GCL ALTERNATIVE LINER AND CRITICAL SLOPE STABILITY – UNIQUE CASE HISTORY INVOLVING ENCAPSULATED DESIGN APPROACH

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SUMMARY: The Coffin Butte landfill in Oregon, USA chose to use a geosynthetic clay liner (GCL) as part of a bottom liner system for a lateral expansion. Environmental containment and slope stability issues were addressed by encapsulating a non-reinforced bentonite between two geomembranes. The design basis for this project conservatively estimated how much the bentonite might hydrate over hundreds of years through potential geomembrane defects and overlaps, and prorated the shear strength between the dry and hydrated state. The advantages of an encapsulated design approach are: (a) greatly improved environmental protection, (b) improved bentonite durability during construction, and (c) improved slope stability. Design assumptions were verified by exhumation of the bentonite after one year.

1. INTRODUCTION

The bottom liner system chosen for the Coffin Butte landfill lateral expansion is shown in Figure 1. The primary barrier layer consisted of a geosynthetic clay liner plus a supplemental geomembrane. The type of GCL used employed a textured geomembrane carrier to support the bentonite. By installing this type of GCL with the bentonite side face-up, and subsequently deploying another textured geomembrane over the exposed bentonite, the bentonite would be encapsulated such that both sides of the unreinforced bentonite are protected by a geomembrane. The upper geomembrane was welded. The lower geomembrane-supported GCL was simply shingled with 0.23 m overlaps as shown in Figure 1. There are three advantages to such a design. The first advantage is enhanced environmental protection (i.e., reduced leakage). For example, Thiel et al (2001) present calculations showing that an encapsulated design may have over four orders of magnitude less leakage than a conventional composite liner system using compacted clay with a hydraulic conductivity of 1×10^{-7} cm/s. The second advantage is that the bentonite durability during construction is improved because it is protected from hydration by a geomembrane on both sides. The third advantage is improved slope stability, which is the main subject of this paper.

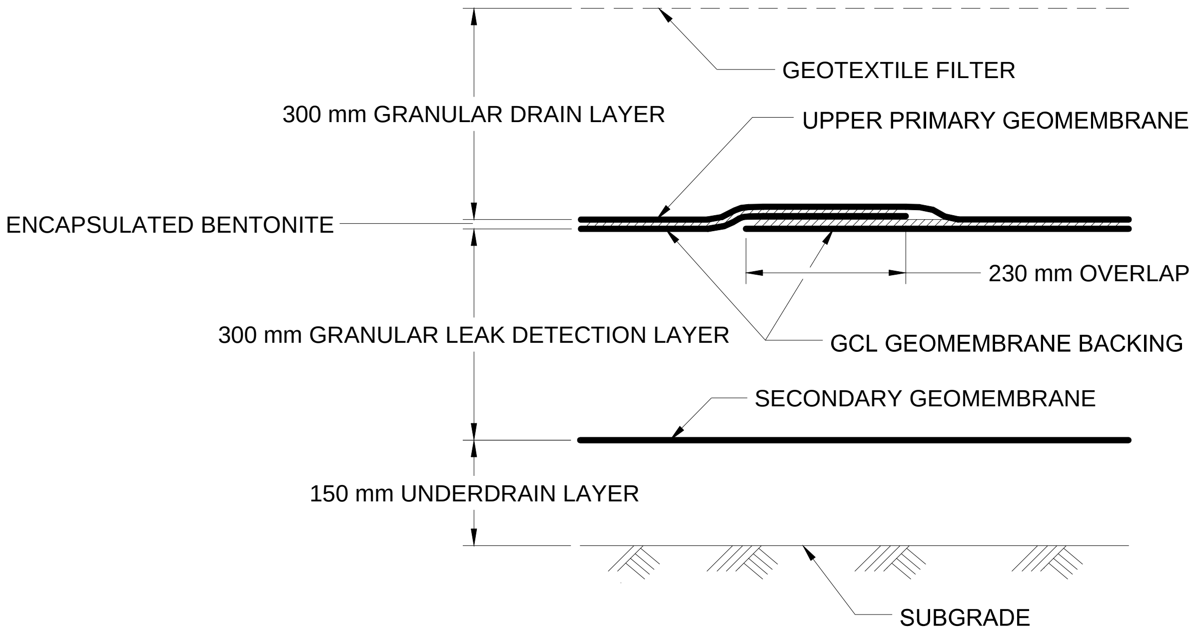

Figure 1. Bottom liner system used for Coffin Butte Landfill.

