APPENDIX VI-H.5

GEOMEMBRANE STRAIN DUE TO LOCALIZED DIFFERENTIAL SETTLEMENT

Geosyntec consultants

COMPUTATION COVER SHEET

Client: DRPI **Project:** DRPI Landfill Expansion **Project #:** ME1571 **Task #:** 1

TITLE OF COMPUTATIONS LOCALIZED SETTLEMENT EVALUATION

COMPUTATIONS BY:

Signature _____ 2/21/2018 DATE

Printed Name and Title: Andrew Stallings, Senior Staff Engineer

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Printed Name and Title: Chunling Li, Project Engineer

COMPUTATIONS BACKCHECKED BY: (Originator)

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APPROVED BY: (PM or Designate)

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APPROVAL NOTES:

REVISIONS (Number and initial all revisions)

NO.	SHEET	DATE	BY	CHECKED BY	APPROVAL

LOCALIZED SETTLEMENT EVALUATION

PURPOSE

The purpose of this calculation package is to evaluate potential deformation of the final cover system caused by localized settlement at the Delaware Recyclable Products, Inc. (DRPI) Landfill in Wilmington, Delaware. Additionally, this calculation evaluates the potential deformation caused by localized settlement for the liner system overlay that will be constructed over the existing unlined disposal area (Cells 1, 2, and 3). The localized settlement is a result of debris heterogeneity.

These settlement calculations model a zone of debris that is of greater compressibility than the surrounding debris. Differential settlement may develop around zones of greater compressibility that could result in a change in grade or in the development of tensile strain within the cover system/overlay liner. Of particular importance is the integrity of the geomembrane component of the cover system/overlay liner. Calculations of settlement are based on procedures developed by Sagaseta [1987]. Based on the settlement calculations, the minimum post-settlement slope and the maximum tensile strain in the geomembrane will be evaluated.

METHOD

1. Use Sagaseta's [1987] plane strain model to estimate the maximum deflection caused by a void developing in the underlying material, as follows:

Horizontal Deformation	Vertical Deformation
$S_X = S_{x1} + S_{x2} + S_{x3}$	$S_Z = S_{Z1} + S_{Z2} + S_{Z3}$
$S_{x1} = -\left(\frac{a^2}{2}\right)\left(\frac{x}{r_1^2}\right)$	$S_{Z1} = -\left(\frac{a^2}{2}\right)\left(\frac{z-h}{r_1^2}\right)$
$S_{x2} = \left(\frac{a^2}{2}\right)\left(\frac{x}{r_2^2}\right)$	$S_{Z2} = \left(\frac{a^2}{2}\right)\left(\frac{z+h}{r_2^2}\right)$
$S_{x3} = \left(\frac{-a^2 x}{r_2^2}\right)\left(1 - \frac{2z(z+h)}{r_2^2}\right)$	$S_{Z3} = \left(\frac{a^2 z}{r_2^2}\right)\left(1 - 2\frac{x^2}{r_2^2}\right)$

where:

$$r_1 = \sqrt{x^2 + (z - h)^2}$$

$$r_2 = \sqrt{x^2 + (z + h)^2}$$

x = x coordinate or horizontal position of point of interest;
z = z coordinate or vertical position of point of interest;
a = radius of void;
h = vertical distance between center of void and point of interest;
r_1 = distance from point of interest to center of void; and
r_2 = distance from point of interest to mirror image of void center.

2. Estimate the total deformation in the horizontal and vertical directions for points along the surface of the geomembrane.

3. Calculate the tensile strain in the geomembrane and the post-settlement slope between adjacent "points":

$$\varepsilon = \frac{\text{Final length of segment} - \text{Initial length of segment}}{\text{Initial length of segment}} \times 100 \text{ percent}$$

$$\text{Length of segment} = \sqrt{(x_1 - x_2)^2 + (z_1 - z_2)^2}$$

$$\textit{Final}\,(\text{post-settlement})\ \text{slope of segment} = \frac{z_{1\text{-final}} - z_{2\text{-final}}}{x_{1\text{-final}} - x_{2\text{-final}}} \times 100 \text{ percent}$$

4. Compare the calculated strain to the maximum allowable tensile strain in the geomembrane, which is 5 percent as recommended by Berg and Bonaparte [1993] for HDPE geomembranes.

INPUT PARAMETERS

The following cases are considered in this evaluation:

Case 1 – Cover System with 2 percent slope;
Case 2 – Cover System with 33 percent slope; and
Case 3 – Overlay liner system with 2 percent slope.

Prior to installing the cover system on the waste disposal area, a minimum 0.5-ft thick layer of intermediate cover soil is assumed to be installed. According to the original design, a minimum 2-ft thick layer of common fill was placed on the waste of the overlay liner area.

A grading layer with thickness ranging from 0 to 10 ft was placed above the existing waste to create the drainage slope for the overlay liner. For this analysis, the more critical condition with 0 ft grading layer is considered.

Based on the Sagaseta equations, the magnitude of localized settlement increases as the proximity of the void to the point of interest decreases. The point of interest for this analysis is the surface of the soil layer immediately underneath the geomembrane (i.e., the surface on which the geomembrane lies). For this analysis, assume that the largest potential void space is approximately 3-ft diameter.

- After placing the 0.5-ft thick layer intermediate cover soil for Cases 1 and 2 (i.e., final cover system), the surface will be compacted to identify any compressible zones or voids that may be near the surface. It is assumed that compaction will identify voids that are within 3 ft of the surface for cover system construction.
- For Case 3 (i.e., liver over the overlay area), the existing 2-ft thick layer of common fill is taken into consideration. It is assumed placement of a 10-30 thick stockpile and operation of heavy equipment over most of the overlay area has conservatively resulted in sufficient compaction within 6 ft of the existing waste surface.
- Assume that radius of void, a = 1.5 ft. Therefore, total thickness between geomembrane and the compressible zone, h, is 5.0 ft for Cases 1 and 2 (h = 3.0 ft + 1.5 ft + 0.5 ft = 5.0 ft.) and is 9.5 ft for Case 3 (h = 6.0 ft + 1.5 ft + 2.0 ft = 9.5 ft).
- Assume that -15 ft < X < 15 ft, where X is the horizontal distance from the center point of the void. Therefore, for Case 1 (2 percent slopes), -0.3 ft < Z < 0.3 ft, for Case 2 (33 percent slopes), -4.95 ft < Z < 4.95 ft, and for Case 3 (2 percent slopes) -0.3 ft < Z < 0.3 ft, where Z is the vertical distance from the ground surface at the current horizontal location to the ground surface above the center of the void.
- Assume that horizontal increment = 0.5 ft.

RESULTS

To compute localized settlement, the equations presented above are entered into a Microsoft Excel™ spreadsheet. The calculations are presented in Attachment A to this calculation package. The results are summarized in the following table.

