ANNEXURE B- DESIGN CALCULATIONS

Checked by:

The protection layer needs to be anchored adequately to resist activating forces. Reinforcement is permanent and the number and type of reinforcement (if required) is determined by the following:

a) The base material (i.e. the embankment) density;
b) The material of infilling and its unit weight;
c) Length of slope;
d) Slope gradient;
e) Angle of internal friction of the fill material and of the slope soil (the smaller of the two is used),
f) Height / Depth of LCS
g) Presence of geomembrane liner (if any).

The mechanism of driving and resisting forces for a geocell protected slope is shown in Fig 1.

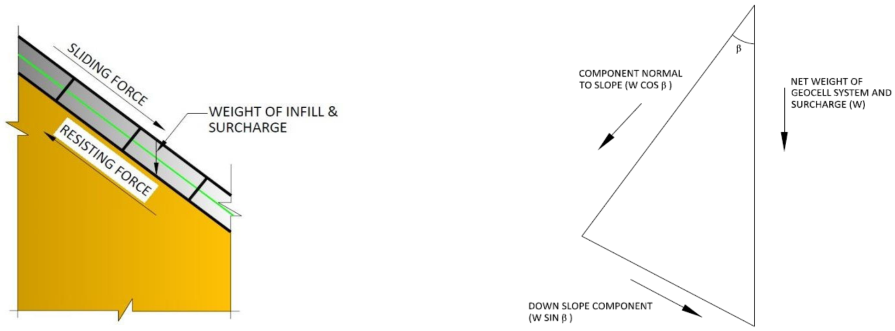


Fig. 1: Mechanism of driving and resisting forces for stability analysis in infinite slope

Before selecting an reinforcement method, the net sliding force (NSF), or the force that would have to be overcome to keep the slope from sliding along the failure plane with a safety factor, is determined. If the NSF is negative, then the friction force between the overburden and the liner and the slope is sufficient to hold the system in place.

Note that all friction angles used below are minimum residual values from lab testing, conducted under saturated conditions

$Net\ Sliding\ Force =$ $\{[d \times Ls \times \gamma] \times [(sin\beta) - (cos\beta \times tan\varphi)]\}$

FORCE CALCULATION

d - Depth of the overburden layer (m)		0.25
Ls - Inclined length of the Slope (m)		13.6
- Unit weight of the overburden (kN/m^3)		20
ß - Slope angle (°)		18.43
ø - Lowest value of angle of interface friction (°) (GMB-Smth vs. PROT)		20
Factor of Safety against Sliding		1
$d \times Ls \times \gamma$		68.00
$sin\beta$		0.32
$cos\beta$		0.95
$tan\varphi$		0.36
NSF (KN/m width)		**-1.98**
Ultimate Sliding Force (KN/m width)		**-1.98**

FOS CALCULATION

Driving Force	21.50	kN/m
Resisting Force	23.48	kN/m
FOS	1.092	

RESULT:

The Slope does not require reinforcement to be stable, when analysing the inteface between the protection layer & geomembrane below. The calculation also assumes that the geocell will not carry any tensile load, exludes the interlocking nature of the geocell blocks and does not take account of the cementious nature of the soilcrete which is conservative.

Geocell Tensile Properties

Geocell ultimate tensile strength (KN/m)	26
Tendon strength reduction factor	1.5
Tendon allowable tensile strength (KN)	17.33
FOS	-8.770

Lafarge: Additives and Coal Stockyard Pollution Control Dams **Lafarge**
GMB and GCL

LCS needs to be anchored adequately to resist activating forces. This is key to performance of the LCS.
Reinforcement is permanent and the number and type of reinforcement is determined by the following:

a) The base material (i.e. the embankment) density;
b) The material of infilling and its unit weight;
c) Length of slope;
d) Slope gradient;
e) Angle of internal friction of the fill material and of the slope soil (the smaller of the two is used),
f) Height / Depth of LCS
g) Presence of geomembrane liner (if any).
The mechanism of driving and resisting forces for a geocell protected slope is shown in Fig 1.

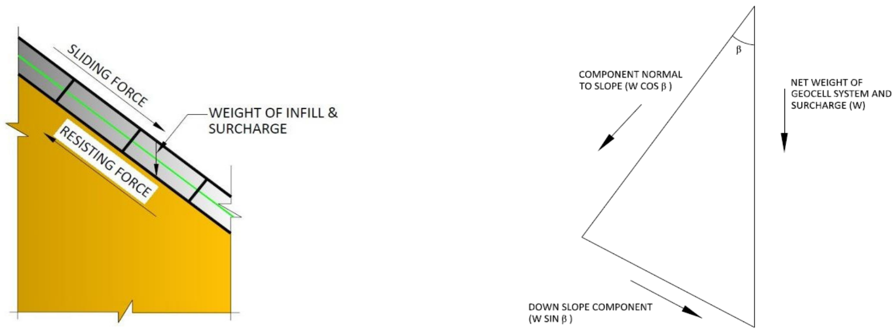


Fig. 1: Mechanism of driving and resisting forces for stability analysis in infinite slope

Before selecting an reinforcement method, the net sliding force (NSF), or the force that would have to be overcome to keep the slope from sliding along the failure plane with a safety factor, is determined. If the NSF is negative, then the friction force between the overburden and the liner and the slope is sufficient to hold the system in place.