Over time, encapsulated bentonite can hydrate from a relatively dry state, to one that is more saturated. Relatively dry means, from a shear strength point of view, that the bentonite is drier than 35% moisture. Moisture contents above 40% to 50% will result in reduced bentonite shear strength (Daniel et al, 1993). By estimating the fraction of the installed bentonite area that may become hydrated, the global shear strength of the bentonite layer can be prorated (i.e., % of dry area vs. % of hydrated area). With a given relative hydrated vs. dry area of bentonite in an encapsulated GCL installation, a design methodology can be applied to prorate the shear strength over the design life of a project. The approach of prorating shear strength for encapsulated GCLs has been utilized successfully in several landfill designs since 1994 for projects in the Western U.S. (GSE, 2001). This paper presents a case history to discuss the methodology used for estimating what fraction of an encapsulated GCL installation may become hydrated over the life of a project, and how the prorated shear strength envelope was used to determine the long-term slope stability performance of the encapsulated design.

2. ENCAPSULATED BENTONITE HYDRATION

Since the as-manufactured moisture content of the product used for Coffin Butte is less than 25%, it is reasonable to require that the bentonite be installed with a moisture content no greater than 30%. There are two potential hydration mechanisms that could result in localized bentonite moisture increases; landfill moisture from above through defects in the upper welded geomembrane, and subgrade moisture from below coming in through the overlaps. Thiel et al (2001) also discuss potential hydration from water diffusion through the geomembranes and conclude that this hydration mechanism is insignificant.

2.1 Hydration from Above Through Defects

Equation (1) for radial hydration of encapsulated bentonite, caused by liquid entering a defect in the overlying geomembrane, was developed by Dr. J.P. Giroud (Thiel et al, 2001).

$$\hat{t} = \frac{n\,R^2}{4\,k\,\Delta h}\left[2\,ln(R/r) - 1 + \left(\frac{r}{R}\right)^2\right] \tag{1}$$

Definition of the parameters in Equation (1) as used for Coffin Butte are:

- $\hat{t}$ = time
- *n* = available porosity. A typical value for the total porosity of bentonite is approximately 0.6. If the bentonite is installed with an initial moisture content of 25%, and the final hydrated moisture content is estimated at approximately 75%, then the available porosity for further hydration would be 2/3 of the total porosity. Therefore, the value for *n* in Eqn (1) would be *n* = 0.67(0.6) = 0.4.
- *k* = bentonite hydraulic conductivity, which could be estimated from Thiel et al (2001) as a function of the average confining stress. A conservative value for the Coffin Butte landfill is a confining stress of 200 kPa for which *k* would be 6×10^{-12} m/s.
- Δh = total head driving moisture (suction plus liquid head). Based on tests conducted over 5 months by Estornell and Daniel (1992), and observations of overlap hydration at the Cincinnati GCL cover test plots (Koerner et al, 1996) after 4.5 years on a wet subgrade, Dr. Daniel estimated that the wetting-front suction head in bentonite on a wet subgrade ranged from 1.5 to 2 m. A conservative value of Δh = 3.0 m for the wetting-front suction head is recommended for bentonite where there is a continuous water supply. To this would be added whatever liquid head is assumed acting on the liner system. For Coffin Butte a total head of Δh = 3.3 m was used for leakage from above.
- *r* = radius of defect, assumed to be r = 5.6 mm (hole area = 1 cm2) in this case.
- *R* = radius of the wetting front in the bentonite layer.

The results for Coffin Butte are plotted in Figure 2. Over a 250-year period, the radius of hydrated area is calculated to be less than 0.5 m. Relative to one hectare, after 250 years, the hydrated area beneath a single defect is calculated to be less than 0.008% of the total area. Thus, if there were 10 defects per hectare in both the bottom and top geomembranes located randomly (very conservative assumption), the total number of defects per hectare would be 20, and the percent of the total area that is hydrated would be 20 x 0.008% = 0.16%. This magnitude of hydration beneath occasional imperfections in the geomembrane is negligible. Of course, this analysis assumes good contact between the geomembranes and bentonite. Wrinkles in the geomembrane could produce greater lateral spreading. The analysis also assumes a continuous head of water, so if conditions were comparatively dry, the hydration would be less. Therefore, it is conservative to assume that 5% of the total installed area might become hydrated due to geomembrane defects.

