*1*	*2*	*3*	*5*	*10*	*11.284*
0.01	2.6×10^{-7}	1.4×10^{-6}	7.5×10^{-6}	2.0×10^{-5}	7.0×10^{-5}	3.8×10^{-4}	5.1×10^{-4}
0.03	1.4×10^{-7}	7.7×10^{-7}	4.1×10^{-6}	1.1×10^{-5}	3.8×10^{-5}	2.1×10^{-4}	2.8×10^{-4}
0.1	7.3×10^{-8}	3.9×10^{-7}	2.1×10^{-6}	5.7×10^{-6}	2.0×10^{-5}	1.1×10^{-4}	1.4×10^{-4}
0.3	3.8×10^{-8}	2.1×10^{-7}	1.1×10^{-6}	3.0×10^{-6}	1.0×10^{-5}	5.6×10^{-5}	7.5×10^{-5}
1	1.8×10^{-8}	9.5×10^{-8}	5.1×10^{-7}	1.4×10^{-6}	4.7×10^{-6}	2.6×10^{-5}	3.4×10^{-5}
3	7.1×10^{-9}	3.8×10^{-8}	2.1×10^{-7}	5.6×10^{-7}	1.9×10^{-6}	1.0×10^{-5}	1.4×10^{-5}

Notes: The tabulated values of k_G were calculated using Equation 2 with $C_{qo} = 0.21$ (good contact) and $t_s = 0.6$ m. The defect diameter of 11.284 mm corresponds to a defect surface area of 1 cm^2.

quality of the contact between the geomembrane and the CCL. All geomembranes require some form of surcharge to maintain intimate contact with the clay liner. This is achieved by using a protective cover, as described below.

Impoundment leakage—geomembrane liner

For a geomembrane liner acting on its own, the leakage through liner defects commonly is determined with Bernoulli's equation, which originally was suggested by Giroud (1984):

$$Q = 0.6\,a\,(2gh)^{1/2} \qquad \text{Equation 3,}$$

where:

a is the area of the defect (m^2)

h is the head that acts on the liner (m)

g is the acceleration due to gravity (m^2/s).

Equation 3 is based on the assumption that a protective layer over the liner or the collection layer beneath the liner freely drains so that flow is not impeded. Additionally, Giroud cautions that defects should be larger than 0.5 mm to minimize potential capillary-related restrictions on flow.

Giroud recently quantified "free drainage" restrictions on layers that overly the geomembrane (Giroud, et al. 1997a). **Figure 1** shows the minimum values of K_{OM} (permeability of overlying material) for 1% and 5% errors related to free drainage. Unfortunately, quantifying "free drainage" in underlying layers is more difficult since it is a function not only of the permeability of the underlying layer but also the layer thickness and slope. Fortunately, though, Giroud (Giroud et al. 1997b) did not rest on his integrals and quantified this more difficult set of conditions. He determined that minimum transmissivity of a drainage layer beneath the geomembrane in a surface impoundment can be calculated as follows:

$$K_{LCL}T_{LCL}^2 \geq 0.6a\sqrt{2gh_{prim}} \qquad \text{Equation 4,}$$

where:

K_{LCL} is the permeability of the collection layer (m/s)

T_{LCL} is the thickness of the collection layer (m)

h_{prim} is the liquid depth in the impoundment (m).

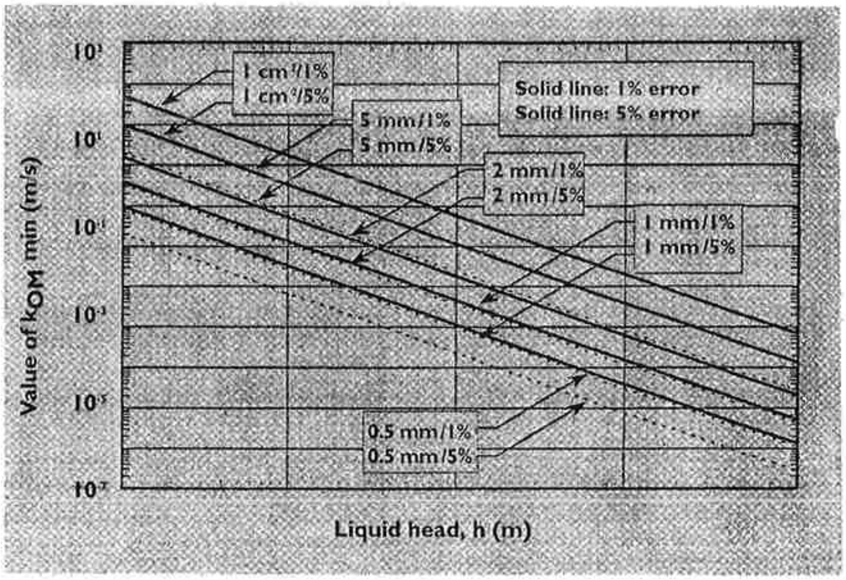

Figure 1. Minimum values of K_{OM} (permeability of overlying material) for 1% and 5% errors related to free drainage.