Parameter	Case 1 Cover (2%)	Case 2 Cover (33%)	Case 3 Liner Overlay (2%)	Comparison of Results with Performance Criteria	Evaluation
Maximum Settlement (ft)	0.45 ft	0.46 ft	0.24 ft	---	O.K.
Maximum Tensile Strain (percent)	1.22 percent	3.45 percent	0.33 percent	Less than 5 percent recommended maximum [Berg and Bonaparte, 1993].	O.K.
Minimum Slope (percent)	-4.0 percent (i.e., grade reversal)	26.3 percent	0.4 percent	Greater than zero.	Case 1 can be fixed by adding soil to maintain positive drainage

CONCLUSIONS

Based on this evaluation of tensile strain and post-settlement slopes, differential settlement caused by local waste heterogeneity will not damage the geomembrane or impair the performance of the geomembrane for Cases 1 and 2 or the geomembrane overlay liner for Case 3.

A grade reversal does occur for Case 1 (the 2 percent slope of the cover). Because of the relatively small area affected by the grade reversal in Case 1, this problem can easily be fixed during the post closure monitoring period by filling the area with soil to reach the desired slope.

For Case 3, the minimum post-settlement slope is 0.4 percent. However, this case represents a worst-case scenario at the toe of the slope where there is no grading layer. The majority of the overlay liner area will have grading layer with thickness ranging from 0 to 10 ft which is conservatively ignored in this calculation. The potential for larger localized settlements at the toe of the slope should be mitigated by thorough subgrade preparation and compaction in this area prior to construction of the overlay liner. Liner settlements that occur prior to the placement of waste above the overlay liner system should be filled to maintain positive drainage.

REFERENCES

Berg, R.R. and Bonaparte, R., "Long-Term Allowable Tensile Stresses for Polyethylene Geomembranes", *Geotextiles and Geomembranes*, Vol. 12, 1993, pp. 287-306.

Sagaseta, C., *"Analysis of Undrained Deformation Due to Ground Loss"*, Géotechnique, Vol. 37, No. 3, pp. 301-320.

ATTACHMENT A

Analysis of Localized Settlement of the Cover System due to Debris Heterogeneity

Analysis of Localized Settlement of the Cover System due to Debris Heterogeneity
Case 1 - 2 Percent Slope

Depth of Void Below Cover (ft) =	5.00
Void Radius (ft) =	1.50
Horizontal Increment (ft) =	0.5

X	Z	r_1^2	r_2^2	S_{X1}	S_{X2}	S_{X3}	$S_{X\text{-}TOTAL}$	S_{Z1}	S_{Z2}	S_{Z3}	$S_{Z\text{-}TOTAL}$	New X	New Z	Initial Length	Final Length	Strain (%)	Slope (%)
-15.0	-0.30	253	247	0.07	-0.07	0.14	0.14	0.02	0.02	0.00	0.05	-14.86	-0.25				
-14.5	-0.29	238	232	0.07	-0.07	0.14	0.14	0.02	0.02	0.00	0.05	-14.36	-0.24	0.50	0.50	0.77	-2.55
-14.0	-0.28	224	218	0.07	-0.07	0.15	0.14	0.03	0.02	0.00	0.05	-13.86	-0.23	0.50	0.50	0.80	-2.60
-13.5	-0.27	210	205	0.07	-0.07	0.15	0.15	0.03	0.03	0.00	0.06	-13.35	-0.21	0.50	0.50	0.84	-2.66
-13.0	-0.26	197	191	0.07	-0.08	0.15	0.15	0.03	0.03	0.00	0.06	-12.85	-0.20	0.50	0.50	0.88	-2.72
-12.5	-0.25	184	179	0.08	-0.08	0.16	0.16	0.03	0.03	0.00	0.06	-12.34	-0.19	0.50	0.50	0.92	-2.79
-12.0	-0.24	171	167	0.08	-0.08	0.16	0.16	0.03	0.03	0.00	0.07	-11.84	-0.17	0.50	0.50	0.97	-2.87
-11.5	-0.23	160	155	0.08	-0.08	0.17	0.17	0.04	0.03	0.00	0.07	-11.33	-0.16	0.50	0.51	1.01	-2.97
-11.0	-0.22	148	144	0.08	-0.09	0.17	0.17	0.04	0.04	0.00	0.08	-10.83	-0.14	0.50	0.51	1.05	-3.07
-10.5	-0.21	137	133	0.09	-0.09	0.18	0.18	0.04	0.04	0.00	0.09	-10.32	-0.12	0.50	0.51	1.10	-3.19
-10.0	-0.20	127	123	0.09	-0.09	0.19	0.18	0.05	0.04	0.00	0.09	-9.82	-0.11	0.50	0.51	1.14	-3.32
-9.5	-0.19	117	113	0.09	-0.09	0.19	0.19	0.05	0.05	0.00	0.10	-9.31	-0.09	0.50	0.51	1.17	-3.47
-9.0	-0.18	108	104	0.09	-0.10	0.20	0.19	0.05	0.05	0.00	0.11	-8.81	-0.07	0.50	0.51	1.20	-3.65
-8.5	-0.17	99	96	0.10	-0.10	0.20	0.20	0.06	0.06	0.00	0.12	-8.30	-0.05	0.50	0.51	**1.22**	-3.84
-8.0	-0.16	91	87	0.10	-0.10	0.21	0.21	0.06	0.06	0.00	0.13	-7.79	-0.03	0.50	0.51	**1.22**	-4.07
-7.5	-0.15	83	80	0.10	-0.11	0.22	0.21	0.07	0.07	0.00	0.14	-7.29	-0.01	0.50	0.51	1.21	-4.33
-7.0	-0.14	75	73	0.10	-0.11	0.22	0.22	0.08	0.08	0.00	0.15	-6.78	0.01	0.50	0.51	1.16	-4.62
-6.5	-0.13	69	66	0.11	-0.11	0.23	0.22	0.08	0.08	0.00	0.17	-6.28	0.04	0.50	0.51	1.07	-4.95
-6.0	-0.12	62	60	0.11	-0.11	0.23	0.23	0.09	0.09	0.00	0.19	-5.77	0.07	0.50	0.50	0.92	-5.32
-5.5	-0.11	56	54	0.11	-0.11	0.23	0.23	0.10	0.10	0.00	0.20	-5.27	0.09	0.50	0.50	0.70	-5.73
-5.0	-0.10	51	49	0.11	-0.11	0.23	0.23	0.11	0.11	0.00	0.23	-4.77	0.13	0.50	0.50	0.39	-6.18
-4.5	-0.09	46	44	0.11	-0.11	0.23	0.23	0.12	0.12	0.00	0.25	-4.27	0.16	0.50	0.50	-0.06	-6.64
-4.0	-0.08	42	40	0.11	-0.11	0.23	0.22	0.14	0.14	0.00	0.27	-3.78	0.19	0.50	0.50	-0.65	-7.12
-3.5	-0.07	38	37	0.10	-0.11	0.22	0.22	0.15	0.15	0.00	0.30	-3.28	0.23	0.50	0.49	-1.42	-7.55
-3.0	-0.06	35	33	0.10	-0.10	0.21	0.20	0.16	0.17	0.00	0.33	-2.80	0.27	0.50	0.49	-2.39	-7.90
-2.5	-0.05	32	31	0.09	-0.09	0.19	0.18	0.18	0.18	0.00	0.36	-2.32	0.31	0.50	0.48	-3.54	-8.07
-2.0	-0.04	29	29	0.08	-0.08	0.16	0.16	0.19	0.20	0.00	0.39	-1.84	0.35	0.50	0.48	-4.84	-7.98
-1.5	-0.03	28	27	0.06	-0.06	0.13	0.13	0.21	0.21	0.00	0.41	-1.37	0.38	0.50	0.47	-6.18	-7.50
-1.0	-0.02	26	26	0.04	-0.04	0.09	0.09	0.22	0.22	0.00	0.43	-0.91	0.41	0.50	0.46	-7.43	-6.56
-0.5	-0.01	25	25	0.02	-0.02	0.04	0.04	0.22	0.22	0.00	**0.44**	-0.46	0.43	0.50	0.46	-8.39	-5.15
0.0	0.00	25	25	0.00	0.00	0.00	0.00	0.23	0.23	0.00	**0.45**	0.00	0.45	0.50	0.46	-8.91	-3.37
0.5	0.01	25	25	-0.02	0.02	-0.04	-0.04	0.22	0.22	0.00	**0.45**	0.46	0.46	0.50	0.46	-8.89	-1.41
1.0	0.02	26	26	-0.04	0.04	-0.09	-0.09	0.22	0.22	0.00	0.43	0.91	0.45	0.50	0.46	-8.32	0.46
1.5	0.03	27	28	-0.06	0.06	-0.12	-0.12	0.21	0.21	0.00	0.41	1.38	0.44	0.50	0.46	-7.33	2.02
2.0	0.04	29	29	-0.08	0.08	-0.15	-0.15	0.20	0.19	0.00	0.39	1.85	0.43	0.50	0.47	-6.09	3.14
2.5	0.05	31	32	-0.09	0.09	-0.17	-0.18	0.18	0.18	0.00	0.36	2.32	0.41	0.50	0.48	-4.77	3.79
3.0	0.06	33	35	-0.10	0.10	-0.19	-0.20	0.17	0.16	0.00	0.33	2.80	0.39	0.50	0.48	-3.53	**4.02**