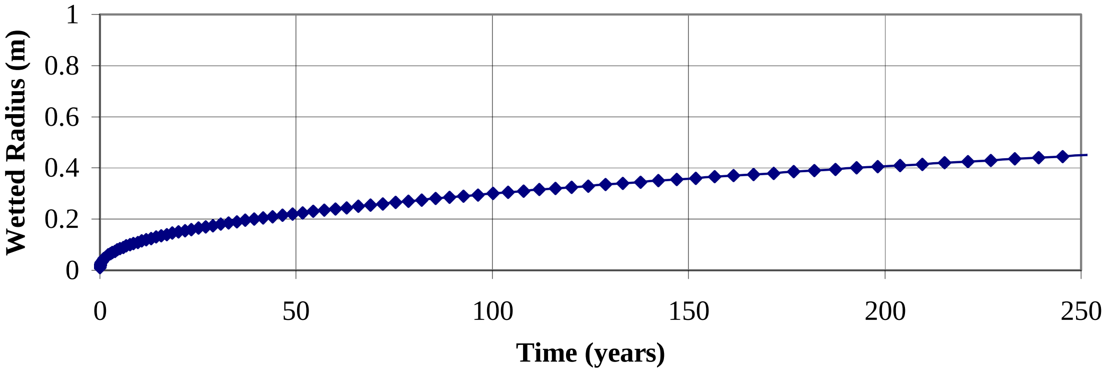

Figure 2. Predicted Wetting of the Encapsulated Bentonite Through A Single Defect in the Overlying Geomembrane at the Coffin Butte Landfill.

2.2 Hydration from Below Through Overlaps

At the GCL overlap seam area, where the geomembrane-supported GCL is deployed with the geomembrane face-down against a soil subgrade, moisture will be absorbed into the exposed bentonite edge of the overlap due to the difference in matric suction between the bentonite and the subgrade soils. The extent and rate of wetting along the exposed bentonite edge of the overlap are dependent on the water content of the soil in contact with the bentonite. The method for calculating the hydration rates along this exposed edge was developed by Dr. J.P. Giroud (Thiel et al, 2001). The reference by Thiel et al (2001) provides examples showing how the bentonite might become hydrated between 5% and 34% of its area over a period of 250 years depending on whether the subgrade on which the encapsulated liner was placed was relatively dry or wet.

At Coffin Butte the GCL was installed over a secondary geomembrane and leak detection layer. This situation not only severely limited the source of potential moisture that would be available to the bentonite, but also provided a large capillary break. The thickness of the gravel leak detection layer (30 cm) was greater than the maximum capillary rise (6 cm) in that material. Since no water would be available in this design to hydrate the bentonite from below, except perhaps for a minor amount of incidental water initially available in the gravel, the hydration vs time would essentially be zero. Nonetheless, a conservative hydration of 5% of the area was assumed due to moisture intrusion at the overlaps. Therefore, the total long-term assumed hydrated area for the bentonite in this design was 5+5 = 10%.

3. SLOPE STABILITY ANALYSIS

The shear strength along a slip plane within the bentonite of the GCL would be a proration of both the hydrated and dry shear strength properties of bentonite. Given the random nature of geomembrane defect locations, and the generally even spacing of overlapped GCL seams, the hydration pattern in the bentonite area could be assumed to be relatively uniformly distributed over a project area. Therefore, it is reasonable to define a weighted average for the global shear strength based on the hydrated and dry shear strengths of bentonite, and the corresponding assumed fractions of hydrated and dry areas.