Surface-impoundment geomembrane liners that are not surcharged over their entire submerged-surface area must be designed with an underdrain of sufficient flow capacity to eliminate leachate build up. If such build up occurs, the geomembrane has the potential to float. The allowable defect area, a_{allow}, relates to the ability of the leak-collection layer and larger capacity underdrains to tolerate more leakage before the liner floats.

Giroud also presented the solution for leakage through a geomembrane over a semi-permeable soil (Giroud, et al. 1997c). Though unusual in environmental applications, in water-storage applications, it is very common to place the geomembrane directly over a semi-permeable subgrade. The leakage rate for this application can be determined from the following:

$$\log Q = 0.3195 + 2\log d + 0.5\log h - 0.74\left(\frac{5 + 2\log d - \log k}{n}\right)^n \qquad \text{Equation 5,}$$

where:

$$n = 4.6380 - 0.4324\log d + 0.5405\log h + 1.3514\log\left[1 + 0.1\left(\frac{h}{D}\right)^{0.95}\right] \qquad \text{Equation 6}$$

Equations 5 and 6 are semi-empirical and only can be used with the following units: Q (m^3/s), d (m), k (m/s), h (m), D (m).

Design with protective cover

Geomembrane liners in surface impoundments commonly are covered by protective layers to prevent future damage from a rigorous leak survey. They also are installed to provide a vertical normal load (or surcharge) that ensures intimate contact between the geomembrane and the underlying CCL. The protective cover must consist of a material that can be placed without damaging the geomembrane. The substance also must remain stable for the service life of the surface impoundment. Most designers hope that the protective cover also will be of reasonable cost (more about this concern later).

Common protective covers include natural soil layers, segmental blocks placed on geotextile cushions, and common grout-injected erosion-control blankets. While all of these alternatives can provide an adequate normal load, their stability and design considerations over the service life of the impoundment vary dramatically. Designs for soil protective covers commonly evaluate soil stability in an "as constructed" condition. In these cases, designers commonly use actual laboratory interface-friction values, s, obtained between the soil and the liner system. These "as constructed" factor of safety (FS) calculations are based on the simple infinite-strip model (typical values for a 4H:1V slope are provided), as follows:

$$FS = \frac{\tan\delta}{\tan\beta} = \frac{\tan 22^\circ}{\tan 14^\circ} = 1.62 \qquad \text{Equation 7}$$

Two significant forces that may act on the soil liner are neglected in this calculation: surface erosion due to run-on, rain, or waves on the protective soil cover; and potential seepage forces that can act within the protective soil cover. Erosion controls include vegetation of the soil above the liquid level, gravel armor and geosynthetic mats.

When evaluating seepage forces within

the protective cover, the designer must consider the condition caused by rapidly draining a surface impoundment after it has been in service (e.g., full of liquid) for an extended period. The liquid within the impoundment can drain much faster than the liquid within the soil protective cover. If the liquid is drained very quickly, the pore pressures at the protective cover/geomembrane interface will reflect the pressures of the full impoundment head and failure will occur. If the draw down is slow enough to allow these excess pressures to dissipate, the protective cover remains saturated, and the pore water within this layer drains parallel to the geomembrane surface.

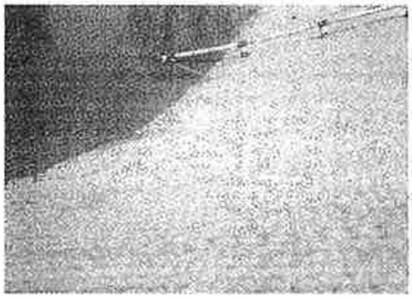
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Photo 1. Grout-filled erosion-control blankets provide drainage benefits over soil.

Drainage within the protective soil cover produces two effects that reduce the stability of the protective cover. First, the gravity-driven drainage of pore waters through the soil cover causes seepage forces within this protective layer. Secondly, residual pore-water pressures remain below the soil protective cover. These additional stability forces are accounted for with the following modification to Equation 7:

$$FS = \frac{\text{Resisting Forces} = \gamma_{sat} t_{cs} \cos\beta \tan\delta}{\text{Driving Forces } \gamma_{sat} t_{cs} \sin\beta + \gamma_w t_{cs} \sin\beta}$$

Equation 8,

where:

t_{cs} is the thickness of the soil cover (m)

γ_{sat} is the saturated unit weight of the cover soil (kg/m^3)

γ_w is the unit weight of water (kg/m^3).