Analysis of Localized Settlement of the Cover System due to Debris Heterogeneity
Case 1 - 2 Percent Slope

Depth of Void Below Cover (ft) =	5.00
Void Radius (ft) =	1.50
Horizontal Increment (ft) =	0.5

X	Z	r_1^2	r_2^2	S_{X1}	S_{X2}	S_{X3}	$S_{X\text{-}TOTAL}$	S_{Z1}	S_{Z2}	S_{Z3}	$S_{Z\text{-}TOTAL}$	New X	New Z	Initial Length	Final Length	Strain (%)	Slope (%)
3.5	0.07	37	38	-0.11	0.10	-0.20	-0.21	0.15	0.15	0.00	0.30	3.29	0.37	0.50	0.49	-2.43	**3.95**
4.0	0.08	40	42	-0.11	0.11	-0.21	-0.22	0.14	0.14	0.00	0.28	3.78	0.36	0.50	0.49	-1.51	3.68
4.5	0.09	44	46	-0.11	0.11	-0.22	-0.22	0.12	0.12	0.00	0.25	4.28	0.34	0.50	0.50	-0.78	3.28
5.0	0.10	49	51	-0.11	0.11	-0.22	-0.22	0.11	0.11	0.00	0.23	4.78	0.33	0.50	0.50	-0.22	2.82
5.5	0.11	54	56	-0.11	0.11	-0.22	-0.22	0.10	0.10	0.00	0.20	5.28	0.31	0.50	0.50	0.21	2.35
6.0	0.12	60	62	-0.11	0.11	-0.21	-0.22	0.09	0.09	0.00	0.18	5.78	0.30	0.50	0.50	0.51	1.90
6.5	0.13	66	69	-0.11	0.11	-0.21	-0.21	0.08	0.08	0.00	0.17	6.29	0.30	0.50	0.50	0.73	1.48
7.0	0.14	73	75	-0.11	0.10	-0.20	-0.21	0.08	0.08	0.00	0.15	6.79	0.29	0.50	0.50	0.88	1.09
7.5	0.15	80	83	-0.11	0.10	-0.20	-0.20	0.07	0.07	0.00	0.14	7.30	0.29	0.50	0.50	0.98	0.75
8.0	0.16	87	91	-0.10	0.10	-0.20	-0.20	0.06	0.06	0.00	0.12	7.80	0.28	0.50	0.51	1.03	0.44
8.5	0.17	96	99	-0.10	0.10	-0.19	-0.19	0.06	0.06	0.00	0.11	8.31	0.28	0.50	0.51	1.06	0.17
9.0	0.18	104	108	-0.10	0.09	-0.18	-0.19	0.05	0.05	0.00	0.10	8.81	0.28	0.50	0.51	1.07	-0.07
9.5	0.19	113	117	-0.09	0.09	-0.18	-0.18	0.05	0.05	0.00	0.10	9.32	0.29	0.50	0.51	1.06	-0.28
10.0	0.20	123	127	-0.09	0.09	-0.17	-0.18	0.04	0.05	0.00	0.09	9.82	0.29	0.50	0.51	1.04	-0.46
10.5	0.21	133	137	-0.09	0.09	-0.17	-0.17	0.04	0.04	0.00	0.08	10.33	0.29	0.50	0.51	1.01	-0.62
11.0	0.22	144	148	-0.09	0.08	-0.16	-0.17	0.04	0.04	0.00	0.07	10.83	0.29	0.50	0.51	0.98	-0.76
11.5	0.23	155	160	-0.08	0.08	-0.16	-0.16	0.03	0.04	0.00	0.07	11.34	0.30	0.50	0.50	0.95	-0.89
12.0	0.24	167	171	-0.08	0.08	-0.16	-0.16	0.03	0.03	0.00	0.06	11.84	0.30	0.50	0.50	0.92	-0.99
12.5	0.25	179	184	-0.08	0.08	-0.15	-0.15	0.03	0.03	0.00	0.06	12.35	0.31	0.50	0.50	0.88	-1.09
13.0	0.26	191	197	-0.08	0.07	-0.15	-0.15	0.03	0.03	0.00	0.06	12.85	0.32	0.50	0.50	0.84	-1.18
13.5	0.27	205	210	-0.07	0.07	-0.14	-0.14	0.03	0.03	0.00	0.05	13.36	0.32	0.50	0.50	0.81	-1.25
14.0	0.28	218	224	-0.07	0.07	-0.14	-0.14	0.02	0.03	0.00	0.05	13.86	0.33	0.50	0.50	0.77	-1.32
14.5	0.29	232	238	-0.07	0.07	-0.14	-0.14	0.02	0.02	0.00	0.05	14.36	0.34	0.50	0.50	0.74	-1.38
15.0	0.30	247	253	-0.07	0.07	-0.13	-0.13	0.02	0.02	0.00	0.04	14.87	0.34	0.50	0.50	0.71	-1.43