Note that all friction angles used below are minimum residual values from lab testing, conducted under saturated conditions

Net Sliding Force = **$\{[d \times Ls \times \gamma] \times [(\sin\beta) - (\cos\beta \times \tan\varphi)]\}$**

FORCE CALCULATION

d - Depth of the overburden layer (m)		0.25
Ls - Inclined length of the Slope (m)		13.6
- Unit weight of the overburden (kN/m^3)		20
ß - Slope angle (°)		18.43
ø - Lowest value of angle of interface friction (°) (GMB-Tex vs. GCL)		15
Factor of Safety against Sliding		1
$d \times Ls \times \gamma$		68.00
$\sin\beta$		0.32
$\cos\beta$		0.95
$\tan\varphi$		0.27
NSF (KN/m width)		**4.22**
Ultimate Sliding Force (KN/m width)		**4.22**

FOS CALCULATION

Driving Force	23.48	kN/m
Resisting Force	17.29	kN/m
FOS	0.736	

1.5mm Geomembrane

GMB ultimate tensile strength (KN/m)		22
Tendon strength reduction factor		1.5
Tendon allowable tensile strength (KN)		14.67
	FOS	3.477

RESULT:

The Geomembrane Layer may take the veneer load due to the lower angle of friction between the GM and the GCL, however if there is load transfer through, or if the GTX interface properties were higher then 15 degrees, then the specified geomembrane would be required to take load. For this scenario to occur, a complete failure of the protection layer would have had to occur, with the soilcrete layer and the geocell sliding , which is very unlikely, given the interlocking nature of the geocell and soilcrete infill. This check does however show that the geomembrane has sufficient capacity to prevent failure, in this unlikely scenario.

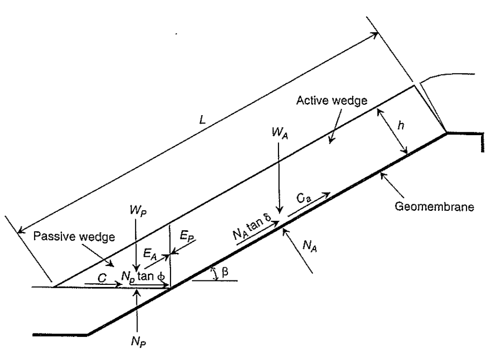
LAFARGE ADDITIVES AND COAL STOCKYARD PCDs
VENEER SOIL COVERS DESIGN

PROJECT IDENTIFICATION	
Title	Lafarge Additives and Coal Stockyard Pollution Control Dams
Project number	5707
Client	Lafarge Lichtenburg
Designed	MM
Checked	JN
Approved	JN

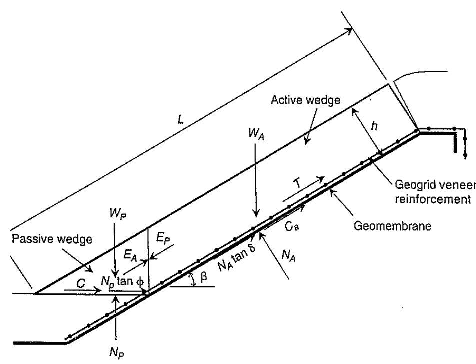
DESCRIPTION
Veneer Reinforcement Calculations for Protection Layer on 1:3 Embankments.

COMPANY'S INFORMATION	
Name	Lafarge Lichtenburg

Ref. Designing with Geosynthetics - 5th edition - Robert M Koerner 3.2.7 pag 380-383
Whenever a slope is covered with soil, a stability calculation should be made to assess the potential for sliding failure of the soil on the barrier layer.Four situations come to mind: landfill liners with leachate collection sand or gravel above them until such time that the solid waste acts as a passive resistance restraint; surface impoundment liners where the cover soil is placed over the geomembrane to shield it from ultraviolet light, heat degradation, and equipment damage; landfill covers that have topsoil and protection soil placed over the geomembrane; and general slopes and embankments containing geotextiles or erosion control materials being covered with a layer of soil. In all cases the soil layer is relatively thin (0.3 to 1.0 m), hence the sliding stability of such a veneer of cover soil is the issue.



(a) Without reinforcement



(b) With the use of geogrid veneer reinforcement

WA = total weight of the active wedge,
WP = total weight of the passive wedge,
NA = effective force normal to the failure plane of the active wedge,
NP = effective force normal to the failure plane of the passive wedge,
γ = unit weight of the cover soil,
h = thickness of the cover soil,
L = length of slope measured along the geomembrane,
β = soil slope angle beneath the geomembrane,
φ = friction angle of the cover soil,
δ = interface friction angle between cover soil and geomembrane,
Ca = adhesive force between cover soil of the active wedge and the geomembrane,
ca = adhesion between cover soil of the active wedge and the geomembrane,
C = cohesive force along the failure plane of the passive wedge,
c = cohesion of the cover soil,
EA = interwedge force acting on the active wedge from the passive wedge,
EP = interwedge force acting on the passive wedge from the active wedge, and
FS = factor of safety against cover soil sliding on the geomembrane.