If you substitute typical soil-unit weights into Equation 8, the factor of safety for an 18-in. soil cover is reduced to 1.03 with typical 4 H:1V slope values. Because this value is too close to one, slope failure may result.

As **Photo 1** shows, grout-filled erosion control blankets also can be used as a protective cover layer. Such materials provide free drainage and tensile strengths that are not available in soil protective covers.

The downside to such protective covers is price. Common soil protective covers cost approximately \$0.50/ft², while the system cost of the grout-filled erosion mats can approach \$4/ft².

Design without protective cover

Owners frequently prefer to clean and inspect the surface-impoundment geomembrane liner at regular intervals during its service life. Obviously, the presence of a protective cover prevents future inspection of the liner and limits the effective cleaning of an impoundment. However, without a protective cover, the geomembrane liner can be damaged more easily. Therefore, the impact of a penetration must be accounted for in the design of an unprotected liner.

Liquids that move through a defect in an unprotected geomembrane must be able to freely drain so that they do not lift the geomembrane and eventually whale. **Photo 2** shows whales developing in a leachate surface impoundment.

A drainage system must be placed immediately beneath an unprotected geomembrane so that liquids may freely drain through a penetration. This drainage system must have sufficient transmissivity to allow the leakage to freely drain without lifting the geomembrane and to be underlain by a second geomembrane. The hydraulic capacity of the under drain will determine the number of defects that can be tolerated in the primary liner system before repairs are required. Thus the rate at which-leakage is collected in the lower system should be monitored to confirm that repairs are not needed. This is analogous to action-leakage rates (ALR) for leak-detection systems in solid-waste-liner systems. The rate of leakage to the under drain should be determined by the designer and incorporated in the service monitoring of the impoundment.

Surface impoundments with exposed geomembranes must be leak-tested on an annual basis, if the quantity of leakage to the underlying drain is not monitored. Electrical leak surveys can detect a current flow through the liner via the defect. Two distinct electrical approaches can be taken to detect leaks in exposed liners:

- Surveys that use the underlying ground or saturated detection zone as a conductor
- Surveys performed using a geomembrane with a conductor grid or coating on the lower side.

Figure 2, provided by Leak Location Services Inc. (LLSI), San Antonio, Texas, illustrates a typical leak-survey setup applicable to any geomembrane. This technique has the advantage of performing surveys while the impoundment is in service. **Figure 3** shows Houston-based GSE Lining Technology's unique conductor sheet that is simple enough for facility personnel themselves to perform a very simple

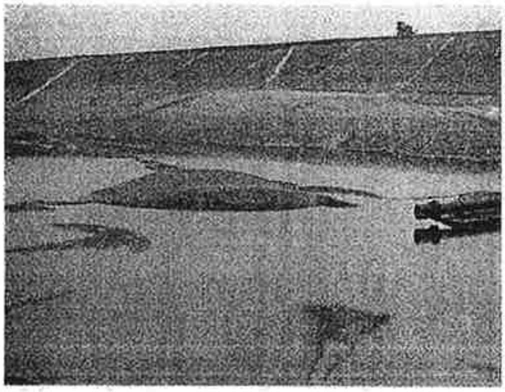
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Photo 2. Pressure from undrained leakage under the geomembrane can cause the liner to lift and appear like a whale.

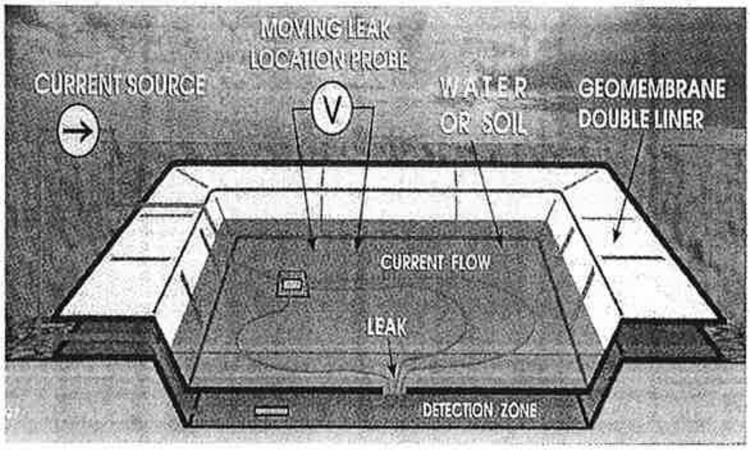

Figure 2. Typical leak-survey setup.

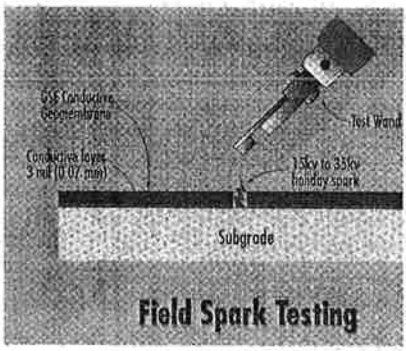

Figure 3. A conductor sheet allows disposal-facility operators to perform leak-location tests on their own.