Maximum Settlement of Geomembrane Cap (ft)	Maximum Tensile Strain in Geomembrane Cap (percent)	Minimum Slope of Geomembrane Cap (percent)
0.45	1.22	4.02

Analysis of Localized Settlement of the Cover System due to Debris Heterogeneity
Case 2 - 33 Percent Slope

Depth of Void Below Cover (ft) =	5.00
Void Radius (ft) =	1.50
Horizontal Increment (ft) =	0.5

X	Z	r_1^2	r_2^2	S_{X1}	S_{X2}	S_{X3}	$S_{X\text{-}TOTAL}$	S_{Z1}	S_{Z2}	S_{Z3}	$S_{Z\text{-}TOTAL}$	New X	New Z	Initial Length	Final Length	Strain (%)	Slope (%)
-15.0	-4.95	324	225	0.05	-0.07	0.15	0.13	0.03	0.00	0.05	0.08	-14.87	-4.87				
-14.5	-4.79	306	210	0.05	-0.08	0.16	0.13	0.04	0.00	0.05	0.09	-14.37	-4.70	0.53	0.53	1.14	-33.47
-14.0	-4.62	289	196	0.05	-0.08	0.16	0.14	0.04	0.00	0.05	0.09	-13.86	-4.53	0.53	0.53	1.22	-33.50
-13.5	-4.46	272	183	0.06	-0.08	0.17	0.14	0.04	0.00	0.05	0.10	-13.36	-4.36	0.53	0.53	1.32	-33.54
-13.0	-4.29	255	170	0.06	-0.09	0.18	0.15	0.04	0.00	0.06	0.10	-12.85	-4.19	0.53	0.53	1.42	-33.58
-12.5	-4.13	240	157	0.06	-0.09	0.19	0.16	0.04	0.01	0.06	0.11	-12.34	-4.02	0.53	0.53	1.54	-33.63
-12.0	-3.96	224	145	0.06	-0.09	0.20	0.16	0.04	0.01	0.06	0.11	-11.84	-3.85	0.53	0.54	1.67	-33.68
-11.5	-3.80	210	134	0.06	-0.10	0.21	0.17	0.05	0.01	0.06	0.12	-11.33	-3.68	0.53	0.54	1.81	-33.73
-11.0	-3.63	195	123	0.06	-0.10	0.22	0.18	0.05	0.01	0.06	0.13	-10.82	-3.50	0.53	0.54	1.96	-33.78
-10.5	-3.47	182	113	0.06	-0.10	0.23	0.19	0.05	0.02	0.07	0.13	-10.31	-3.33	0.53	0.54	2.13	-33.84
-10.0	-3.30	169	103	0.07	-0.11	0.24	0.20	0.06	0.02	0.07	0.14	-9.80	-3.16	0.53	0.54	2.31	-33.90
-9.5	-3.14	156	94	0.07	-0.11	0.26	0.21	0.06	0.02	0.07	0.15	-9.29	-2.98	0.53	0.54	2.50	-33.97
-9.0	-2.97	145	85	0.07	-0.12	0.27	0.22	0.06	0.03	0.07	0.16	-8.78	-2.81	0.53	0.54	2.70	-34.03
-8.5	-2.81	133	77	0.07	-0.12	0.29	0.24	0.07	0.03	0.07	0.17	-8.26	-2.64	0.53	0.54	2.91	-34.10
-8.0	-2.64	122	70	0.07	-0.13	0.31	0.25	0.07	0.04	0.07	0.18	-7.75	-2.46	0.53	0.54	3.10	-34.16
-7.5	-2.48	112	63	0.08	-0.13	0.32	0.26	0.07	0.05	0.07	0.19	-7.24	-2.28	0.53	0.54	3.28	-34.22
-7.0	-2.31	102	56	0.08	-0.14	0.34	0.28	0.08	0.05	0.07	0.20	-6.72	-2.11	0.53	0.54	3.41	-34.28
-6.5	-2.15	93	50	0.08	-0.15	0.36	0.29	0.09	0.06	0.06	0.21	-6.21	-1.93	0.53	0.54	**3.45**	-34.34
-6.0	-1.98	85	45	0.08	-0.15	0.38	0.31	0.09	0.08	0.06	0.23	-5.69	-1.75	0.53	0.54	**3.36**	-34.42
-5.5	-1.82	77	40	0.08	-0.15	0.39	0.32	0.10	0.09	0.05	0.24	-5.18	-1.58	0.53	0.54	3.07	-34.54
-5.0	-1.65	69	36	0.08	-0.16	0.41	0.33	0.11	0.10	0.04	0.25	-4.67	-1.40	0.53	0.54	2.50	-34.74
-4.5	-1.49	62	33	0.08	-0.16	0.41	0.34	0.12	0.12	0.02	0.26	-4.16	-1.22	0.53	0.53	1.57	-35.09
-4.0	-1.32	56	30	0.08	-0.15	0.40	0.33	0.13	0.14	0.01	0.28	-3.67	-1.04	0.53	0.53	0.23	-35.70
-3.5	-1.16	50	27	0.08	-0.15	0.39	0.32	0.14	0.16	-0.01	0.29	-3.18	-0.87	0.53	0.52	-1.50	-36.66
-3.0	-0.99	45	25	0.08	-0.13	0.35	0.29	0.15	0.18	-0.03	0.30	-2.71	-0.69	0.53	0.51	-3.45	-38.06
-2.5	-0.83	40	24	0.07	-0.12	0.31	0.26	0.16	0.20	-0.04	0.32	-2.24	-0.50	0.53	0.50	-5.36	-39.85
-2.0	-0.66	36	23	0.06	-0.10	0.25	0.21	0.18	0.21	-0.04	0.35	-1.79	-0.31	0.53	0.49	-6.87	-41.73
-1.5	-0.50	32	23	0.05	-0.07	0.18	0.16	0.19	0.22	-0.04	0.38	-1.34	-0.12	0.53	0.49	-7.73	-43.16
-1.0	-0.33	29	23	0.04	-0.05	0.11	0.10	0.20	0.23	-0.03	0.40	-0.90	0.07	0.53	0.48	-7.92	-43.59
-0.5	-0.17	27	24	0.02	-0.02	0.05	0.05	0.22	0.23	-0.02	0.43	-0.45	0.27	0.53	0.49	-7.67	-42.75
0.0	0.00	25	25	0.00	0.00	0.00	0.00	0.23	0.23	0.00	0.45	0.00	0.45	0.53	0.49	-7.27	-40.78
0.5	0.17	24	27	-0.02	0.02	-0.04	-0.04	0.23	0.22	0.01	**0.46**	0.46	0.62	0.53	0.49	-6.92	-38.11
1.0	0.33	23	29	-0.05	0.04	-0.07	-0.08	0.23	0.20	0.02	**0.46**	0.92	0.79	0.53	0.49	-6.65	-35.21
1.5	0.50	23	32	-0.07	0.05	-0.09	-0.11	0.22	0.19	0.03	0.44	1.39	0.94	0.53	0.49	-6.35	-32.44
2.0	0.66	23	36	-0.10	0.06	-0.10	-0.14	0.21	0.18	0.03	0.42	1.86	1.08	0.53	0.50	-5.92	-30.08
2.5	0.83	24	40	-0.12	0.07	-0.11	-0.16	0.20	0.16	0.03	0.39	2.34	1.22	0.53	0.50	-5.30	-28.28
3.0	0.99	25	45	-0.13	0.08	-0.11	-0.17	0.18	0.15	0.03	0.36	2.83	1.35	0.53	0.50	-4.51	-27.10