DESIGN INFORMATION			
SYMBOL	VALUE	UNIT	DESCRIPTION
γ	20	kN/m^3	unit weight of cover soil (soilcrete)
ϕ	42.00	deg	friction angle of the cover soil
c	20	kpa	cohesion of the cover soil
h	0.25	m	thickness of the cover soil
β	13.60	°	soil slope angle
L	24	m	length of the slope
c_a	0		adhesion between cover soil of the active wedge and geomembrane
δ	20	°	interface friction angle between GTX and smooth geomembrane

WITHOUT REINFORCEMENT			
SYMBOL	VALUE	UNIT	DESCRIPTION
Wa	114.8	kN/m^3	total weight of the active wedge
Na	111.6	kN	effective force normal to the failure plane of the active wedge
Ca	0.0	kN	adhesive force between cover soil and gsy
Wp	2.7	kN/m^3	total weight of the passive wedge
C	21.3	kN	cohesive force along the failure plane of the passive wedge
a	6.2		n/a
b	-16.2		n/a
c	2.0		n/a

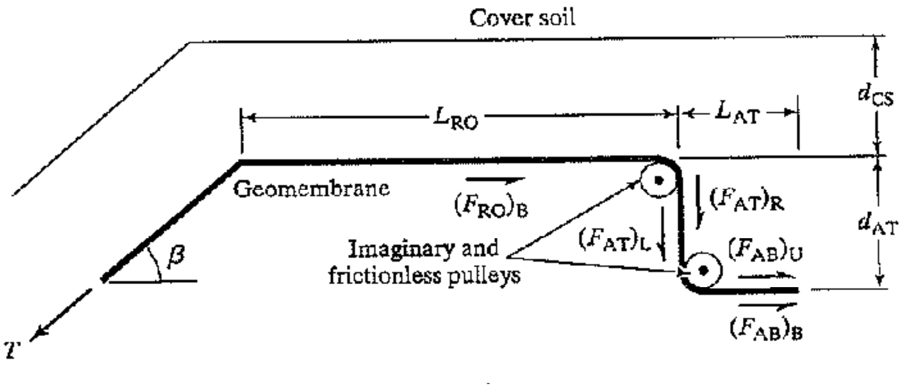
$FoS_{unreinf}$	**2.49**

The slope is safe from sliding block failure, without reinforcement.

Calculations below show the FOS against sliding failure, as well as anchor trench requirements accounting for the protection geotextiles anchorage needs to mobolise the necessary tension.

LAFARGE ADDITIVES AND COAL STOCKYARD PCDs ANCHOR

TRENCH DESIGN



Ref. Geotechnical Aspects of landfill design and construction - X. Qian, R.M. Koerner, D. H. Gray - par. 4.7.2

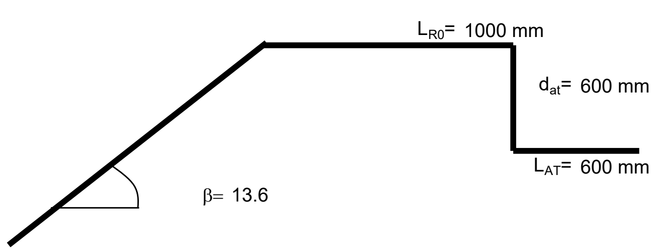
DESIGN INFORMATION

SYMBOL	VALUE	UNIT	DESCRIPTION
β	13.60	°	side slope angle
d_{cs}	0.25	m	thickness covering soil
γ_{soil}	20	kn/m^3	weight of soil
d_{at}	0.6	m	trench depth
L_{R0}	1	m	length of geosynthetic runout
L_{AT}	0.6	m	length of geosynthetic inside the trench
ϕ_{soil}	20	°	trench soil friction angle
δ_C	15	°	friction angle between the geosynthetics and the underlying soil
δ_F	20	°	friction angle between the geosynthetic and the backfill soil
Tuts	22	kN/m	Ultimate tensile strengh of the geosynthetic
RF	2		Reduction factor ($RF=RF_{cr}xRF_{id}xRF_{env}xFS$)
Tall	11.00	kN/m	Allowable tensile strength

RESULTS

SYMBOL	VALUE	UNIT	DESCRIPTION
$(F_{R0})_B$	2.76	KN/m	friction force beneath runout geosynthetics
$(F_{AT})_R$	1.58	KN/m	friction force between the right side of the geosynthetic and the side wall of ancho trench
$(F_{AT})_L$	1.16	KN/m	friction force between the left side of the geosynthetic and the side wall of anchor trench
$(F_{AB})_B$	2.73	KN/m	friction force between the right side of the geosynthetics and the underlying soil at the botton of anchor trench
$(F_{AB})_U$	3.71	KN/m	friction force between the right side of the geosynthetics and the overlying soil at the botton of anchor trench
T_{MAX}	10.05	KN/m	geosynthetic tensile force developed by the anchor trench
T_D	4.70	KN/m	geosynthetic design tensile force

FoS (T_{MAX}/T_D)	**2.14**



GEOTEXTILE PROTECTION LAYER (FOR GEOMEMBRANE)
DESIGN CALCULATIONS

Protection of the geomembrane for strains induced by large sized particles, of particular concern during the installation of a geomembrane.

This may occur either:

(a) When a a stone or pebble is left on top of the GCL below a geomembrane in a composite lining system, and large isolated particles have found there way onto the surface of the GCL. BELOW CASE
OR/.