"spark" test for leak location. A future Designer's Forum will be dedicated to a more rigorous look at the leak-detection alternatives available to owners and designers.

Summary and acknowledgements

Properly designed and maintained geomembrane-lined surface impoundments provide reliable storage for industry. Understanding and properly implementing the basic leakage equations developed by Giroud is key to the proper design of surface impoundments. Geomembrane liners must either be designed with sufficient surcharge loading to ensure intimate contact with an underlying soil liner, or with a lateral-drainage system to adequately remove leakage and gas that may develop beneath the geomembrane.

Surface impoundments that use exposed geomembranes also will require a formal in-service monitoring and repair program to ensure the integrity of the liner system. Such programs must be defined by the designer and implemented by the owner.

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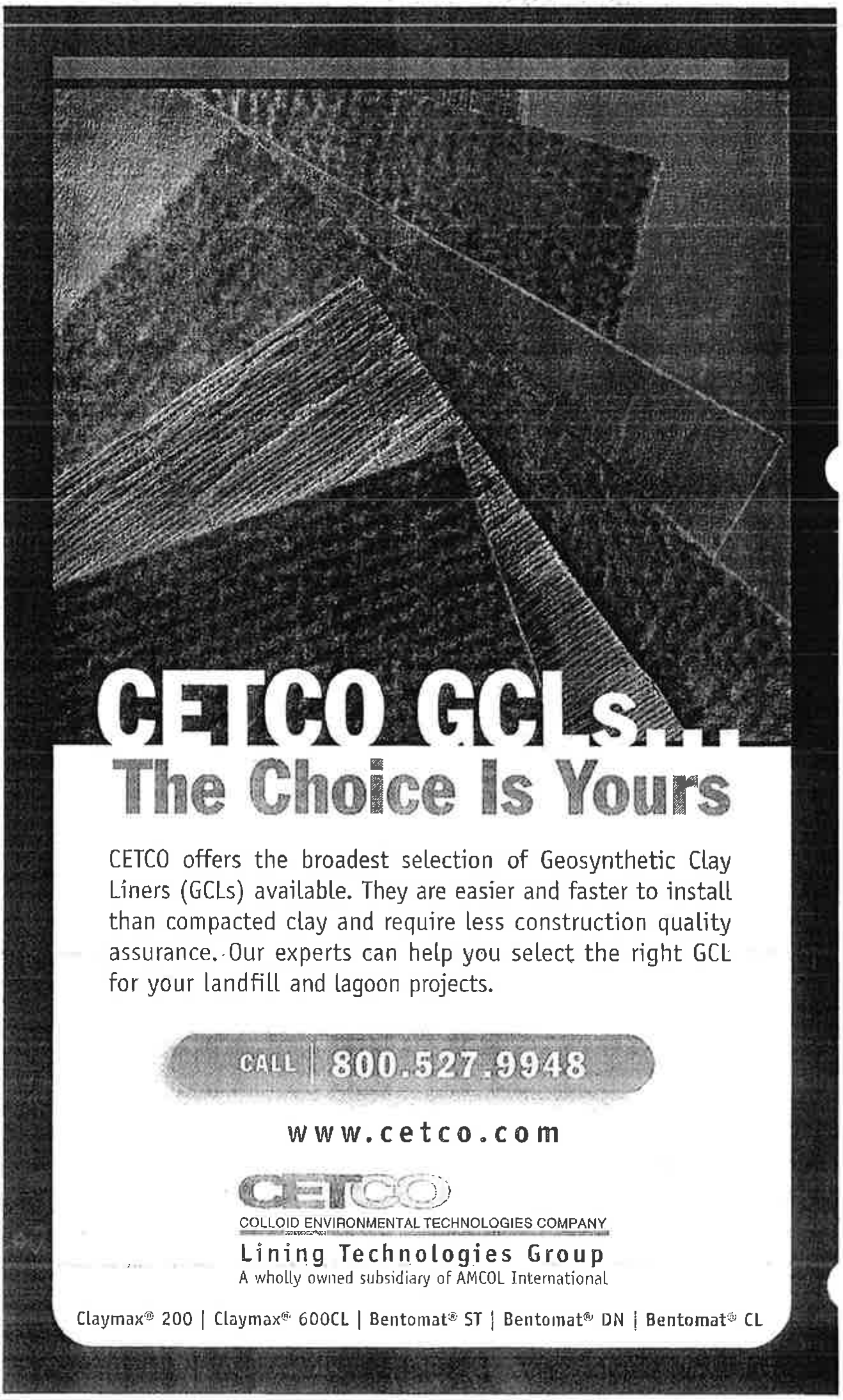
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