CH2M HILL
Engineers
Planners
Economists
Scientists

February 13, 1996

117956.28

Mr. John Ruddell
Director of the Division of Waste Management
Florida Department of Environmental Protection
2600 Blair Stone Road
Twin Tower Office Building
Tallahassee, Florida 32399-2400

Dear Mr. Ruddell:

Subject: Landfill Sideslope Subbase Design
Request for Alternate Procedure
Citrus County Central Landfill Phase 1A Expansion

CH2M HILL has prepared and submitted to the FDEP Tampa District office a permit application to construct the Citrus County Central Landfill Phase 1A Expansion on behalf of Citrus County. The purpose of this correspondence is to request approval of an alternate landfill sideslope subbase design in accordance with Rule 62-701.310, Florida Administrative Code (FAC). All of the criteria for this request included in Rule 62-701.310(2), FAC are summarized in the following table. A more detailed discussion of each of the criteria is provided under the headings which follow the summary table. A fee of $2000 in accordance with Rule 62-701.310(6), FAC is also attached.

Tampa Office
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Rule	Criteria	Response
62-701.310(2)(a), FAC	Facility.	Citrus County Central Landfill Phase 1A Expansion.
62-701.310(2)(b), FAC	Specific provisions for which an exception is sought.	6-inch-thick lining subbase for a double geomembrane lining (Rule 62-701.400(3)(c)(1), FAC.
62-701.310(2)(c), FAC	Basis for the exception.	A lining subbase is not practical based on constructability and benefit considerations.
62-701.310(2)(d), FAC	Alternative procedure and demonstration of equal degree of protection.	Placement of the lower geomembrane of the sideslopes on prepared, in place naturally occurring subgrade soils. Alternative provides for a greater degree of protection.
62-701.310(2)(e), FAC	Demonstration of effectiveness	Estimated leachate flow through the Phase 1A Expansion sideslopes is negligible.

Rule 62-701.310(2)(a), FAC The specific facility for which an exception is sought:

This exception is being sought for the Citrus County Central Landfill Phase 1A Expansion in Lecanto, Florida.

Rule 62-701.310(2)(b), FAC The specific provisions from which an exception is sought:

The lining base grade plan for the Citrus County Central Landfill Phase 1A Expansion is shown on Drawing No. C-4 in Attachment A. The boundary of the east and west sideslopes of the proposed expansion are indicated with a heavy dashed line on the drawing. A detail of the proposed lining for both the sideslopes and bottom of the landfill expansion is shown in Detail 18 on Drawing No. C-14 (Attachment A). A double geomembrane lining in general accordance with Rule 62-701.400(3)(c), FAC is proposed for the expansion. An exception is being sought for the lining subbase provisions of the referenced rule. Rule 62-701.400(3)(c)(1), FAC includes provisions for at least a 6-inch-thick lining subbase with a maximum hydraulic conductivity of 1 x 10^{-5} centimeters per second (cm/sec). As shown in Detail 18 on Drawing No. C-14 (Attachment A), a lining subbase is proposed for the bottom lining in the Phase 1A Expansion; however, a lining subbase is not proposed for the sideslopes of the expansion. Placement of the lower geomembrane on prepared, in place, naturally occurring subgrade soils is planned.

Rule 62-701.310(2)(c), FAC The basis for the exception:

This exception is based on the practicality, from both constructability and benefit considerations, of a lining subbase beneath the sideslopes of the proposed Phase 1A Expansion.

During Phase 1 construction of the facility, the sideslopes in the area of the Phase 1A expansion were excavated to approximately the proposed lining base grade elevations shown in Drawing No. C-4 (Attachment A). At that time, provisions for subbases were not part of the regulations and the Phase 1 lining and excavation for the future Phase 1A expansion were constructed in accordance with existing standards and permit provisions. Placement of a low-permeability, 6-inch lining subbase on the already excavated sideslopes is not practical with available construction technology. If attempted, it is unlikely that the subbase would be effective and support for the overlying lining system may even be compromised. The length of the slope, which is over 200 feet, precludes the use of geocomposite clay lining without an intermediate anchor trench in the middle of a slope. Both flattening the slope and providing for an intermediate anchor trench would require the placement of fill on the bottom portion of the slope since site boundaries prevent widening the limits of the excavation at the top. However, placement of soil fill on the bottom portion of the sideslope is undesirable because a weakened foundation support zone could be developed between the interface of the soil fill and in place soils below the landfill.

The lining subbase provisions are intended to inhibit lining leakage and contain leachate below the bottom of landfills to protect the public and environment. This protection usually applies to groundwater resources, which are typically within several feet of landfill bottoms in Florida. The use of a low permeable, 6-inch-thick sideslope lining subbase for this protection does not provide practicable benefits for the Phase 1A Expansion because of the following site specific conditions:

- The lining sideslopes will be at approximately 2 horizontal to 1 vertical slopes and composite drainage nets will be used for both the primary and secondary leachate collection layers. Therefore, leachate in the collection layers of the lining will be drained away to the landfill bottom quickly. As a result, there will be negligible head on the lower geomembrane lining which could contribute to leakage and make a lining subbase beneficial.

- The groundwater elevation at the site is at elevation 7 feet NGVD and approximately 113 feet below ground surface. This groundwater level is 25 feet from the bottom of the Phase 1A sideslopes. Hydraulic conductivity test results on soils adjacent to and below the sideslopes are summarized on Figure 1 in Attachment B. Tests results range from 1.3×10^{-7} to 2.0×10^{-4} cm/sec, with an average of 3.0×10^{-5} cm/sec. Considering the distance between the bottom of the sideslopes and groundwater, as well as the low permeability of natural soils at the site, placement of a lining subbase will have no practical benefit.

Rule 62-701.310(2)(d), FAC The alternate procedure or requirement for which approval is sought and a demonstration that the alternate procedure or requirement provides an equal degree of protection for the public and the environment:

The alternate procedure being sought is to place the lower geomembrane of the sideslopes at the Phase 1A Expansion on prepared, in place naturally occurring subgrade soils in lieu of a lining subbase. The degree of protection of the sought after alternate procedure and the required lining subbase can be evaluated by considering the amount of leachate that could flow through the lining subbase and, alternatively, in place soils. This flow is characterized using Darcy's law in the calculations in Attachment C. The results are summarized below:

- The expected flow per cross-sectional area through a 6-inch-thick subbase layer in accordance with Rule 62-701.400(3)(c)(1), FAC is 6.6 x 10^{-7} times the head on the subbase, per second.

- The in-place subgrade soils alternative is characterized by a thickness of 25 to 113 feet between the lining and the groundwater level, and ranges in hydraulic conductivity from 1.3 x 10^{-7} to 2.0 x 10^{-4} cm/sec. Based on a conservative thickness equal to 25 feet for the subgrade and the greatest measured hydraulic conductivity value of 2.0 x 10^{-4} cm/sec, the expected flow per cross-sectional area through the in place subgrade alternative is also 2.6 x 10^{-7} times the head on the subbase, per second.

Therefore, potential flow through the alternative is expected to be less than 40 percent of the flow through a 6-inch-thick lining subbase. The proposed alternative provides a greater degree of protection to the public and the environment.

Rule 62-701.310(2)(e), FAC A demonstration of the effectiveness of the proposed alternative procedure:

The effectiveness of the proposed alternative is evaluated in Attachment D by characterizing the proposed Phase 1A Expansion sideslopes' ability to contain landfill leachate. The methodology used in this evaluation is identified in the calculations and based on standard design equations developed by J. P. Giroud. Results are summarized below:

- Based on the slope of the lining, properties of the primary leachate collection layer, and a leachate impingement rate typical of Florida; the maximum expected head on the primary lining is 1 x 10^{-4} meters (m).

- Using this head, the expected size of potential lining defects, and the properties of the underlying leachate secondary collection layer; the maximum expected flow through the primary lining into the secondary leachate collection layer at each potential lining defect is expected to be 2 gallons per day (gal/day).

- Based on the typical size and frequency of lining defects when determining lining effectiveness, a maximum impingement rate through the primary lining and on the secondary lining of 2×10^{-11} meters per second (m/s) is expected.

- Based on the slope of the lining, properties of the secondary leachate collection layer, and this estimated impingement rate; the maximum expected head on the secondary lining is 1×10^{-8} m.

Using this head, the size and frequency of potential lining defects, and the properties of the underlying soils; the maximum expected flow through the secondary lining can be estimated. As shown on Figure 1 in Attachment B, the hydraulic conductivity of soils at the site which will underlie the secondary lining as the proposed alternative ranges from 1.3×10^{-7} to 2.0×10^{-4} cm/sec. The frequency of different ranges in hydraulic conductivity from this data was used to calculate a total maximum flow of approximately 8×10^{-7} gal/day though the proposed Phase 1A Expansion sideslopes. This flow is negligible, which demonstrates the effectiveness of the proposed alternative procedure for the lining subbase.