Analysis of Localized Settlement of the Cover System due to Debris Heterogeneity
Case 2 - 33 Percent Slope

Depth of Void Below Cover (ft) =	5.00
Void Radius (ft) =	1.50
Horizontal Increment (ft) =	0.5

X	Z	r_1^2	r_2^2	S_{X1}	S_{X2}	S_{X3}	$S_{X\text{-}TOTAL}$	S_{Z1}	S_{Z2}	S_{Z3}	$S_{Z\text{-}TOTAL}$	New X	New Z	Initial Length	Final Length	Strain (%)	Slope (%)
3.5	1.16	27	50	-0.15	0.08	-0.11	-0.18	0.16	0.14	0.03	0.32	3.32	1.48	0.53	0.51	-3.65	**-26.49**
4.0	1.32	30	56	-0.15	0.08	-0.11	-0.18	0.14	0.13	0.02	0.29	3.82	1.61	0.53	0.51	-2.81	**-26.34**
4.5	1.49	33	62	-0.16	0.08	-0.11	-0.19	0.12	0.12	0.02	0.26	4.31	1.74	0.53	0.52	-2.05	-26.52
5.0	1.65	36	69	-0.16	0.08	-0.11	-0.19	0.10	0.11	0.01	0.23	4.81	1.88	0.53	0.52	-1.41	-26.91
5.5	1.82	40	77	-0.15	0.08	-0.11	-0.18	0.09	0.10	0.01	0.20	5.32	2.01	0.53	0.52	-0.90	-27.40
6.0	1.98	45	85	-0.15	0.08	-0.11	-0.18	0.08	0.09	0.01	0.18	5.82	2.16	0.53	0.52	-0.51	-27.94
6.5	2.15	50	93	-0.15	0.08	-0.11	-0.17	0.06	0.09	0.00	0.15	6.33	2.30	0.53	0.53	-0.21	-28.47
7.0	2.31	56	102	-0.14	0.08	-0.10	-0.17	0.05	0.08	0.00	0.14	6.83	2.45	0.53	0.53	0.00	-28.97
7.5	2.48	63	112	-0.13	0.08	-0.10	-0.16	0.05	0.07	0.00	0.12	7.34	2.60	0.53	0.53	0.16	-29.43
8.0	2.64	70	122	-0.13	0.07	-0.10	-0.15	0.04	0.07	0.00	0.11	7.85	2.75	0.53	0.53	0.27	-29.84
8.5	2.81	77	133	-0.12	0.07	-0.10	-0.15	0.03	0.07	0.00	0.09	8.35	2.90	0.53	0.53	0.34	-30.21
9.0	2.97	85	145	-0.12	0.07	-0.09	-0.14	0.03	0.06	-0.01	0.08	8.86	3.05	0.53	0.53	0.39	-30.53
9.5	3.14	94	156	-0.11	0.07	-0.09	-0.14	0.02	0.06	-0.01	0.07	9.36	3.21	0.53	0.53	0.42	-30.81
10.0	3.30	103	169	-0.11	0.07	-0.09	-0.13	0.02	0.06	-0.01	0.07	9.87	3.37	0.53	0.53	0.44	-31.05
10.5	3.47	113	182	-0.10	0.06	-0.09	-0.13	0.02	0.05	-0.01	0.06	10.37	3.52	0.53	0.53	0.45	-31.26
11.0	3.63	123	195	-0.10	0.06	-0.09	-0.12	0.01	0.05	-0.01	0.05	10.88	3.68	0.53	0.53	0.45	-31.45
11.5	3.80	134	210	-0.10	0.06	-0.08	-0.12	0.01	0.05	-0.01	0.05	11.38	3.84	0.53	0.53	0.44	-31.61
12.0	3.96	145	224	-0.09	0.06	-0.08	-0.12	0.01	0.04	-0.01	0.04	11.88	4.00	0.53	0.53	0.44	-31.75
12.5	4.13	157	240	-0.09	0.06	-0.08	-0.11	0.01	0.04	-0.01	0.04	12.39	4.16	0.53	0.53	0.43	-31.88
13.0	4.29	170	255	-0.09	0.06	-0.08	-0.11	0.00	0.04	-0.01	0.03	12.89	4.32	0.53	0.53	0.41	-31.99
13.5	4.46	183	272	-0.08	0.06	-0.08	-0.10	0.00	0.04	-0.01	0.03	13.40	4.48	0.53	0.53	0.40	-32.08
14.0	4.62	196	289	-0.08	0.05	-0.08	-0.10	0.00	0.04	-0.01	0.03	13.90	4.65	0.53	0.53	0.39	-32.17
14.5	4.79	210	306	-0.08	0.05	-0.07	-0.10	0.00	0.04	-0.01	0.02	14.40	4.81	0.53	0.53	0.38	-32.24
15.0	4.95	225	324	-0.07	0.05	-0.07	-0.10	0.00	0.03	-0.01	0.02	14.90	4.97	0.53	0.53	0.36	-32.31

Maximum Settlement of Geomembrane Cap (ft)	Maximum Tensile Strain in Geomembrane Cap (percent)	Minimum Slope of Geomembrane Cap (percent)
0.46	3.45	26.34

Analysis of Localized Settlement of the Cover System due to Debris Heterogeneity
Case 3 - 2 Percent Slope of Overlay Liner System

Depth of Void Below Liner (ft)=	9.50
Void Radius (ft)=	1.50
Horizontal Increment (ft)=	0.5