For example, if the hydrated fraction [$Area_{(hydrated)}/Area_{(total)}$]of the GCL was assumed to be 10%, Figure 3 illustrates how the prorated design shear strength envelope would appear for a high-normal load peak strength. The prorated strength [$\tau_{(design)}$] is calculated as:

$$\tau(design) = \tau(dry) - \frac{Area(hydrated)}{Area(total)}\left(\tau(dry) - \tau(hydrated)\right) \qquad (2)$$

The curved shear strength envelopes shown on Figure 3 were discretized into linear segments for use in the slope stability program. The critical geometry, material properties, and results of the slope stability analysis for Coffin Butte are presented on Figure 4, which used the prorated shear strength envelope for the GCL interface. The factor of safety for this analysis is 1.5. Although this satisfied the basic design requirements for slope stability, one additional requirement was established that the factor of safety be greater than 1.0 assuming the bentonite was fully hydrated. The stability analysis results for this case, presented in Figure 5, showed that the design met this requirement as well (FS = 1.1).

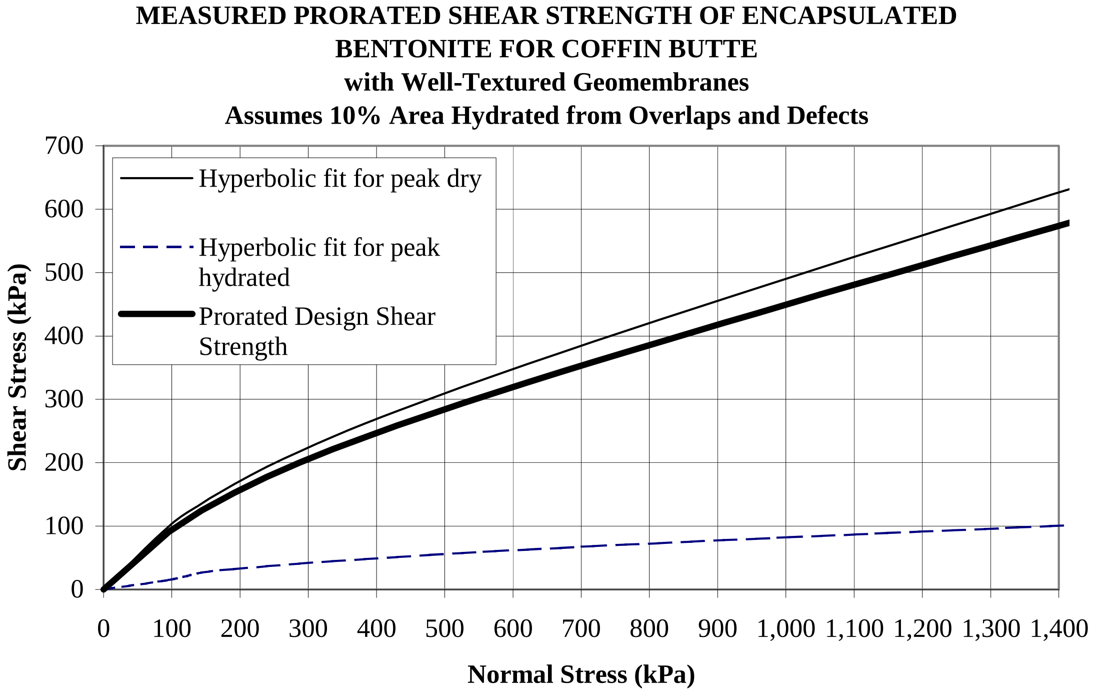

Figure 3. Prorated Shear Strength Curve for Encapsulate, Partially-Hydrated Bentonite.

FS = 1.48

Soil Desc.	Soil Type No.	Total Unit Wt. (kN/m3)	Saturated Unit Wt. (kN/m3)	Cohesion Intercept (kPa)	Friction Angle (deg)
SUBGRADE	1	18.8	20.4	23.9	35.0
WASTE	2	11.8	14.9	0.0	28.0
LINER1	3	15.7	15.7	0.0	11.0
GCL	4	15.7	15.7	117.4	18.4