As requested by your office, we are submitting seven additional copies of this correspondence. We look forward to receiving your comments on our requested alternative procedure. Please do not hesitate to contact me if you have any questions or need additional information to assist in your review process.

Sincerely,

CH2M HILL

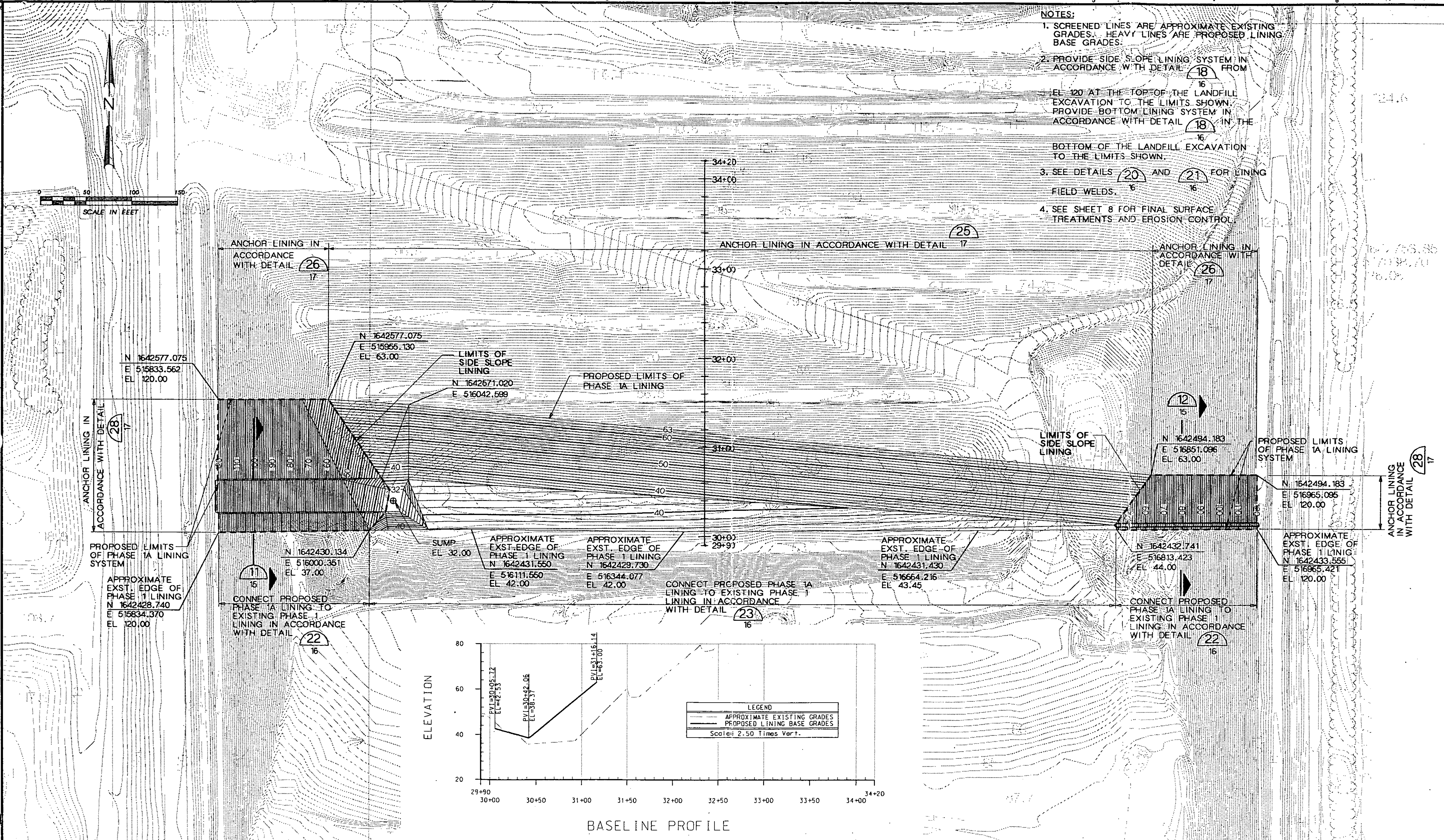
Gary L. Panozzo, P.E.
Project Manager

2/12/96

lLET015.DOC

cc: Kim Ford - FDEP Tampa District
Susan Metcalfe, P.G. - Citrus County

Attachment A
Drawings



CH2M HILL

DSGN	L. REID / G.L. PANOZZO			
DR	B.J.MCCORKLE			
CHK	G.L. PANOZZO			
APVD	JOHN WOOD	NO.	DATE	REVISION	BY	APVD

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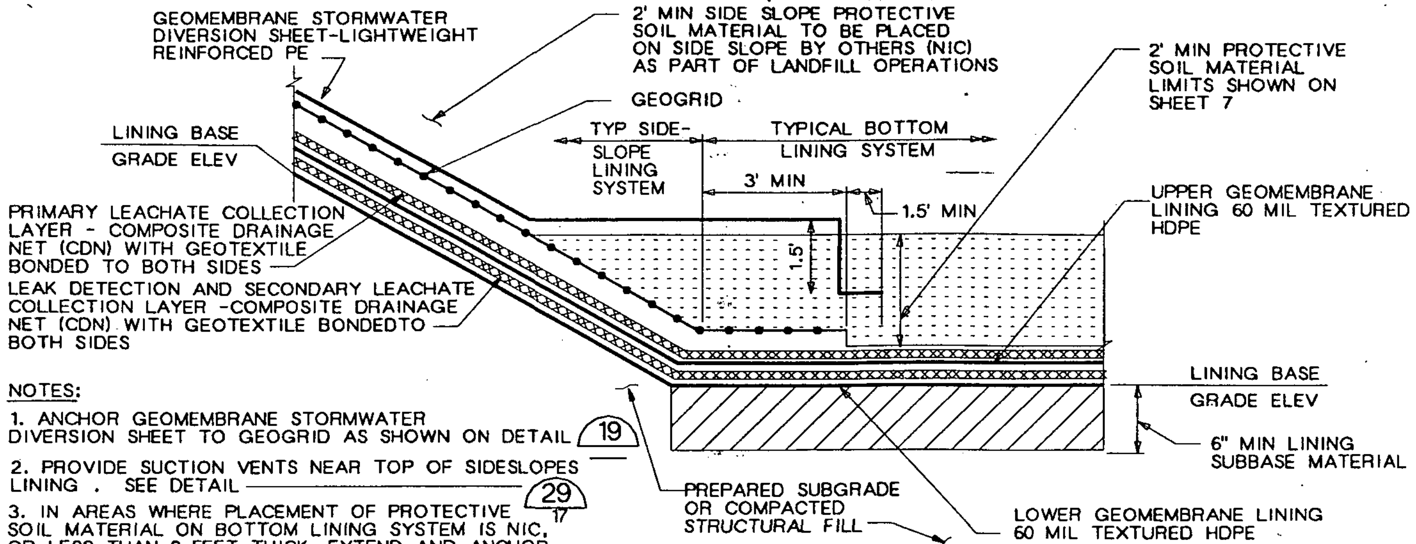
CITRUS COUNTY
CENTRAL LANDFILL
PHASE 1A EXPANSION
CITRUS COUNTY, FLORIDA

LINING BASE GRADE PLAN

SHEET	6
DWG NO.	C-4
DATE	12-29-95
PROJ NO.	130786.28.03

9450C003.dlv



NOTES:

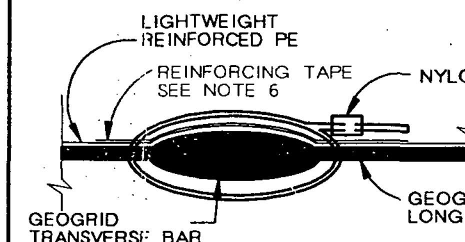
1. ANCHOR GEOMEMBRANE STORMWATER DIVERSION SHEET TO GEOGRID AS SHOWN ON DETAIL 19
2. PROVIDE SUCTION VENTS NEAR TOP OF SIDESLOPES LINING . SEE DETAIL 29/17
3. IN AREAS WHERE PLACEMENT OF PROTECTIVE SOIL MATERIAL ON BOTTOM LINING SYSTEM IS NIC, OR LESS THAN 2 FEET THICK, EXTEND AND ANCHOR GEOMEMBRANE STORMWATER DIVERSION SHEET TO LIMITS OF GEOGRID.
4. CONTRACTOR SHALL PROVIDE 35,000 SF (TEN PANELS, 200 FT BY 17.5 FT EACH) OF LIGHT WEIGHT REINFORCED PE FOR OWNERS USE IN ADDITION TO MATERIALS TO BE INSTALLED UNDER THIS CONTRACT. ADDITIONAL MATERIAL SHALL BE DELIVERED TO ON SITE LOCATION APPROVED BY ENGINEER IN FACTORY PACKAGING.