X	Z	r_1^2	r_2^2	S_{X1}	S_{X2}	S_{X3}	$S_{X\text{-}TOTAL}$	S_{Z1}	S_{Z2}	S_{Z3}	$S_{Z\text{-}TOTAL}$	New X	New Z	Initial Length	Final Length	Strain (%)	Slope (%)
-15.0	-0.30	321	310	0.05	-0.05	0.11	0.11	0.03	0.03	0.00	0.07	-14.89	-0.23				
-14.5	-0.29	306	295	0.05	-0.06	0.11	0.11	0.04	0.04	0.00	0.07	-14.39	-0.22	0.50	0.50	0.33	-2.65
-14.0	-0.28	292	281	0.05	-0.06	0.11	0.11	0.04	0.04	0.00	0.08	-13.89	-0.20	0.50	0.50	0.32	-2.69
-13.5	-0.27	278	267	0.05	-0.06	0.12	0.11	0.04	0.04	0.00	0.08	-13.39	-0.19	0.50	0.50	0.31	-2.73
-13.0	-0.26	264	254	0.06	-0.06	0.12	0.12	0.04	0.04	0.00	0.08	-12.88	-0.18	0.50	0.50	0.30	-2.78
-12.5	-0.25	251	242	0.06	-0.06	0.12	0.12	0.04	0.04	0.00	0.09	-12.38	-0.16	0.50	0.50	0.29	-2.83
-12.0	-0.24	239	230	0.06	-0.06	0.12	0.12	0.05	0.05	0.00	0.09	-11.88	-0.15	0.50	0.50	0.26	-2.88
-11.5	-0.23	227	218	0.06	-0.06	0.12	0.12	0.05	0.05	0.00	0.10	-11.38	-0.13	0.50	0.50	0.24	-2.94
-11.0	-0.22	215	207	0.06	-0.06	0.12	0.12	0.05	0.05	0.00	0.10	-10.88	-0.12	0.50	0.50	0.21	-3.00
-10.5	-0.21	205	197	0.06	-0.06	0.12	0.12	0.05	0.05	0.00	0.11	-10.38	-0.10	0.50	0.50	0.17	-3.06
-10.0	-0.20	194	186	0.06	-0.06	0.12	0.12	0.06	0.06	0.00	0.11	-9.88	-0.09	0.50	0.50	0.12	-3.12
-9.5	-0.19	184	177	0.06	-0.06	0.12	0.12	0.06	0.06	0.00	0.12	-9.38	-0.07	0.50	0.50	**0.06**	-3.19
-9.0	-0.18	175	168	0.06	-0.06	0.12	0.12	0.06	0.06	0.00	0.12	-8.88	-0.06	0.50	0.50	**0.00**	-3.25
-8.5	-0.17	166	159	0.06	-0.06	0.12	0.12	0.07	0.07	0.00	0.13	-8.38	-0.04	0.50	0.50	**-0.08**	-3.32
-8.0	-0.16	157	151	0.06	-0.06	0.12	0.12	0.07	0.07	0.00	0.14	-7.88	-0.02	0.50	0.50	-0.17	-3.39
-7.5	-0.15	149	144	0.06	-0.06	0.12	0.12	0.07	0.07	0.00	0.15	-7.38	0.00	0.50	0.50	-0.27	-3.45
-7.0	-0.14	142	137	0.06	-0.06	0.12	0.12	0.08	0.08	0.00	0.15	-6.88	0.01	0.50	0.50	-0.39	-3.51
-6.5	-0.13	135	130	0.05	-0.06	0.11	0.11	0.08	0.08	0.00	0.16	-6.39	0.03	0.50	0.50	-0.52	-3.56
-6.0	-0.12	129	124	0.05	-0.05	0.11	0.11	0.08	0.09	0.00	0.17	-5.89	0.05	0.50	0.50	-0.67	-3.60
-5.5	-0.11	123	118	0.05	-0.05	0.11	0.10	0.09	0.09	0.00	0.18	-5.40	0.07	0.50	0.50	-0.83	-3.63
-5.0	-0.10	117	113	0.05	-0.05	0.10	0.10	0.09	0.09	0.00	0.18	-4.90	0.08	0.50	0.50	-1.01	-3.64
-4.5	-0.09	112	109	0.05	-0.05	0.09	0.09	0.10	0.10	0.00	0.19	-4.41	0.10	0.50	0.49	-1.19	-3.63
-4.0	-0.08	108	105	0.04	-0.04	0.09	0.09	0.10	0.10	0.00	0.20	-3.91	0.12	0.50	0.49	-1.38	-3.59
-3.5	-0.07	104	101	0.04	-0.04	0.08	0.08	0.10	0.10	0.00	0.21	-3.42	0.14	0.50	0.49	-1.58	-3.53
-3.0	-0.06	100	98	0.03	-0.03	0.07	0.07	0.11	0.11	0.00	0.21	-2.93	0.15	0.50	0.49	-1.77	-3.44
-2.5	-0.05	97	96	0.03	-0.03	0.06	0.06	0.11	0.11	0.00	0.22	-2.44	0.17	0.50	0.49	-1.95	-3.31
-2.0	-0.04	95	93	0.02	-0.02	0.05	0.05	0.11	0.11	0.00	0.23	-1.95	0.19	0.50	0.49	-2.12	-3.15
-1.5	-0.03	93	92	0.02	-0.02	0.04	0.04	0.12	0.12	0.00	0.23	-1.46	0.20	0.50	0.49	-2.26	-2.96
-1.0	-0.02	92	91	0.01	-0.01	0.02	0.02	0.12	0.12	0.00	0.23	-0.98	0.21	0.50	0.49	-2.37	-2.74
-0.5	-0.01	91	90	0.01	-0.01	0.01	0.01	0.12	0.12	0.00	**0.24**	-0.49	0.23	0.50	0.49	-2.45	-2.50
0.0	0.00	90	90	0.00	0.00	0.00	0.00	0.12	0.12	0.00	**0.24**	0.00	0.24	0.50	0.49	-2.49	-2.24
0.5	0.01	90	91	-0.01	0.01	-0.01	-0.01	0.12	0.12	0.00	**0.24**	0.49	0.25	0.50	0.49	-2.48	-1.97
1.0	0.02	91	92	-0.01	0.01	-0.02	-0.02	0.12	0.12	0.00	0.23	0.98	0.25	0.50	0.49	-2.44	-1.70
1.5	0.03	92	93	-0.02	0.02	-0.04	-0.04	0.12	0.12	0.00	0.23	1.46	0.26	0.50	0.49	-2.35	-1.44
2.0	0.04	93	95	-0.02	0.02	-0.05	-0.05	0.11	0.11	0.00	0.23	1.95	0.27	0.50	0.49	-2.23	-1.20
2.5	0.05	96	97	-0.03	0.03	-0.06	-0.06	0.11	0.11	0.00	0.22	2.44	0.27	0.50	0.49	-2.09	-0.99
3.0	0.06	98	100	-0.03	0.03	-0.07	-0.07	0.11	0.11	0.00	0.22	2.93	0.28	0.50	0.49	-1.92	**-0.81**

Analysis of Localized Settlement of the Cover System due to Debris Heterogeneity
Case 3 - 2 Percent Slope of Overlay Liner System

Depth of Void Below Liner (ft)=	9.50
Void Radius (ft)=	1.50
Horizontal Increment (ft)=	0.5