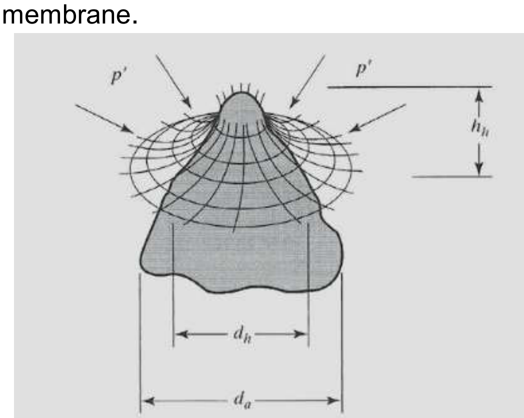
(b) When a stone layer is used above a geomembrane, or when a cushioning layer has large or oversized particles as part of its make-up. ABOVE CASE

1) For the BELOW CASE

Where there is a GCL, Koerner (2012) supported by Yu, Rowe (2018) and Brachman (2008; 2010) support the use of careful quality control when installing the geomembrane, with the isolated stones needing to be physically removed from the GCL prior to final placement. The CQA and material specification has been carefully worded to include this as part of the installation process and is to be monitored carefully on site.

There is 0% tolerance for particles over 15mm in diameter, oversized particles are to be removed prior to geomembrane placement.

A design check is conducted based on Koerner (2012) to check the ability of the geomembrane to resist puncture forces under the design loading. Figure 1 below provides a visual representation of the deformation imparted in the geomembrane under load with a sharp object protruding into the membrane.



$$F_{reqd} = p' \cdot {d_a}^2 \cdot S_1 \cdot S_2 \cdot S_3$$

Figure 1: Stone puncturing geomembrane by Koerner (2012)

GEOTEXTILE PROTECTION LAYER (FOR GEOMEMBRANE)
DESIGN CALCULATIONS

Where:

F_{req} = required vertical puncturing force to be resisted
d_a = average diameter of the puncturing aggregate
p' = pressure exerted on the geomembrane
S1 = Protrusion factor of the puncturing object
S2 = Scale factor to adjust the ASTM D4833 puncture test value that uses 8.0mm diameter puncture problem to the d_a specified
S3 = Shape factor to adjust the ASTM D4833 flat puncture probe to the actual shape of aggregate

Table 2.9 from Koerner (2012) provides recommended values for puncture analysis (i.e. S1, S2 and S3 values) for different aggregate shapes and sizes. Table 2.9 is reproduced below:

Puncturing Object	S1	S2	S3
Angular and Large	0.9	0.8	0.9
Angular and Small	0.6	0.6	0.7
Sub-Rounded and Large	0.7	0.6	0.6
Sub-Rounded and Small	0.4	0.4	0.5
Rounded and Large	0.5	0.4	0.4
Rounded and Small	0.2	0.2	0.3

NOTE:
in excess of 25mm is considered large

1.1) DESIGN CALCULATION

The max. design pressure on the 1.5mm geomembrane is 52 kPa.
Assuming a 20mm stone is left within the GCL by accident:

$$F_{reqd} = p' \cdot {d_a}^2 \cdot S_1 \cdot S_2 \cdot S_3$$

$$F_{reqd} = 52 \cdot 1000 \cdot (0.0020)^2 \cdot 0.9 \cdot 0.8 \cdot 0.9$$

$$F_{reqd} = 21.06\ N$$

(R1) 21.06 N

Puncture Resistance of a 1.5mm/2mm Geomembrane meeting GRI -GM13 is: 480 N / 640 N — **See GRI-GM13** Table 1(b)

FOS against PUNCTURE (1.5mm HDPE) = 11.40 **SAFE**

This is an accidental case design ensuring that the geomembrane will not be punctured should after the CQA, something be missed.

GEOTEXTILE PROTECTION LAYER (FOR GEOMEMBRANE)
DESIGN CALCULATIONS

1.2) GEOMEMBRANE STRAIN CALCULATION

For a GRI-GM13 compliant, 1.5mm thick membrane:

Min Yield Strength:	22 kN/m	as per ASTM
Min Yield Elongation:	12 %	D 6693

Based on ASTM D 6693, the gage length of a sample is 33mm therefore
a 12% strain at 22kN load equates to a deflection of 3.96 mm

Calculating the Secant Modulus at yield therefore equates to:

$$E_s = {\sigma_y}/{\delta_y}$$

$$E_s = {22\ 000}/{0.00396}$$

$$E_s = 5.55\ MPa$$

As Geomembrane behave ELASTICALLY AND THEN plastically as it approaches yield
lower then what would be expected at 2 to 3% strains, with Brachman &
Gudina (2008) reporting Secant Moduli of between 240 and 310 MPa at 2%
strain across various products available on the market. However, as the
GRI-GM3 does not require or stipulate this requirement, the calculated Es
has been used in the calculation to be conservative.

Based on the calculated force imparted onto the secondary geomembrane
based on the worst case loading conditions [See value (R1) calculated above]
The following strain would be imparted into the geomembrane:

$$\delta_F = {\sigma_F}/{E_s}$$

$$\delta_F = {21.06\ N}/{5.55 \times 10^6\ N/m}$$

$$\delta_F = 2.04 \times 10^{-5}\ m$$

$$\delta_F = 0.00204\ mm/1.5\text{mm (thick membrane)}$$

$$\boldsymbol{\varepsilon_F = 0.25}\%$$

ε = 2.53E-01

With a geomembrane strain not exceeding 0.25% under the design loading
the design loading can be considered to be safe even in the accidental design case

GEOTEXTILE PROTECTION LAYER (FOR GEOMEMBRANE)
DESIGN CALCULATIONS

2) For the ABOVE CASE

In order to effectively protect the geomembrane from large sized stones, debris and light traffic loads a protection layer (geocell with soilcrete infill) has been specified.
No drainage layer is required as the facility is designed to store liquids above the Class C liner

However, choosing a non-woven geotextile with sufficient mass per m^2 becomes critical to provide sufficient protection to the geomembrane, if used in place of the 100mm sandy silt protection layer as defined in Type C Landfill Liner as per GNR 636.