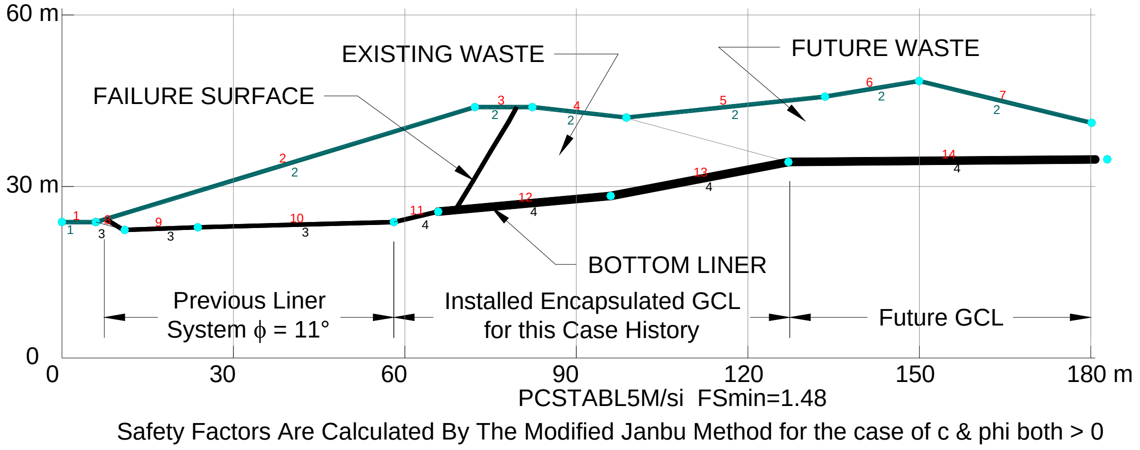

Figure 4. Slope stability analysis using prorated shear strength parameters.

FS = 1.11

Soil Desc.	Soil Type No.	Total Unit Wt. (kN/m3)	Saturated Unit Wt. (kN/m3)	Cohesion Intercept (kPa)	Friction Angle (deg)
SUBGRADE	1	18.8	20.4	23.9	35.0
WASTE	2	11.8	14.9	0.0	28.0
LINER1	3	15.7	15.7	0.0	11.0
GCL	4	15.7	15.7	28.9	3.1

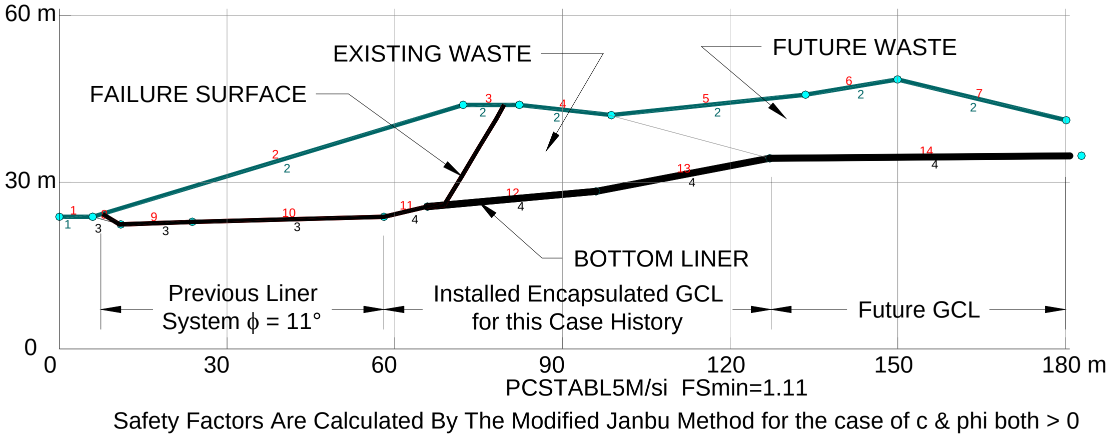

Figure 5. Slope stability analysis using hydrated shear strength parameters.

4. INSTALLATION AND DURABILITY

The engineering assumptions used in design are hinged on the geosynthetics' integrity being maintained through the construction process. Geosynthetics are generally specified and manufactured with adequate durability to survive construction and service loadings. Designers, installers, contractors, and operators must be aware, however, that there are limits to the level of abuse that geosynthetics can survive. This is the case for any manufactured geosynthetic lining or drainage product.

For a GCL, there are three significant durability issues, all related to covering the liner with soil, that occur during construction that could affect its fundamental design performance if the construction procedures are not closely monitored and followed. The three durability issues related to covering a GCL with soil are (1) covering soon enough, (2) covering carefully enough, and (3) covering thick enough.