X	Z	r_1^2	r_2^2	S_{X1}	S_{X2}	S_{X3}	$S_{X\text{-}TOTAL}$	S_{Z1}	S_{Z2}	S_{Z3}	$S_{Z\text{-}TOTAL}$	New X	New Z	Initial Length	Final Length	Strain (%)	Slope (%)
3.5	0.07	101	104	-0.04	0.04	-0.07	-0.08	0.10	0.10	0.00	0.21	3.42	0.28	0.50	0.49	-1.74	**-0.66**
4.0	0.08	105	108	-0.04	0.04	-0.08	-0.08	0.10	0.10	0.00	0.20	3.92	0.28	0.50	0.49	-1.55	-0.54
4.5	0.09	109	112	-0.05	0.05	-0.09	-0.09	0.10	0.10	0.00	0.19	4.41	0.28	0.50	0.49	-1.36	-0.45
5.0	0.10	113	117	-0.05	0.05	-0.09	-0.10	0.09	0.09	0.00	0.19	4.90	0.29	0.50	0.49	-1.18	-0.40
5.5	0.11	118	123	-0.05	0.05	-0.10	-0.10	0.09	0.09	0.00	0.18	5.40	0.29	0.50	0.50	-1.00	-0.37
6.0	0.12	124	129	-0.05	0.05	-0.10	-0.11	0.09	0.08	0.00	0.17	5.89	0.29	0.50	0.50	-0.84	-0.37
6.5	0.13	130	135	-0.06	0.05	-0.11	-0.11	0.08	0.08	0.00	0.16	6.39	0.29	0.50	0.50	-0.68	-0.38
7.0	0.14	137	142	-0.06	0.06	-0.11	-0.11	0.08	0.08	0.00	0.15	6.89	0.29	0.50	0.50	-0.54	-0.41
7.5	0.15	144	149	-0.06	0.06	-0.11	-0.11	0.07	0.07	0.00	0.15	7.39	0.30	0.50	0.50	-0.42	-0.46
8.0	0.16	151	157	-0.06	0.06	-0.11	-0.11	0.07	0.07	0.00	0.14	7.89	0.30	0.50	0.50	-0.31	-0.51
8.5	0.17	159	166	-0.06	0.06	-0.11	-0.12	0.07	0.07	0.00	0.13	8.38	0.30	0.50	0.50	-0.21	-0.57
9.0	0.18	168	175	-0.06	0.06	-0.11	-0.12	0.06	0.06	0.00	0.12	8.88	0.30	0.50	0.50	-0.12	-0.63
9.5	0.19	177	184	-0.06	0.06	-0.11	-0.12	0.06	0.06	0.00	0.12	9.38	0.31	0.50	0.50	-0.05	-0.70
10.0	0.20	186	194	-0.06	0.06	-0.11	-0.12	0.06	0.06	0.00	0.11	9.88	0.31	0.50	0.50	0.01	-0.76
10.5	0.21	197	205	-0.06	0.06	-0.11	-0.12	0.05	0.05	0.00	0.11	10.38	0.32	0.50	0.50	0.07	-0.83
11.0	0.22	207	215	-0.06	0.06	-0.11	-0.11	0.05	0.05	0.00	0.10	10.89	0.32	0.50	0.50	0.11	-0.89
11.5	0.23	218	227	-0.06	0.06	-0.11	-0.11	0.05	0.05	0.00	0.10	11.39	0.33	0.50	0.50	0.15	-0.96
12.0	0.24	230	239	-0.06	0.06	-0.11	-0.11	0.05	0.05	0.00	0.09	11.89	0.33	0.50	0.50	0.18	-1.02
12.5	0.25	242	251	-0.06	0.06	-0.11	-0.11	0.04	0.04	0.00	0.09	12.39	0.34	0.50	0.50	0.21	-1.07
13.0	0.26	254	264	-0.06	0.06	-0.11	-0.11	0.04	0.04	0.00	0.08	12.89	0.34	0.50	0.50	0.23	-1.13
13.5	0.27	267	278	-0.06	0.05	-0.11	-0.11	0.04	0.04	0.00	0.08	13.39	0.35	0.50	0.50	0.25	-1.18
14.0	0.28	281	292	-0.06	0.05	-0.11	-0.11	0.04	0.04	0.00	0.07	13.89	0.35	0.50	0.50	0.26	-1.23
14.5	0.29	295	306	-0.06	0.05	-0.10	-0.11	0.04	0.04	0.00	0.07	14.39	0.36	0.50	0.50	0.27	-1.28
15.0	0.30	310	321	-0.05	0.05	-0.10	-0.11	0.03	0.03	0.00	0.07	14.89	0.37	0.50	0.50	0.28	-1.32

Maximum Settlement of Geomembrane Cap (ft)	Maximum Tensile Strain in Geomembrane Cap (percent)	Minimum Slope of Geomembrane Cap (percent)
0.24	0.33	-0.37

APPENDIX VI-H.6

GEOMEMBRANE PUNCTURE RESISTANCE - COVER

Geosyntec consultants

COMPUTATION COVER SHEET

Client: DRPI **Project:** DRPI Landfill Expansion **Project #:** ME1571 **Task #:** 1

TITLE OF COMPUTATIONS FINAL COVER GEOMEMBRANE PUNCTURE RESISTANCE

COMPUTATIONS BY:
Signature
Printed Name and Title: Chunling Li, Project Engineer
DATE: 2/19/2018

ASSUMPTIONS AND PROCEDURES CHECKED BY:
(Peer Reviewer)
Signature
Printed Name and Title: Andrew Stallings, Senior Staff Engineer
DATE: 2/20/2018

COMPUTATIONS CHECKED BY:
Signature
Printed Name and Title: Andrew Stallings, Senior Staff Engineer
DATE: 2/20/2018

COMPUTATIONS BACKCHECKED BY: (Originator)
Signature
Printed Name and Title: Chunling Li, Project Engineer
DATE: 2/20/2018

APPROVED BY:
(PM or Designate)
Signature
Printed Name and Title: David Espinoza, Senior Principal
DATE: 2/21/2018

APPROVAL NOTES:

REVISIONS (Number and initial all revisions)

NO.	SHEET	DATE	BY	CHECKED BY	APPROVAL

FINAL COVER GEOMEMBRANE PUNCTURE RESISTANCE

PURPOSE

The purpose of this analysis is to evaluate the puncture resistance of the proposed 50-mil Super Gripnet geomembrane to be used in the final cover system at the Delaware Recyclable Products, Inc. (DRPI) landfill. In order for the geomembrane to work efficiently as a barrier layer, puncturing of the geomembrane should be minimized. Also presented in this calculation package is a bearing capacity calculation for failure of the overlying soil due to construction equipment.

METHOD

The factor of safety against puncture (FS) resistance for a given loading condition is defined as the ratio of the allowable force (F_{allow}) to the required force ($F_{required}$) and given as:

$$FS = \frac{F_{allow}}{F_{required}} \tag{1}$$

For this analysis, the factor of safety is calculated based on an estimate of the actual force acting on the geomembrane ($F_{required}$) for a series of assumed loading conditions (i.e., construction traffic and waste placement) and the allowable force on the geomembrane surface (F_{allow}) is calculated according to the design methodology proposed by Koerner [2005]. The resulting factors of safety for each of the loading conditions are compared to the minimum design criteria and the outcome is reported.