TYPICAL LINING DETAIL 18/6

NTS

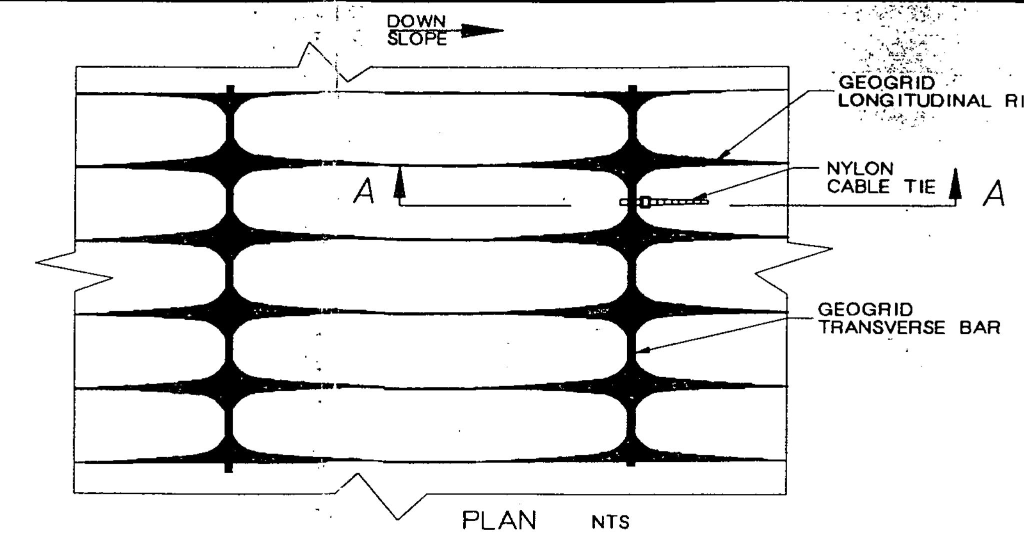
NOTES:

1. INSTALL NYLON CABLE TIES AS SHOWN 10 FT ON CENTERS EACH WAY ON ENTIRE SIDE SLOPE LINING.
2. LIGHTWEIGHT REINFORCED PE NOT SHOWN ON PLAN VIEW FOR CLARITY.
3. ENSURE NYLON CABLE TIE WRAPS OVER 2 OR MORE SCRIM THREADS IN LIGHT WEIGHT REINFORCED PE.
4. ATTACH CABLE TIES ONLY TO TRANSVERSE BARS OF GEOGRID.
5. TIGHTEN CABLE TIE SECURELY TO GEOGRID.
6. INSTALL CABLE TIES OVER 4"X4" REINFORCING TAPE POSITIONED OVER TRANSVERSE BAR OF GEOGRID.



SECTION A-A

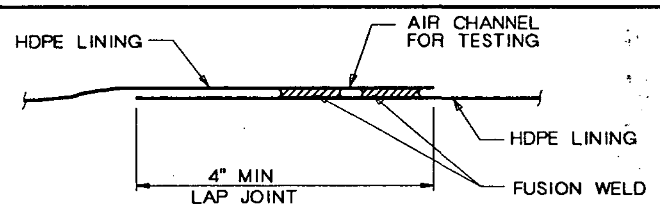
NTS



PLAN NTS

GEOMEMBRANE STORMWATER DIVERSION SHEET/GEOGRID ANCHOR 19

NTS

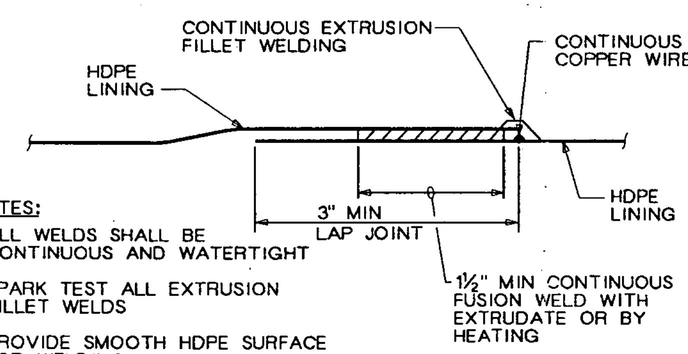


NOTES:

1. ALL WELDS SHALL BE CONTINUOUS AND WATERTIGHT.
2. REMOVE UNBONDED TOP EDGE IF AIR CHANNEL TEST FAILS AND VACUUM BOX TEST IS USED.
3. PROVIDE SMOOTH HDPE SURFACE FOR WELDING.

HDPE LINING DOUBLE WEDGE WELD 20/6

NTS

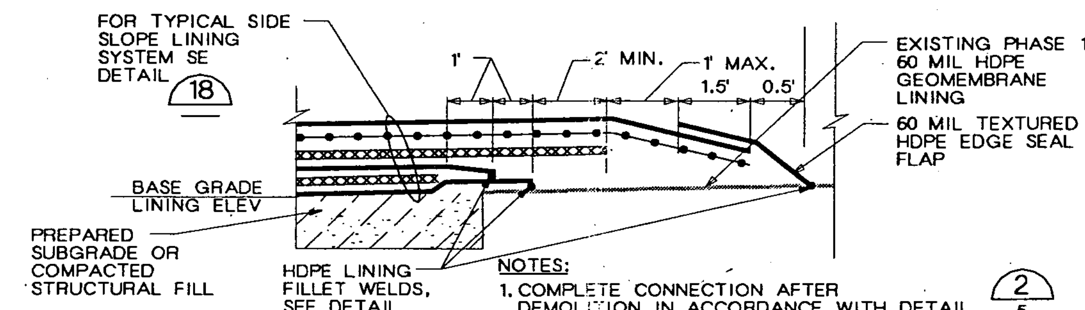


NOTES:

1. ALL WELDS SHALL BE CONTINUOUS AND WATERTIGHT
2. SPARK TEST ALL EXTRUSION FILLET WELDS
3. PROVIDE SMOOTH HDPE SURFACE FOR WELDING.

HDPE LINING FILLET WELD 21/6

NTS

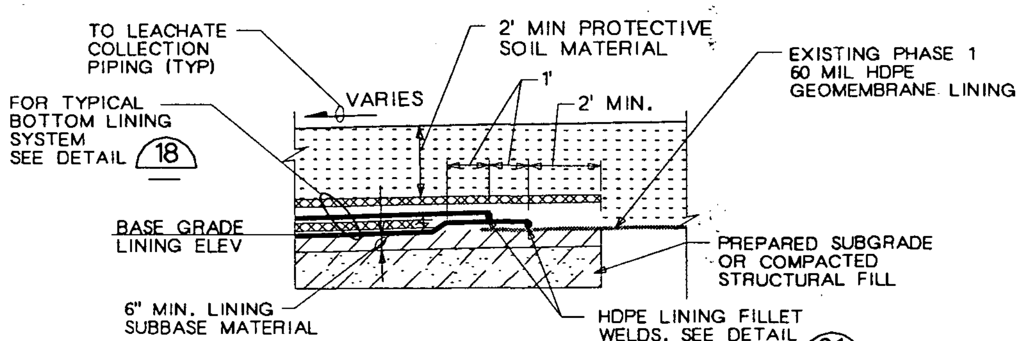


NOTES:

1. COMPLETE CONNECTION AFTER DEMOLITION IN ACCORDANCE WITH DETAIL 2/5
2. REDUCE DIMENSIONS AS REQ'D AND APPROVED BY THE ENGINEER TO PREVENT THE REMOVAL OF ANY EXISTING MATERIAL ON EXISTING PHASE 1 SIDE SLOPES.