Covering in a Timely Manner. The objective of covering a GCL in a "timely manner" is to prevent the bentonite from hydrating with no confining pressure. In the case of an encapsulated GCL, however, the issue is significantly reduced, if not eliminated altogether, as long as the GCL is covered with the overlying geomembrane at the end of each working day.

Covering in a Careful Manner. The high level of performance demonstrated by composite liners assumes that certain size defects in the geomembrane would be backed up by the underlying bentonite from the GCL. Very large defects through a GCL, however, might be beyond a GCL's sealing ability. Spinning wheels or tracks on construction equipment, for example, could rip a large gap in a geosynthetics-only lining system. Therefore, industry accepted construction installation and monitoring practices must be followed (such as those established by ASTM D6102, or the manufacturer's recommendations) to preclude these types of defects from occurring. After at least 0.3 m of soil material is in place over the liner system, the potential for further construction- or operations-induced damage becomes remote. For the liner system's integrity to be ensured, therefore, it is crucial that placement and spreading of the cover soil layer atop the liner be rightly executed. Two installation and monitoring practices were followed to eliminate the possibility of large through-liner defects for the project. They were:

- Development of appropriate construction specifications that alerted the installer, general contractor, and owner which specific actions and activities must be taken and avoided.
- Provision for a high level of construction quality control (CQC) and construction quality assurance (CQA) during liner deployment and covering operations. Typically this involved having two ground-persons, one from the contractor and one from the CQA organization, directly monitoring the cover soil placement operation 100% of the time that the geosynthetics were being covered with soil.

Thicker Covering for Roads. Hydrated bentonite may have a tendency to migrate and thin in response to differential stresses, depending on the magnitude of confinement and level of differential stresses. Because of the incapsulated design, this was not as much of a concern. Nonetheless, areas over the liner system that experienced heavy construction loads were required to have adequate soil cover to protect the liner system under the wheel paths. At least 0.3 m of cover soil was deemed adequate for track equipment. For haul routes that were used by rubber-tired equipment a minimum soil cover of 0.6-0.9 m was required, depending on the intensity of use and size of equipment. The extra material on the haul routes was spread out with a dozer at the end of the construction project.

5. FIELD EXHUMATIONS

Hydration in the bentonite was monitored one year after installation using both instrumentation (fiberglass moisture gages) and direct visual observation by exhumation. After six months the moisture gage readings indicated that the bentonite was hydrating. The lining system was exhumed in two locations, and the primary liner was cut open to examine the bentonite. One of the locations was exactly where a moisture gage was located, and the other location was below about 3 m of refuse. In both cases, the bentonite was found to be as dry as the day it was installed, leading to the conclusion that the moisture gages had mal-functioned, and the project was performing as designed.

6. SUMMARY AND CONCLUSIONS

Design of encapsulated GCL liner systems can provide greatly enhanced environmental protection and improved slope stability. Design methods are available to evaluate the improved hydraulic performance and long-term slope stability of encapsulated systems. As with any geosynthetic installation, good construction practices and a high level of construction monitoring are required to ensure that the project integrity is maintained in accordance with the design intent.

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REFERENCES

ASTM D6102, *Standard Guide for Installation of Geosynthetic Clay Liners*, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA.

Daniel, D.E., Shan, H.Y., and Anderson, J.D. (1993) "Effects of Partial Wetting on the Performance of the Bentonite Component of a Geosynthetic Clay Liner". *Proceedings from IFAI's Geosynthetics '93 Conference*, Vancouver, B.C., March 30-April 1. Pp. 1483-1496

Estornell, P. and Daniel, D.E. (1992) "Hydraulic Conductivity of Three Geosynthetic Clay Liner." *ASCE Journal of Geotechnical Engineering*, Vol. 118, No. 10, pp. 1592-1606.

GSE (2001) *GundSeal Product Manual.*

Koerner, R.M., Carson, D.A., Daniel, D.E., and Bonaparte, R. (1996) "Current Status of the Cincinnati GCL Test Plots". *Proceedings of the 10th GRI Seminar*: Field Performance of Geosynthetics and

Geosynthetic Related Systems. Geosynthetic Research Institute. Drexel University. Philadelphia, PA.

Thiel, R., Daniel, D., Erickson, R., Kavazanjian, E., and Giroud, J.P. (2001) *GundSeal Design Manual*, GSE, Houston, Texas.