Based on a number of ASTM 5514 experiments conducted by Wilson-Fahmy, et al. (1996) Narejo et al. (1996), and Koerner et al. (1996) based on a limit state approach, an empirical relationship was developed to show relative performance and protection of a geotextile when used to protect a geomembrane.
This is supported by work by Brachman & Guidana (2008) as well as Yu & Rowe (2018).

The Koerner Equation is as follows:

$$p_{allow} = \left(50 + 0.000045\,\frac{M}{H^2}\right)\left[\frac{1}{MF_s \times MF_{PD} \times MF_A}\right]\left[\frac{1}{RF_{CR} \times RF_{CBD}}\right]$$

Where:		Used in Calcs:
p_{allow} =	allowable pressure (kPa)	**155 kPa** as below Appx 1
M =	geotextile mass per unit area (g/m^2)	Solve for
H =	protrusion height (m)	**20mm**
MF_S =	modification factor for protrusion shape	1 (Angular)
MF_{PD} =	modification factor for packing density	**1.0** (Isolated)
MF_A =	modification factor for arching in solids	**1.00**
RF_{CR} =	reduction factor for long term creep	**1.5**
RF_{CBD} =	reduction factor for long term chemical/biological degradation	**1.1** (Mild Leachate)
FOS =	factor of safety against failure	**2.0**

Note: Modication Factors adopted based on Koerner (2012)

1.00	0.59171598
0.59	34.35
	37.40

$$155 = \left(50 + 0.00045\left(\frac{M}{(0.022)^2}\right)\right)\left[\frac{1}{1.0 \times 1.0 \times 1.0}\right]\left[\frac{1}{1.5 \times 1.1}\right]$$

Solving for M: M (g/m^2) = 183.5

Therefore at minimum **600 g/m^2 geotextile would be required** to completely remove the need for a 100mm silty sand cushioning layer

CHECKED BY:
JC Norris

3) REFERENCES

1) **Brachman, R.W.I., Gudina, S., (2008)**. Geomembrane strains from coarse gravel and wrinkles in a GM/GCL composite liner. Geotext. Geomembranes 26 (6), 488–497.

2) **Brachman, R.W.I., Sabir, A., (2010)**. Geomembrane puncture and strains from stones in an underlying clay layer. Geotext. Geomembranes 28 (4), 335–343.

3) **Wilson-Fahmy, R.F., Narejo, D., and Koerner R.M., (1996)**. " Puncture Protection of Geomembranes. Part I: Theory," *Geosynthetics Int.,* Vol. 3, No. 5, 1996, pp. 605-628.

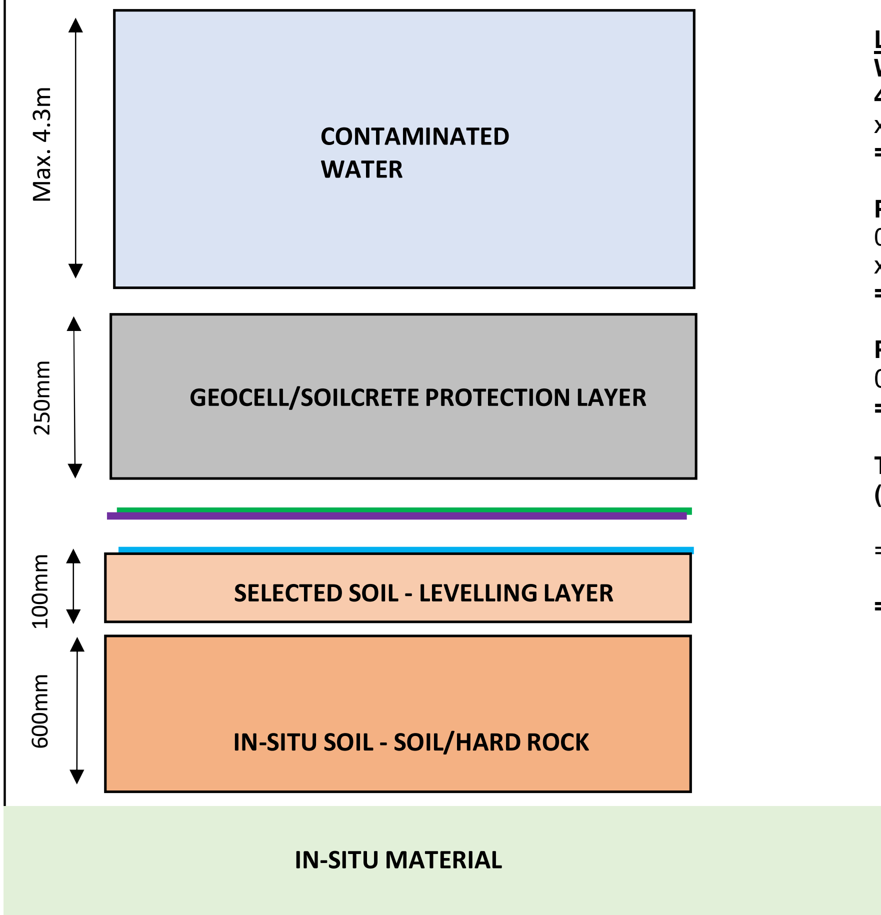
4) **Narejo, D., and Koerner R.M., Wilson-Fahmy, R.F., (1996)**. " Puncture Protection of Geomembranes. Part II: Experimental," *Geosynthetics Int.,* Vol. 3, No. 5, 1996, pp. 629-653.