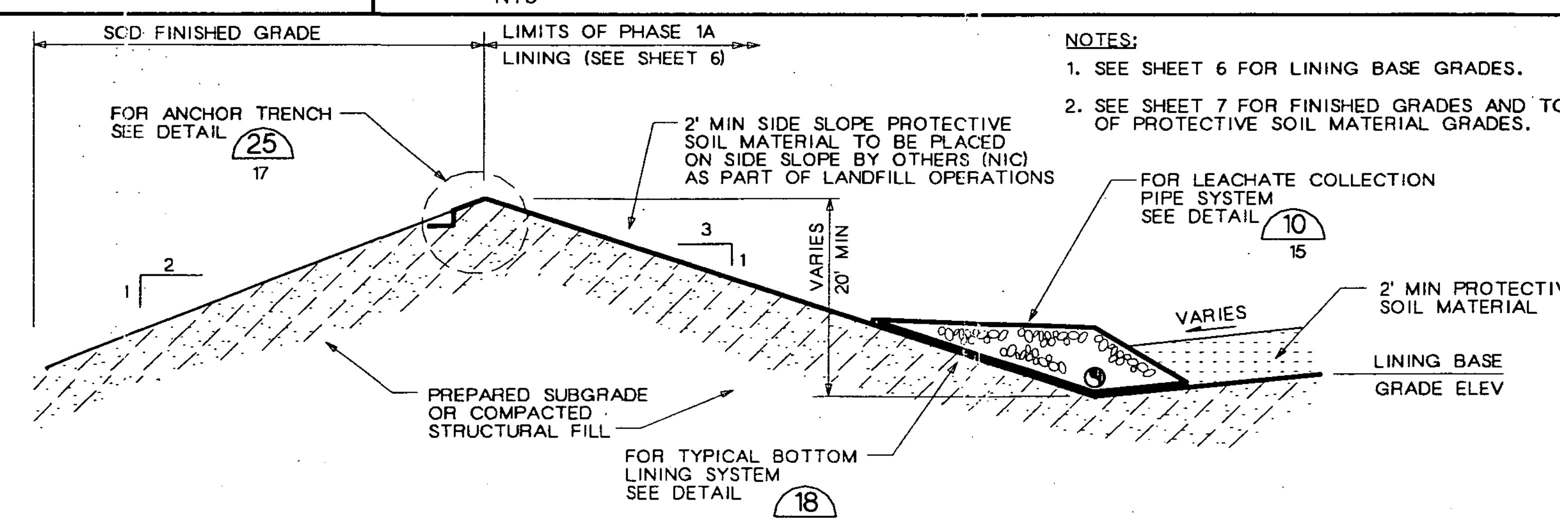
TYPICAL 2:1 SIDE SLOPE LINING CONNECTION TO EXISTING PHASE 1 LINING 22/6

NTS



TYPICAL BOTTOM LINING CONNECTION TO EXISTING PHASE 1 LINING 23/6

NTS



NOTES:

1. SEE SHEET 6 FOR LINING BASE GRADES.
2. SEE SHEET 7 FOR FINISHED GRADES AND TOP OF PROTECTIVE SOIL MATERIAL GRADES.

NORTHERN TERMINATION OF BOTTOM LINING 24/7

NTS

CH2M HILL	DSGN G.L. DELRIO G.L. PANOZZO	NO.	DATE	REVISION	BY	APVD
	DR G.L. DELRIO					
	CHK G.L. PANOZZO					
	APVD JOHN WOOD					

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CITRUS COUNTY CENTRAL LANDFILL PHASE 1A EXPANSION CITRUS COUNTY, FLORIDA

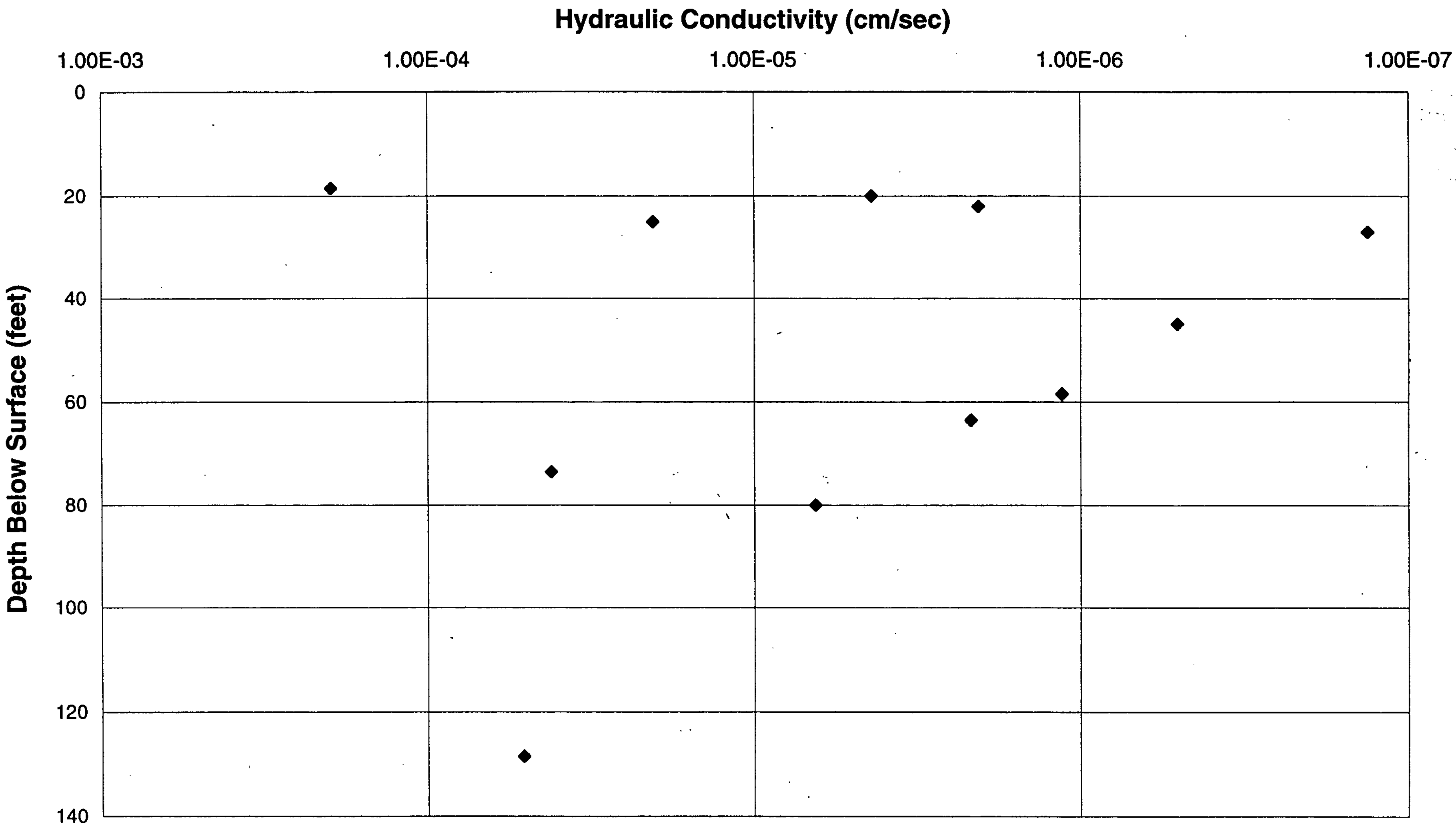
LINING DETAILS

SHEET	16
DWG NO.	C-14
DATE	12-29-95
PROJ NO.	130786.28.03

9450DT04.DLV

Attachment B
Figures

Figure 1


Hydraulic Conductivity (cm/sec)
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
Depth Below Surface (feet)
0
20
40
60
80
100
120
140

Attachment C
Equal Degree of Protection Calculations

SUBJECT CCLF PHASE 1A EXPANSION ALTERNATE SIDE SLOPE LINING SUBBASE | BY G. PANOZZO | DATE 2/6/95 | SHEET NO. 1 of 1 | PROJECT NO. 117956.28

CH2M HILL

I. DETERMINE FLOW THROUGH REQUIRED LINING SUB BASE:

USING DARCY'S LAW

I = HYDRAULIC GRADIENT = CHANGE IN HEAD (ΔH) / L = 6 IN = 15.24 cm

$$Q_{REQ} = K I A$$

$$Q_{REQ} = \left(\frac{1 \times 10^{-5}\ \text{cm}}{\text{sec}}\right)\left(\frac{\Delta H}{15.24\ \text{cm}}\right) A$$

$K = 1 \times 10^{-5}$ cm/sec

$$Q_{REQ} = \frac{6.6 \times 10^{-7}\ \Delta H \cdot A}{\text{sec}}$$

II. DETERMINE FLOW THROUGH IN PLACE SUBGRADE SOIL ALTERNATIVE:

USING DARCY'S LAW

$$Q_{ALT} = K I A$$

I = HYDRAULIC GRADIENT = CHANGE IN HEAD (ΔH) / L = (RANGES FROM 25 to 113') = ASSUME 25' → VERY CONSERVATIVE ←

$$Q_{ALT} = \left(\frac{2.0 \times 10^{-4}\ \text{cm}}{\text{sec}}\right)\left(\frac{\Delta H}{25\ \text{FT} \cdot 12 \cdot 2.54}\right) A$$

K = RANGES FROM 1.3×10^{-7} cm/sec to 2.0×10^{-4} cm/sec = ASSUME 2.0×10^{-4} cm/sec → VERY CONSERVATIVE ←

$$Q_{ALT} = \frac{2.6 \times 10^{-7}\ \Delta H \cdot A}{\text{sec}}$$

Attachment D
Effectiveness Calculations

Determine the head on top of the primary liner on the side slopes:

$$T_{max} = L\left[\sqrt{4(e/K)+\tan^2\beta} - \tan\beta\right] / (2\cos\beta)$$

T_{max} = maximum thickness of leachate in leachate collection layer (meters)
L = length of horizontal projection of the leachate collection layer, from top to collector (meters)
e = impingement rate (or leachate generation rate) (meters/sec)
K = hydraulic conductivity of drainage layer (meters/sec)
β = slope angle (degrees)

e = 25% of the 7-day storm w/ a recurrence period of 100 years

For Florida the 100-year 7-day precipitation is 21 inch or .53 m

$$\therefore\ e = \frac{.25(.53)}{(7)(24)(60)(60)} = 2.2\times10^{-7}\ m/s$$

For a 2:1 slope $\beta = 26.6°$

For a 2.5:1 slope $\beta = 21.8°$

L = 190 feet or 58 m

transmissivity of composite drainage net = 10 gal/min/ft (from technical specifications) or $2.1\times10^{-3}\ \frac{m^2}{sec}$

$$k = \frac{\text{transmissivity}}{\text{thickness of composite drainage net}}$$

thickness CDN = 0.26 inches or .0066 m

$$k = \frac{2.1 \times 10^{-3}\ m^2/sec}{.0066\ m} = 0.3182\ m/s$$

For 2:1 slope:

$$T_{max} = \frac{58\left[\sqrt{4\left(\frac{2.2\times10^{-7}}{0.3182}\right) + \tan^2 26.6^\circ} - \tan 26.6^\circ\right]}{2 \cos 26.6}$$

1.7883

$T_{max} = .0001$ m

For 2.5:1 slope:

$$T_{max} = \frac{58\left[\sqrt{4\left(\frac{2.2\times10^{-7}}{0.3182}\right) + \tan^2 21.8} - \tan 21.8^\circ\right]}{2 \cos 21.8}$$

1.8570

$T_{max} = .0001$ m

use leachate head = .0001 m

References:

Design Example 2, "Leachate Collection System", J.P. Giroud

SUBJECT Citrus County Landfill BY T. Olore DATE 2/1/96
SHEET NO. 3 OF
PROJECT NO. 11795628

Determine rate of leakage through primary lining

From J.P. Giroud's, Design Example 3 "Leakage Evaluation"

Rate of leakage through holes in geomembrane overlain and underlain by high-permeability materials =

$$Q = 0.6\, a \sqrt{2gh}$$

where a = area of geomembrane hole (m^2)
g = acceleration of gravity (m/s^2)
h = head of leachate on top of geomembrane (m)

Equation valid if

$$k_{CDN} > 10^4 a \ (m^2)$$

check $k_{CDN} = 0.3182\ m/s$

For $a = 3 \times 10^{-6}\ m^2$ Hole size from Giroud, typical size hole when evaluating performance of lining systems

$$k_{min} = (1 \times 10^4)(3 \times 10^{-6}) = .03\ m/s$$

$0.3182\ m/s > .03\ m/s$ okay to use equation

$g = 9.81 \ m/s^2$
$a = 3 \times 10^{-6} \ m^2$
$h = .0001 \ m$

$Q = 0.6 (3 \times 10^{-6}) \sqrt{2(9.81)(.0001)}$

$Q = 9.4 \times 10^{-8} \ m^3/s$ or 2 gal/day (for one hole)

Determine rate of leakage through secondary lining.

The impingement rate (e) through the primary liner is:

$e = 9.4 \times 10^{-8} \ m^3/s/acre$ or $2.3 \times 10^{-11} \ m/s$

Thickness of leachate on top of secondary liner is:

For 2.5:1 slope:

$\beta = 21.8°$
$L = 190$ ft or 58 m
$K = .0318 \ m/s$

$$T_{max} = 58 \frac{\left[\sqrt{4\left(\frac{2.3 \times 10^{-11}}{0.3182}\right) + \tan^2 21.8} - \tan 21.8\right]}{2 \cos 21.8}$$

$T_{max} = 1.25 \times 10^{-8} \ m$

From Giroud's "Leakage Evaluation", Design Example 3

Rate of leakage through a composite liner.

$Q = 0.21\, a^{.1} h^{0.9} k_s^{.74}$ for good contact

Where:
Q = rate of leakage through one hole in the geomembrane component of a composite liner
a = are of the hole in the geomembrane (m^2)
h = head of leachate on top of geomembrane (m)
K_s = hydraulic conductivity of the low-permeability soil underlying the geomembrane

$a = 3 \times 10^{-6}\ m^2$
$h = 7.0 \times 10^{-8}\ m$

- To determine Q through a composite liner, the frequency of permeability values was determined based on the number of permeability tests conducted on onsite soils and the results of the tests.
For each permeability value, Q ($m^3/s/acre$) was determined using the above equation. The Q was then multiplied by the percent frequency, and the total acreage of the 2.5:1 side slope.

SUBJECT Citrus County Landfill

BY T. Olge DATE 2/7/96

SHEET NO. 6 OF

PROJECT NO. 117956.28

The Q's for each of the permeability values were added to determine the total amount of leakage through the composite liner system. The attached spreadsheet presents the results of the analysis.

As shown on the spreadsheet the amount of leakage through the composite liner is approximately 7.8×10^{-7} gal/day which is negligible.

Rate of Leakage Through Secondary Liner									
k_s (m/sec)	Data Range (cm/sec)	Number of Tests	Percent Frequency	a (m^2)	h (m)	Q (m^3/sec/acre)	acres	Q (m^3/sec)	Q (gal/day)
1E-06	5E-5 to 4E-4	2	18%	3.00E-06	1.25E-08	1.65E-13	0.15	2.52E-14	5.75E-07
1E-07	5E-6 to 4E-5	3	27%	3.00E-06	1.25E-08	3.00E-14	0.23	6.87E-15	1.57E-07
1E-08	5E-7 to 4E-6	5	45%	3.00E-06	1.25E-08	5.46E-15	0.38	2.08E-15	4.76E-08
1E-09	5E-8 to 4E-7	1	9%	3.00E-06	1.25E-08	9.93E-16	0.08	7.59E-17	1.73E-09
Total		11	100%				0.84	3.42E-14	7.81E-07

DESIGN EXAMPLE 2

LEACHATE COLLECTION SYSTEM

PREPARED BY J.P. GIROUD
GEOSYNTEC CONSULTANTS

1. DESIGN

1.1 Equation

Leachate thickness in LCS

The maximum thickness of leachate in the leachate collection layer is approximately given by the following equation (Figure 1) [Giroud et al., 1993]:

$$T_{max} = L\,[\sqrt{4(e/k) + \tan^2\beta} - \tan\beta]/(2\cos\beta)$$

this is revised Moore's equation and is accurate to within 10%? - more conservative than Moore's.

where: T_{max} = maximum thickness of leachate in leachate collection layer; L = length of horizontal projection of the leachate collection layer, from top to collector; e = impingement rate (or leachate generation rate); k = hydraulic conductivity (coefficient of permeability) of the drainage layer; and β = slope angle. Basic SI units are: T_{max} (m), L (m), e (m/s), k (m/s), and β (degrees).

1.2 Comment on the Impingement Rate

e = precipitation - runoff - evaporation - waste and soil moisture storage

The impingement rate can be determined by performing a water balance model to represent the landfill in operating conditions. Suitable water balance models available are the USEPA water balance method [USEPA, 1975] and the Hydrologic Evaluation of Landfill Performance (HELP) model

[USEPA, 1984a and 1984b].

An alternative but conservative approach is to use an impingement rate equal to 25% of the 7-day storm with a recurrence period of 100 years. For example, in Florida the 100-year 7-day precipitation is 21 in. (0.53 m). This results in:

8.7×10^{-6} in/sec

$$e = 0.25 \times 0.53/(7 \times 24 \times 60 \times 60) = 2.2 \times 10^{-7} \text{ m/s}$$

assumptions

In the following design examples, it is assumed that the impingement rate was obtained from the HELP model. It is assumed that for the considered landfill, the HELP model indicated that approximately 40% of the average monthly rainfall will percolate through the proposed landfill as leachate. It is also assumed that the worst month is June, with a mean precipitation equal to 12.6 in. (0.32 m). This results in:

$$e = 0.40 \times 0.32/(30 \times 24 \times 60 \times 60)$$

$$e = 5.0 \times 10^{-8} \text{ m/s} = 2.0 \times 10^{-6} \text{ in./s} = 4{,}620 \text{ gpad}$$

(gpad = gallons/acre/day)

1.3 Comment on T_{max}

To prevent pressure buildup in the leachate collection layer, T_{max} should satisfy the following criterion:

$$T_{max} < t$$

where: t = thickness of the leachate collection layer (m). meters

In addition, it is recommended that T_{max} be smaller than 0.3 m (1 foot) to minimize leakage through the liner.

2. EXAMPLES

2.1 Sand Drainage Layer

Given:

$\tan \beta = 2\%$ = 0.02 L = 30 m (100 ft) = distance from peak to pipe.
$k = 1 \times 10^{-4}$ m/s t = 0.45 m (1.5 ft)
$e = 5 \times 10^{-8}$ m/s = impingement rate

Calculations:

Can use any system of units if consistent

Giroud's equation:

$$T_{max} = 30\,[\sqrt{4(5 \times 10^{-8})/(1 \times 10^{-4}) + (0.02)^2} - 0.02]/(2 \times 0.9998)$$

$$= 0.435 \text{ m} \qquad = 17 \text{ in.} \qquad = 1.43 \text{ ft}$$

It appears that the leachate thickness does not exceed the thickness of the drainage layer, but exceeds the recommended maximum leachate thickness of 0.3 m (1 ft). In this case, the drainage length, L, may be reduced or the slope, β, increased to meet the requirements of 0.3 m (1 ft) maximum leachate thickness. Alternatively, a material with higher hydraulic conductivity may be used as the drainage medium. For example, if the drainage length is reduced to 21 m (69 ft), the calculated leachate thickness becomes 0.3 m (1 ft).