5) **Koerner R.M., Wilson-Fahmy, R.F., and Narejo, D., (1996)**. " Puncture Protection of Geomembranes. Part III: Examples," *Geosynthetics Int.,* Vol. 3, No. 5, 1996, pp. 655-676.

6) **Koerner, R.M, (2012)**. Designing with Geosynthetics, Volume 1 and 2. Published 2012 by Xlibris, New York, USA. ISBN 978-1-4628-8289-2

GEOTEXTILE PROTECTION LAYER (FOR GEOMEMBRANE)
DESIGN CALCULATIONS

APPENDIX 1: LOAD CALCULATIONS



LOAD CALC

WATER
4.3m x 1000 kg/m3
x 9.81/1000
= 42.183 kN/m^2

PROTECTION LAYER
0.25 x 2000 kg/m3
x 9.81/1000
= 4.905 kN/m^2

PROTECT GTX
0.6kg/m^2 x 9.81/1000
= 0.006 kN/m^2

TOTAL LOAD ON GMB (WC)

= 47 kPa x 1.1 FOS

=52 kPa

Where:

- Is a 600 g/m2 GEOTEXTILE PROTECTION LAYER ON THE BASIN FLOOR ONLY
- Is a 1.5mm HDPE SMOOTH-SMOOTH GEOMEMBRANE (SMOOTH-TEXTURED ON SIDE SLOPES)
- Is a 4500 g/m2 GEOSYNTHETIC CLAY LINER

LAFARGE- POLLUTION CONTROL DAMS LINING DESIGN BASED ON TYPE C BARRIER (GNR 636)

COMPLETED BY:
M Muvhali

GEOMEMBRANE TENSILE STRAIN (ON SLOPE)
DESIGN CALCULATIONS

1) INTRODUCTION
In order to ensure the stability of the geomembrane and limit tensile strains developing in the geomembrane; as well as the entire composite lining system on sloped areas of the cell, a slope stability assessment is conducted as follows:

VENEER REINFORCEMENT CHECK

Due to the fact that the lining system contains a number of potentially critical interfaces with different shear strengths at each interface, each must be modelled as part of the 1) and 2) check to ensure that the lining system will not slip when used in a sloping application.

2) IDENTIFYING CRITICAL INTERFACES

As noted by Koerner (2012), multi-lined side slope soil stability is complex as the liner protection layer particularly when the facility is empty, gravitationally induce shear stress through the multi-lined system. However, Koerner further notes that if all interface shear strengths are greater then the slope angle, stability is achieved and the only deformation involved is a small amount to achieve elastic equilibrium. This is supported by studies by Wilson-Fahmy et. Al (1996), Dixon & Jones (2003a and b), and Giroud & Beech (1989)

For the Additives and Coal Stockyard PCDs Design, the slopes are uniform around the facility at a grade of 1V:3H, with the exception of the access ramp which has a grade of 1V:12H and the retaining wall for the Coal Stockyard PCD which has been analysed for stability, see Pages 56-58 of the Preliminary Design report.
The steepest slope is therefore:

	MAX. SLOPE			
	%	Grade (H)		Deg (°)
Additives PCD	33.33	1V :	3.0	18.43
Coal Stockyard PCD	33.33	1V :	3.0	18.43

In principle therefore, if the lowest interface friction between materials is above 18.43°, then the slope will be stable once placed, across all interface layers without mobilising the membrane in tension

CHECKED BY:
JC Norris

GEOMEMBRANE TENSILE STRAIN (ON SLOPE)