2.2 Geonet Drainage Layer

Given:

$\tan \beta = 2\%$ = 0.02 L = 30 m (100 ft)

Geonet hydraulic transmissivity measured under a compressive stress equal to the expected landfill overburden stress:

must do a test to determine this value.

= transmissivity

2 values depending on how geonet is tested

θ = 2.0×10^{-5} m^2/s for the considered geonet between geotextile and geomembrane

geotextile restricts flow of geonet & reduces Transmissivity value

θ = 2.0×10^{-4} m^2/s for the considered geonet between two geomembranes

Geonet thickness:

t_g = 4 mm = 0.004 m (assumes one layer)

Leachate impingement rate:

e = 5×10^{-8} m/s (see section 1.2)

Calculations:

Geonet hydraulic conductivity: geonet thickness in meters

$k = \theta/t_g = 2 \times 10^{-5}/0.004 = 5 \times 10^{-3}$ m/s = 0.5 cm/sec

Giroud's equation:

$$T_{max} = 30 \left[\sqrt{4(5 \times 10^{-8})/(5 \times 10^{-3}) + (0.02)^2} - 0.02\right]/(2 \times 0.9998)$$

$$= 0.0146 \text{ m} = 14.6 \text{ mm}$$ > 4 mm (thickness of geonet). = 0.57 inches

greater than drainage layer

This leachate thickness exceeds the geonet thickness, which is 4 mm; one layer of geonet is insufficient. Therefore, try two layers of geonet.

upper geonet keeps filter fabric out of wer geonet.

A hydraulic transmissivity $\theta = 2 \times 10^{-4}$ m^2/s should be used for the lower layer geonet, which is between a geomembrane and a geonet (compared to the upper geonet which is in contact with a geotextile, and for which a hydraulic transmissivity of 2×10^{-5} m^2/s is used). The new value of hydraulic conductivity to consider is:

$$k = \theta/t_g = 2 \times 10^{-4}/0.004 = 0.05 \text{ m/s}$$

Giroud's equation is then used for the lower geonet only, the transmissivity of the upper geonet being negligible compared to that of the lower geonet:

Note: 2 geosynthetics in contact mean must check slope stability and bottom slip also. Can get small friction angles.

$$T_{max} = 30\ [\sqrt{4(5 \times 10^{-8})/0.05 + (0.02)^2} - 0.02]/(2 \times 0.9998)$$

$$= 1.5 \times 10^{-3} \text{ m} = 1.5 \text{ mm}$$ < thickness of 1 geonet.

This calculation assumes 2 geonets and filter fabric on top.

This value being less than 4 mm, it is sufficient to have one layer of geonet not in contact with a geotextile. Therefore, two layers of geonets are needed, one geonet (the upper geonet) in contact with the geotextile filter, and the other between the upper geonet and the geomembrane.

REFERENCES

USEPA, "*Use of Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites*", EPA/530/SW-169, U.S. Environmental Protection Agency, oct 1975, 40 p.

USEPA, "*The Hydrologic Evaluation of Landfill Performance (HELP) Model, Vol. I, User's Guide for Version I*, EPA/530-SW-84-009, U.S. Environmental Protection Agency, Washington, DC, Jun 1984a, 120 p.

USEPA, "*The Hydrologic Evaluation of Landfill Performance (HELP) Model, Vol. II, Documentation for Version I*, EPA/530-SW-84-010, U.S. Environmental Protection Agency, Washington, DC, Jun 1984b, 256 p.

Giroud, J.P., Gross, B.A., and Darrasse, J., "Flow in Leachate Collection Layers", to be published, 1993.

IFAI will soon publish this book

Depth of leachate
Thickness of leachate vs Head

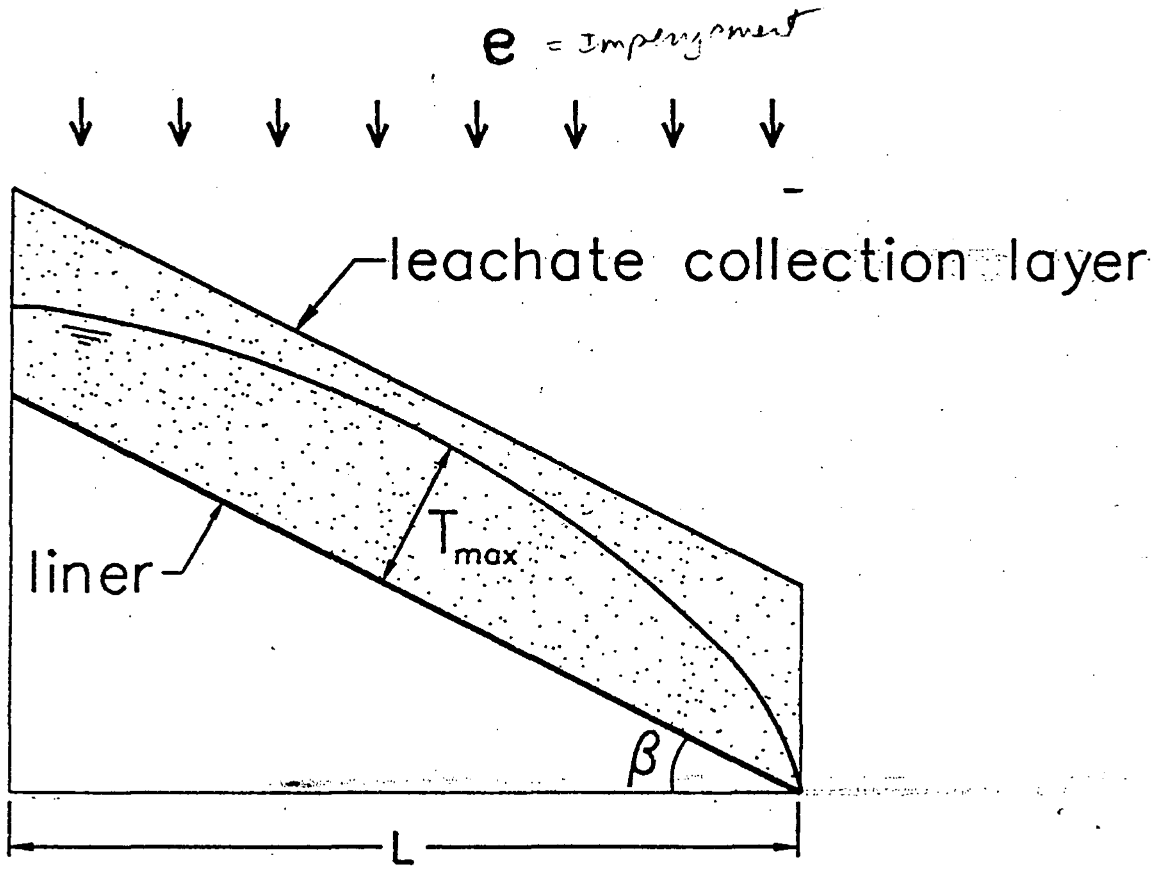


Figure 1. *Leachate Thickness in the Leachate Collection System.*

DESIGN EXAMPLE 3

LEAKAGE EVALUATION

PREPARED BY J.P. GIROUD

1. DESIGN METHOD

1.1 Leakage Mechanisms

There are essentially two mechanisms of leakage through geomembranes [Giroud and Bonaparte, 1989]: fluid permeation through an intact geomembrane and flow through geomembrane holes. Leakage rates due to geomembrane permeation are generally negligible compared to leakage rates due to flow through geomembrane holes. Therefore, only leakage through geomembrane holes is considered in this design example.

With regard to leakage through geomembrane holes, three cases can be considered:

- The geomembrane is overlain and underlain by high-permeability materials (such as geonet or coarse gravel).
- The geomembrane is placed on a layer of low-permeability soil to form a composite liner.
- The geomembrane is placed on a high-permeability material, and is overlain by a sand or a fine gravel (i.e., a medium permeability material).

1.2 Rate of Leakage Through Holes in Geomembrane Overlain and Underlain by High-Permeability Materials

In this design example, a geomembrane "alone" is a geomembrane overlain and underlain by high-permeability materials (such as geonets or coarse gravel). According to Giroud [1984a, 1984b], the rate of leakage through a hole in such a geomembrane can be evaluated using Bernoulli's equation for free flow through an orifice, provided the underlying material has a hydraulic conductivity greater than k_{min} given by:

$$k_{min}\ (m/s) = 10^4\ a\ (m^2)$$
$$k_{min}\ (cm/s) = 100\ a\ (cm^2)$$

where a = area of geomembrane hole.

Bernoulli's equation is as follows [Giroud and Bonaparte, 1989a]:

$$Q = 0.6\ a\sqrt{2gh}$$

where: Q = leakage rate through one geomembrane hole; a = area of geomembrane hole; g = acceleration of gravity; and h = head of liquid on top of the geomembrane. Basic SI units are: $Q(m^3/s)$, $a(m^2)$, $g(m/s^2)$, and $h(m)$.

1.3 Rate of Leakage Through a Composite Liner

The mechanism of leakage through a composite liner with a hole in the geomembrane is as follows: the liquid first migrates through the hole in the geomembrane; the liquid may then travel laterally some distance in the space, if any, between the geomembrane and the low-permeability soil; and finally, the liquid migrates into and eventually through the low-permeability soil. Therefore, the leakage rate depends on the quality of contact between the geomembrane and the low-permeability soil.

For the typical contact conditions encountered in the field, the leakage rate can be calculated from the following empirical equations [Giroud et al., 1989] based on work by Giroud and Bonaparte [1989b]:

$$Q = 0.21\ a^{0.1}\ h^{0.9}\ k_s^{0.74} \quad \text{for good contact}$$

$$Q = 1.15\ a^{0.1}\ h^{0.9}\ k_s^{0.74} \quad \text{for poor contact}$$

where: Q = rate of leakage through one hole in the geomembrane component of a composite liner; a = area of the hole in the geomembrane; h = head of liquid on top of the geomembrane; and k_s = hydraulic conductivity of the low-permeability soil underlying the geomembrane. The above equations are not dimensionally homogeneous; they can only be used with the following units: $Q(m^3/s)$, $a(m^2)$, $h(m)$, and $k_s(m/s)$.

The above equations should be restricted to cases where:

- the hydraulic conductivity of the low-permeability soil is less than 10^{-6} m/s (10^{-4} cm/s); and
- the head of liquid on top of the geomembrane is less than the thickness of the low-permeability soil layer underlying the geomembrane.

The material overlying the geomembrane has no influence on the rate of leakage as long as its hydraulic conductivity is greater than that of the low-permeability soil underlying the geomembrane.

The good and poor contact conditions are defined as follows [Bonaparte et al., 1989]:

- The good contact condition corresponds to a geomembrane installed with as few wrinkles as possible, on top of a low-permeability soil layer that has been adequately compacted and has a smooth surface.

- The poor contact condition corresponds to a geomembrane that has been installed with a certain number of wrinkles, and/or placed on a low-permeability soil that has not been well compacted and does not appear smooth.

These two contact conditions, which can be considered as typical field conditions, are between the two extremes defined as follows:

- *Best Conditions.* The low-permeability soil is well compacted, flat and smooth, has not been deformed by rutting during construction, and has no clods and cracks, and the geomembrane is flexible and has no wrinkles.

- *Worst Conditions.* The low-permeability soil is poorly compacted, has an irregular surface and is cracked, and the geomembrane is stiff and exhibits a pattern of large, connected wrinkles.

1.4 Rate of Leakage Through a Geomembrane Overlain by a Medium-permeability Drainage Material

If a geomembrane resting on a high-permeability material (such as geonet or coarse gravel) is overlain by a medium-permeability drainage material (such as sand or fine gravel), the flow toward the geomembrane hole is impeded by the drainage material, and the flow rate is less than in the case of free flow (i.e., the case when the geomembrane is underlain and overlain by a high-permeability material). A typical field situation is a geomembrane primary liner overlain by a sand leachate collection layer and underlain by a geonet leakage detection and collection layer. An approximate empirical equation for the calculation of the leakage rate is as follows [Bonaparte et al., 1989]:

$$Q = 3\ a^{0.75}\ h^{0.75}\ k_d^{\ 0.5}$$

where: Q = rate of leakage through one geomembrane hole; a = area of the hole in the geomembrane; h = head of liquid on top of the geomembrane; k_d

$$\frac{\pi}{4} D^2 = 1\ cm^2 = A$$

$$\rightarrow D = \sqrt{\frac{4A}{\pi}}$$

$$= 1.13\ cm = .44\ in$$

= hydraulic conductivity of the drainage material overlying the geomembrane. This equation is not dimensionally homogeneous; it can only be used with the following units: $Q(m^3/s)$, $a(m^2)$, $h(m)$, and $k_d(m/s)$.

This equation is applicable only when the hydraulic conductivity of the drainage layer material, k_d, is greater than 10^{-6} m/s (10^{-4} cm/s). Also, the equation should be limited to cases where the head of liquid on top of the geomembrane, h, is less than the thickness of the drainage layer. (This condition is usually fulfilled in the case of landfills.)

1.5 Hole Frequency

Typically one hole per 4000 m^2 (acre) is considered based on work by Giroud and Bonaparte [1989a]. However, any other frequency can be considered by the design engineer.

1.6 Hole Size

Two hole sizes are typically considered:

- 1 cm^2 = 100 mm^2 = 10^{-4} m^2 (0.16 in.^{2}); and
- 2 mm (0.08 in.) in diameter, i.e., 0.031 cm^2 = 3.14 mm^2 = 3 x 10^{-6} m^2 (4.9 x 10^{-3} in.^{2}).

The large hole is typically considered for sizing the leakage collection system, and the small hole for evaluating the performance of lining systems constructed with adequate quality assurance. Any other hole size can be considered by the design engineer.

large hole ⇒ sizing LCS
small hole ⇒ evaluating performance of liner system

2. DESIGN EXAMPLES

2.1 Example 1

- Size of landfill: 2 acres.
- Head on liner: 0.2 mm on slopes and 1.2 mm on the base, as obtained in the design of the leachate collection system (not given here).
- The liner is a geomembrane alone on the slopes and a composite liner at the base of the landfill.
- Hydraulic conductivity of the clay component of the composite liner: 10^{-8} m/s (10^{-6} cm/s).
- The geomembrane is overlain by a geonet on the slopes and at the base of the landfill.
- Holes with a surface area of 1 cm^2 (0.16 $in.^2$) are considered.

<u>Calculations</u>

- <u>Leakage on side slopes</u>

The liner is a geomembrane alone (i.e., overlain and underlain by a very permeable material) and Bernoulli's equation can be used with:

$$a = 1 \times 10^{-4}\ m^2\ (1\ cm^2)$$

$$h = 2 \times 10^{-4}\ m\ (0.2\ mm)$$

Hence:

$$Q = 0.6 \times 10^{-4} \sqrt{2 \times 9.81 \times 2 \times 10^{-4}}$$

$$Q = 3.76 \times 10^{-6}\ m^3/s$$

$$Q = 0.325\ m^3/day = 86\ \text{gallons/day (for one hole)}$$

This is the leakage rate through one hole with a surface area of 1 cm^2.

- Leakage on base

The liner is a composite liner. Assuming that the contact conditions between the geomembrane and the low-permeability soil layer are good, the following equation can be used:

$$Q = 0.21\ a^{0.1}\ h^{0.9}\ k_s^{0.74}$$

with:

$$a = 1 \times 10^{-4}\ m^2 = 1\ cm^2$$

$$k_s = 1 \times 10^{-8}\ m/s$$

$$h = 1.2 \times 10^{-3}\ m\ (1.2\ mm)$$

The leakage rate is given by:

$$Q = 0.21 \times (10^{-4})^{0.1} \times (1.2 \times 10^{-3})^{0.9}\ (10^{-8})^{0.74}$$

$$Q = 2.36 \times 10^{-10}\ m^3/s$$

$$Q = 2.0 \times 10^{-5}\ m^3/day = 5.4 \times 10^{-3}\ \text{gallons/day (for one hole)}$$

It appears that one hole in the slope generates 16,000 times more leakage than one hole through the base. This is because the liner on the slope is a geomembrane alone, while the liner on the base is a composite liner. The effect of the composite liner is to significantly reduce the rate of leakage through a hole in the geomembrane. (Note that neither of the above calculations take into account any additional head caused by liquid ponding which may be due to geomembrane wrinkles.)

- Leakage through the entire liner

Assuming a frequency of one hole per acre, since the lining system surface area is two acres, there are two holes. Assuming conservatively that the two holes are on the slope, the leakage through the top liner is:

$$Q = 2 \times 3.76 \times 10^{-6}\ m^3/s$$

$$Q = 7.5 \times 10^{-6}\ m^3/s = 0.64\ m^3/day = 640\ liters/day$$

$$Q = 170\ gallons/day$$

The leakage rate per unit area is obtained by dividing the above leakage rate by the landfill surface area, 8,000 m^2 = 0.8 hectare (2 acres):

$$Q = 800\ lphd = 85\ gpad$$

(lphd = liters/hectare/day; gpad = gallon/acre/day)

2.2 Example 2

- Size of landfill: 5 acres

- The primary liner of a double liner is a geomembrane alone on the slopes and at the base.