DESIGN CALCULATIONS

LOAD CALC - DRY

WATER
0 m x 1000 kg/m³
x 9.81/1000
= 0 kN/m²

PROTECTION LAYER
0.25 x 2000 kg/m³
x 9.81/1000
= 4.905 kN/m²

PROTECT GTX
0.6 kg/m² x 9.81/1000
= 0.006 kN/m²

TOTAL LOAD ON GMB

= 5 kPa x 1.1 FOS

= 5.5 kPa

LOAD CALC - WET

WATER
4.3 m x 1000 kg/m³
x 9.81/1000
= 42.183 kN/m²

PROTECTION LAYER
0.25 x 2000 kg/m³
x 9.81/1000
= 4.905 kN/m²

PROTECT GTX
0.6 kg/m² x 9.81/1000
= 0.006 kN/m²

TOTAL LOAD ON GMB

= 47 kPa x 1.1 FOS

= 51.8 kPa

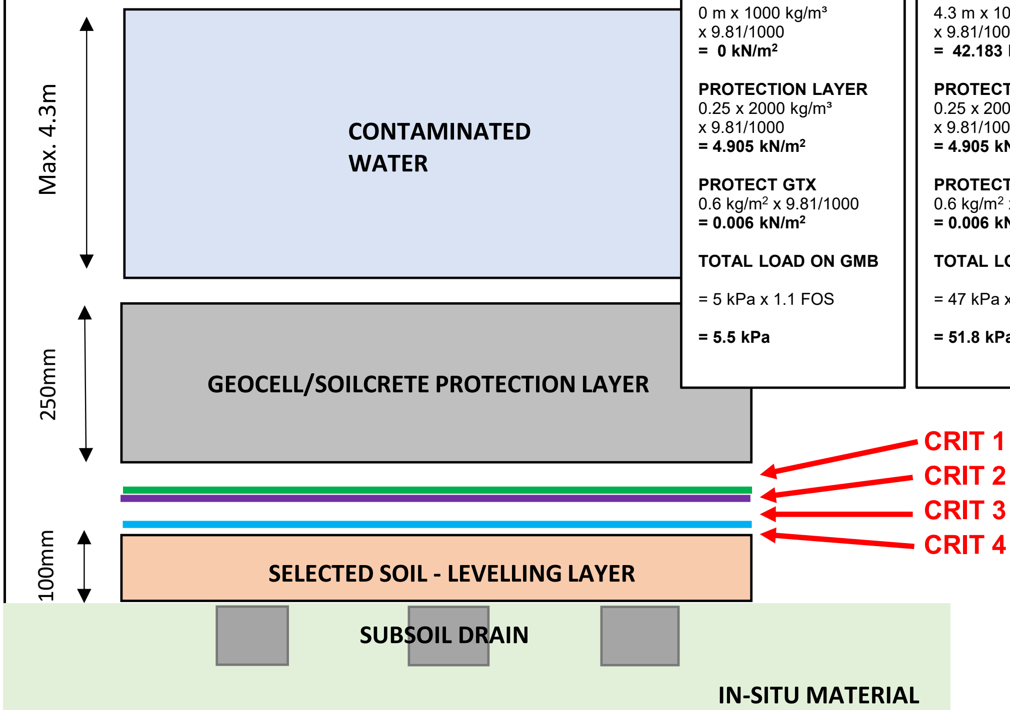


Figure 1: Identification of Critical Interfaces

Where:

- (green line) Is a 600 g/m² NON-WOVEN PROTECTION GEOTEXTILE (NWPG)
- (purple line) Is a 1.5mm HDPE SMOOTH-TEXTURED GEOMEMBRANE
- (blue line) Is a 4500 g/m2 GEOSYNTHETIC CLAY LINER

CHECKED BY:
JC Norris

GEOMEMBRANE TENSILE STRAIN (ON SLOPE)
DESIGN CALCULATIONS

The critical interfaces are identified above in Figure 1, and highlighted below:

Table 1: Identification of Critical Interfaces & Properties

			Interface Properties		
ID	Layer Above	Layer Below	ø' (°)	c' (kPa)	
1	Soilcrete	600 g/m² NWPG	20	0	
2	600 g/m² NWPG	1.5mm GMB - SMTH	11	5	
3	1.5mm GMB - TXTRD	GCL	16	10	Using Residual Values
4	GCL	Base Prep	18	5	Using Residual Values
5					
6					

Note: The Grading Curves & Permeability Test Results for the following layers are available in the appendices as listed below:

	GRADING			Shear Properties		Perm. (cm/s)
Layer	Gravel (%)	Sand, Silt (%)	Clay (%)	φ°	c' (kPa)	
	13-6mm	6-0.075mm	<0.075			
Soilcrete	0	100	0	42	10	N/A
Base Prep	0	44	53	29	19.5	2.65E-09

It is critical that interface frictions between different materials are confirmed via laboratory testing, and used in the design calculations

Compliant materials with industry standards as well as regulations were sourced and used as part of the testing regime with the properties ascertained recorded in the tables above, with the test records attached as appendices to this calculation
These values were then used in the design calculations that follow in Section 3.

3) DESIGN CALCULATIONS

Over and above conducting traditional slope stability analysis using software additional checks on the mobilisation of forces within the geosynthetic materials was conducted.

This was calculated for critical geosynthetic interface, using the interface friction properties acquired from lab testing.

GEOMEMBRANE TENSILE STRAIN (ON SLOPE)

DESIGN CALCULATIONS

Koerner (2012) has analysed the general situation through use of limit equilibrium and a finite slope model, as shown in the Figure below.

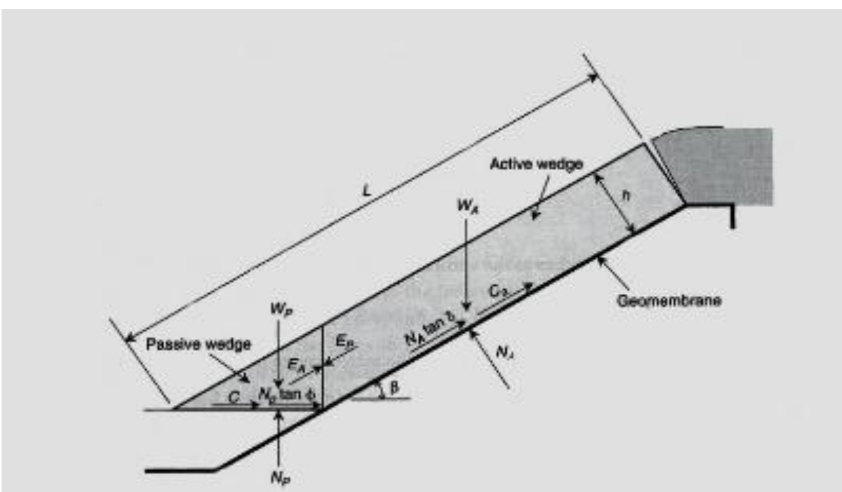
Considering a cover soil placed directly on a geomembrane (or other geosynthetic layer) at a slope angle β. Two discrete zones can be visualized. There is a small passive wedge near the toe of the slope resisting a long thin active wedge extending the length of the slope. It is assumed that the cover soil is of uniform thickness and constant unit weight.