- The geomembrane is underlain by a geonet on the slopes and the base. (The geonet is the leakage collection layer for the double liner.)

- The geomembrane is overlain by a geonet on the slopes and by sand at the base. (The geonet and sand constitute the leachate collection layer material for the double liner.)

- The hydraulic conductivity of the sand is 10^{-5} m/s (10^{-3} cm/s).

- Head on the primary liner: 0.2 mm on slopes and 120 mm on the base.

- A hole size of 10 mm^2 (0.016 in.^{2}) is considered.

<u>Calculations</u>

- Leakage on side slopes

The primary liner is a geomembrane alone overlain and underlain by high-permeability materials. Therefore, Bernoulli's equation can be used. The values of the parameters to be used in Bernoulli's equation are:

$$a = 1 \times 10^{-5}\ \mathrm{m}^2\ (10\ \mathrm{mm}^2),\ \text{i.e., average case}$$

$$h = 2 \times 10^{-4}\ \mathrm{m}\ (0.2\ \mathrm{mm})$$

$$Q = 0.6 \times 10^{-5} \sqrt{2 \times 9.81 \times 2 \times 10^{-4}}$$

$$Q = 3.76 \times 10^{-7}\ \mathrm{m}^3/\mathrm{s}$$

$$Q = 8.6\ \text{gallons/day (for one hole)}$$

This is the leakage rate through one hole with a surface area of 10 mm^2.

- Leakage on base

The primary liner is a geomembrane alone which is overlain by a medium-permeability drainage material (sand) and underlain by a high-permeability material (geonet). The leakage rate through one hole in the geomembrane can be calculated using the following equation:

$$Q = 3\ a^{0.75}\ h^{0.75}\ k_d^{0.5}$$

with:

$$a = 1 \times 10^{-5}\ m^2 = 10\ mm^2$$

$$k_d = 1 \times 10^{-5}\ m/s$$

$$h = 0.12\ (120\ mm)$$

The leakage rate is given by:

$$Q = 3 \times (10^{-5})^{0.75} \times (0.12)^{0.75} \times (10^{-5})^{0.5}$$

$$Q = 3.44 \times 10^{-7}\ m^3/s$$

$$Q = 7.85\ \text{gallons/day (for one hole)}$$

- Leakage through the entire liner

Assuming a frequency of one hole per acre, since the lining system surface area is five acres, there are five holes. Assuming that two holes are on the slope and three holes are at the base, the rate of leakage through the top liner is:

$$Q = 2 \times 3.76 \times 10^{-7} + 3 \times 3.44 \times 10^{-7}$$

$$Q = 1.78 \times 10^{-6}\ m^3/s = 154\ \text{liters/day}$$

$$Q = 40.7\ \text{gallons/day}$$

The leakage rate per unit area is obtained by dividing the above leakage rate by the landfill surface area, 20,000 m^2 = 2 hectares (5 acres):

$$Q = 77 \text{ lphd} = 8.1 \text{ gpad}$$

(lphd = liters/hectare/day; gpad = gallon/acre/day)

REFERENCES

Giroud, J.P., "Impermeability: The Myth and a Rational Approach", *Proceedings of the International Conference on Geomembranes*, Vol. 1, Denver, CO, Jun 1984, pp. 157-162. [1984a]

Giroud, J.P., "*Geotextiles and Geomembranes. Definitions, Properties and Design*", IFAI Publishers, 1984, 325 p. [1984b]

Bonaparte, R., Giroud, J.P., and Gross, B.A., "Rates of Leakage Through Landfill Liners", *Proceedings of Geosynthetics '89* Conference, San Diego, CA, Vol. 1, 1989, pp. 18-28.

Giroud, J.P. and Bonaparte, R., "Leakage through Liners Constructed with Geomembranes, Part I: Geomembrane Liners", *Geotextiles and Geomembranes*, Vol. 8, No. 1, 1989, pp. 27-67. [1989a]

Giroud, J.P. and Bonaparte, R., "Leakage through Liners Constructed with Geomembranes, Part II: Composite Liners", *Geotextiles and Geomembranes*, Vol. 8, No. 2, 1989, pp. 71-111. [1989b]

Giroud, J.P., Khatami, A., and Badu-Tweneboah, K., "Evaluation of the Rate of Leakage through Composite Liners", *Geotextiles and Geomembranes*, Vol. 8, No. 4, 1989, pp. 337-340. [1989]

DESIGN EXAMPLE 4

must not allow drainage layer to flow full.

LEAKAGE COLLECTION LAYER

PREPARED BY J.P. GIROUD
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1. DESIGN METHOD

The purpose of this design example is to size the leakage collection and detection layer located between the two liners of a double liner. The rate of leakage through a hole of the primary liner is assumed to be known. Assume that the collected leakage will flow over a width B of the leakage detection layer. This width B can be arbitrarily chosen between 1 and 5 m (3 and 16 ft.). Then, calculate the flow thickness as follows:

" δ "

This could be used to estimate head on bottom of double liner for leakage calculations

$$D = \frac{Q/B}{k \sin\beta} \qquad \text{(Equation 1)}$$

liquid flow thickness

where: D = flow thickness; Q = flow rate; B = flow width; k = hydraulic conductivity of the drainage medium; and β = slope. Basic SI units are: D (m); Q (m^3/s), B (m), k (m/s), and β (degrees).

Thus This liner

It is then necessary to verify that the flow thickness, D, is less than the thickness of the leakage detection layer or 0.3 m (1 ft), whichever is smaller, to ensure a small head on the secondary liner.

If the leakage detection layer is characterized by its hydraulic transmissivity, the above equation becomes:

$$\frac{D}{T} = \frac{Q/B}{\theta \sin\beta} \qquad \text{(Equation 2)}$$

where: D = flow thickness; T = thickness of the drainage layer; Q = flow rate; B = flow width; θ = hydraulic transmissivity of the drainage layer; and β = slope. Basic SI units are: D (m), T (m), Q (m^3/s), B (m), θ (m^2/s), and β (degrees).

The above equation is particularly useful for geonets. It is used to verify that D/T < 1 or D < 0.3 m, whichever value of D is smaller.

Leak detection time is the time leakage takes to travel from the leak to the nearest collection sump. In this design example, it is assumed that steady-state conditions exist in the leakage detection layer. The steady-state leakage detection time is given by Giroud and Bonaparte [1992]:

$$t_{sL} = n_L L_L/(k_L \sin \beta_L) \qquad \text{(Equation 3)}$$

where: t_{sL} = steady-state leakage travel time in a leakage detection layer; n_L = porosity of the leakage detection layer; L_L = length of the leakage path in the leakage detection layer; k_L = hydraulic conductivity of the leakage detection layer material; and β_L = slope of the leakage detection layer along the leakage path. Basic SI units are: t_{sL}(s), L_L(m); k_L(m/s), and β_L(degrees); n_L and β_L are dimensionless.

The above equation considers only the time during which leakage flows in the leakage collection layer. The time spent by leakage in pipes is not included. A maximum steady-state leak detection time of 24 hours is typically required.

Since the location of leaks is not known, it is conservative to use for L_L the maximum distance between a leak and a collection sump.

2. DESIGN EXAMPLE

Given

The top liner has two holes located near the toe of the side slopes. The leakage rate through each hole is 3.76 x 10^{-6} m^3/s (85 gallons/day). The base slope is 3%. A geonet with a hydraulic transmissivity of 5 x 10^{-4} m^2/s is considered. For leak detection time calculations, a maximum distance of 30 m (100 ft) between hole and collector pipe is considered.

Calculations

Assume a flow width B = 1.5 m (5 ft) and conservatively assume that the two holes are next to each other.

$$\frac{D}{T} = \frac{2 \times 3.76 \times 10^{-6}/1.5}{5 \times 10^{-4} \times 0.03}$$

$$\frac{D}{T} = 0.33$$

The flow thickness is one third of the geonet thickness; in other words, the factor of safety is 3.

To calculate the leak detection time, it is necessary to know the porosity and the hydraulic conductivity of the geonet. A value of 0.8 can be assumed for the porosity. The hydraulic conductivity can be obtained by dividing the hydraulic transmissivity by an assumed thickness of 4 mm as follows:

$$k = \theta/t_g$$

$$k = 5 \times 10^{-4} / 4 \times 10^{-3}$$

$$k = 0.125 \text{ m/s}$$

The leak detection time is then given by Equation 3 as follows:

$$t_{SL} = 0.8 \times 30/(0.125 \times \overset{0.03}{0.\cancel{02}})$$

$$= \overset{6400}{\cancel{9600}} \text{ s} = \overset{1.8}{\cancel{2.7}} \text{ hours}$$

This time is less than 24 hours and is, therefore, acceptable.

REFERENCES

Giroud, J.P. and Bonaparte, R., "*Design and Performance of Geosynthetic Lining System for Waste Conatinment*", book to be published by IFAI, 1992.