At the top of the slope or at an intermediate berm, we anticipate that a tension crack in the cover soil will occur, thereby breaking continuity with the remaining cover soil at the crest. Resisting the tendency for the cover soil to slide is the interface friction and/or adhesion of the cover soil to the specific type of underlying geomembrane.

Note that the passive wedge is assumed to move on the underlying cover soil so that the shear strength parameters φ and c, are also used.

By taking free bodies of the passive and active wedges with the appropriate forces being applied, the formulation for the factor of safety results. The resulting equation is not an explicit solution for the FS, and must be solved using a quadratic equation.

By resolving the Freebody diagram into its component forces, and balance the forces to equilibrium (i.e. balancing active forces to passive forces) resulting in a quadratic equation with the FOS as the variable as follows:



$$E_A = \frac{(FS)(W_A - N_A \cos\beta) - (N_A \tan\delta + C_a)\sin\beta}{\sin\beta\,(FS)}$$ **----- Eqt**

$$E_P = \frac{C + W_P \tan\varphi}{\cos\beta(FS) - \sin\beta \tan\varphi}$$ **----- Eqt**

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GEOMEMBRANE TENSILE STRAIN (ON SLOPE)
DESIGN CALCULATIONS

Putting $E_A = E_P$ and factorising for FS:

$$a(FS)^2 + b(FS) - c = 0$$

$$W_A = OB + \gamma h^2 (\frac{L}{h} - \frac{1}{\sin\beta} - \tan\beta)$$

Where:

$$N_A = W_A \cos\beta$$

$$a = (W_A - N_A \cos\beta)\cos\beta$$

$$C_a = c_a(\mathrm{L} - \frac{h}{\sin\beta})$$

$$b = -[(W_A - N_A\cos\beta)\sin\beta\tan\varphi + (N_A\tan\delta + C_a)\sin\beta\cos\beta + \sin\beta\,(C + W_P\tan\varphi)]$$

and

$$W_P = OB + \frac{\gamma h^2}{\sin 2\beta}$$

$$c = (N_A \tan\delta + C_a)\sin\beta^2 \tan ø$$

$$N_P = W_P + E_P \sin\beta$$

$$C = \frac{(c)(h)}{\sin\beta}$$

With the legend as follows:

W_A =	total weight of the active wedge
W_P =	total weight of the passive wedge
N_A =	effective force normal to the failure plane of the active wedge
N_P =	effective force normal to the failure plane of the passive wedge
γ =	unit weight of the cover soil
h =	thickness of the cover soil
L =	length of the slope measured along the geomembrane
β =	soil slope angle beneath the geomembrane
ø =	friction angle of the cover soil
δ =	interface friction angle between cover soil and geomembrane
C_a =	adhesive force between cover soil of the active wedge and the geomembrane,
c_a =	adhesion between cover soil of the active wedge and the geomembrane
C =	cohesive force along the failure plane of the passive wedge,
c =	cohesion of the cover soil
E_A =	interwedge force acting on the active wedge from the passive wedge
E_P =	interwedge force acting on the passive wedge from the active wedge
FS =	factor of safety against cover soil sliding on the geomembrane.
OB=	Overburden pressure from waste above

The calculation is conducted below on the steepest slope, using the highest loading, with the most critical interface (as identified from the slope stability analysis conducted). Conceivably, if the FOS is acceptable for this case, all cases with higher friction properties under less loading will therefore have a higher FOS.

GEOMEMBRANE TENSILE STRAIN (ON SLOPE)
DESIGN CALCULATIONS

DESIGN INFORMATION			
SYMBOL	**VALUE**	**UNIT**	**DESCRIPTION**
γ	20	kN/m³	unit weight of cover soil (Soilcrete)
ϕ	42.00	deg	friction angle of the cover soil & GMB
c	20	kpa	cohesion of the cover soil
h	0.25	m	thickness of the cover soil
β	18.43	°	soil slope angle
L	13.6	m	length of the slope
ca	0		adhesion between cover soil
δ	20	°	int. friction angle (Protection Layer - SMTH GMB)

WITHOUT REINFORCEMENT			
SYMBOL	**VALUE**	**UNIT**	**DESCRIPTION**
Wa	63.6	kN/m³	total weight of the active wedge
Na	60.4	kN	ffective force normal to the failure plane of the active wedg
Ca	0.0	kN	adhesive force between cover soil and gsy
Wp	2.1	kN/m³	total weight of the passive wedge
C	15.8	kN	cohesive force along the failure plane of the passive wedg
a	6.0		n/a
b	-14.0		n/a
c	2.0		n/a

$FoS_{unreinf}$	**2.17**

The slopes for both Additives and the Coal Stockyard PCDs are safe from sliding block failure, without reinforcement.

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GEOMEMBRANE TENSILE STRAIN (ON SLOPE)
DESIGN CALCULATIONS

3) REFERENCES

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6) **Jones, D.R.V., Dixon, N. (2003b)** " Stability of Landfill Lining Systems: Report No. 2 Guidance," Environment Agency, Bristol UK. ISBN 85705945 X

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