ANALYSIS

Geomembrane Allowable Pressure

The allowable pressure on the geomembrane (p_{allow}) is computed based on the methodology presented by Koerner [2005]. The governing equation for the methodology presented by Koerner is as follows:

$$p_{allow} = \left(50 + 0.00045\,\frac{M}{H^2}\right) \times \left(\frac{1}{MF_S \times MF_{PD} \times MF_A}\right) \times \left(\frac{1}{RF_{CR} \times RF_{CBD}}\right) \tag{2}$$

where:

p_{allow}	=	Allowable pressure on geomembrane, (kPa)
M	=	Mass per unit area of a protective geotextile separation layer, (g/m^2)
H	=	Height of protrusions within the adjoining soil mass, (m)

MF_S = Modification factor for protrusions shape
MF_{PD} = Modification factor for packing density
MF_A = Modification factor for arching in solids
RF_{CR} = Reduction factor for creep
RF_{CBD} = Reduction factor for chemical and biological degradation

For the analysis presented herein the protection provided by an overlying geotextile filter is conservatively neglected and the first term in equation 2 is replaced with a value F_{lab}, which is defined as the ultimate puncture resistance (force, lbs) of the geomembrane as measured according to the procedure, *Standard Test Method, for Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products*, ASTM D4833. The revised equation is presented as follows:

$$F_{allow} = (F_{lab}) \times \left(\frac{1}{MF_S \times MF_{PD} \times MF_A}\right) \times \left(\frac{1}{RF_{CR} \times RF_{CBD}}\right) \quad (3)$$

The second term in equation 2 involves modification factors to account for shape, packing density and arching of soil used. The modification factors used in current calculations are based on Koerner [2005] and presented in Table 1.

Table 1: Modification factors for geomembrane puncture

Notation	***Modification Factor for Cover System Geomembrane***	
	Factor	Comments
MF_S	1.0	Angular particles (conservative)
MF_{PD}	1.0	Isolated protrusions (conservative)
MF_A	1.0	Hydrostatic conditions (conservative)

The third term in equation 2 represents the reduction factors to account for long term creep and degradation of the geomembrane. Geomembrane puncture damage for protrusion height smaller than 12 mm is usually not explicitly addressed in the literature because such small protrusions are not expected to damage the geomembrane. As the maximum particle size for silt layer (4.75 mm) was less than 12 mm, the geomembrane puncture damage reduction factors under worst case scenario are assumed based on values provided by Koerner [2005]. The reduction factor for creep, RF_{CR}, is assumed. Because the water in the final cover system is relatively clean, the reduction factor for chemical and biological degradation, RF_{CBD}, is assumed to be value of 1.1, which corresponds to the mild leachate conditions. Reduction factors used are summarized in Table 2.

Table 2: Reduction factors for geomembrane puncture

Notation	*Cover System - 40mil HDPE Geomembrane*	
	Factor	Comments
RF_{CR}	1.5	For protrusion height of 12 mm
RF_{CBD}	1.1	Mild leachate conditions

The puncture resistance for the 50-mil Super Gripnet geomembrane is 80 lbs (See Figure 1). Based on above inputs, the allowable force on geomembrane is calculated as:

$$F_{allow} = (80) \times (\frac{1}{1.0 \times 1.0 \times 1.0}) \times (\frac{1}{1.5 \times 1.1}) = 48.5 lbs (0.21 kN)$$

For the silt material of the final cover soil, the maximum particle size is typically less than 4.75 mm. Because information of geomembrane puncture damage for particle sizes smaller than 12 mm is not addressed in the literature, a maximum particle size of 12 mm is conservatively assumed in this analysis. Assuming that the full diameter of the particle is in contact with the geomembrane, the allowable pressure applied by the particle to the geomembrane is calculated as follows:

$$p_{allow} = \frac{F_{allow}}{\left(\pi \, D_{average}^{2} / 4 \right)} = 0.21 kN \; / \; \left(\frac{3.14 \times (12/1000 \, m)^2}{4} \right) = 1858 kPa \, (266 psi)$$

Geomembrane Required Pressure (Design Load)

The total vertical stress on the geomembrane is calculated as the sum of the overlying soil pressure and the pressure exerted by the construction equipment as follows:

$$p_{act} = (\gamma_{ave} \times T) + q_{eqp} \qquad (3)$$

where:

p_{act} = vertical stress on the geomembrane
γ_{ave} = average unit weight of the material above geomembrane
T = thickness of the soil material above geomembrane
q_{eqp} = equipment ground pressure

To evaluate the maximum pressure from a construction vehicle on a geomembrane, two typical dozers are assumed: (i) a CAT D6R, and (ii) a CAT D6R, LGP. For this evaluation, a minimum lift thickness of one-foot of soil is evaluated as the most conservative case. As the thickness of

soil above the geomembrane increases, the allowable ground pressure of construction traffic increases. Table 3 presents the required information about the assumed construction equipment and the calculated design pressures.

Table 3: Construction Equipment Information and Calculated Design Pressures

Load Type	Contact Area(in^2)	Ground pressure q_{eqp} (psi)	Vertical Stress p_{act} (psi)
Construction, CAT D6R(1)	4,518	8.82	9.65(2)
Construction, CAT D6R, LGP(1)	9,194	4.94	5.77(2)
Operating	-	-	1.67(3)

Notes:
(1) Equipment data taken from Caterpillar Performance Handbook, Edition 32, Oct, 2001;
(2) Including one foot of overlying soil with a unit weight 120 pcf;
(3) Assuming 2 ft of overlying cover soil with a unit weight of 120 pcf.

Factor of Safety against Puncture Failure

The factor of safety against puncture resistance for the load above the geomembrane is calculated based on equation 1. The results for factor of safety (FS) values for the most critical case are shown in Table 4.

Table 4: Factor of safety for geomembrane puncture

Case Description	Allowable Pressure on Geomembrane p_{allow} (psi)	Applied Pressure on Geomembrane p_{act} (psi)	Factor of safety, $FS=p_{allow}/p_{act}$
Construction, CAT D6R	266	9.65	27.6

A factor of safety against bearing capacity failure of the soils overlying the geomembrane during construction is calculated. The construction equipment is the same as the ones in the previous section. The bearing capacity equation used for analysis is taken from NAV-FAC Design Manual 7.2 [1982] for a continuous strip footing.

$$q_{ult} = \left(\frac{1}{2}\gamma B N_{\gamma}\right) + \left(\gamma D_f N_q\right) \quad (4)$$

where:

q_{ult} = ultimate capacity of the soil
B = footing width (Standard shoe width)

γ	=	unit weight of foundation soil
D_f	=	depth of the footing
N_γ, N_q	=	bearing capacity factors

The bearing capacity factors can be calculated as:

$$N_q = \tan^2(45 + \phi/2)e^{\pi \tan\phi} \tag{5a}$$

$$N_\gamma = 2(N_q + 1)\tan\phi \tag{5b}$$

The construction equipment will work on the surface of the soil. Therefore, the footing depth in the second term of the bearing capacity equation will become zero leaving only the first term. Assuming conservatively a friction angle of 30° for the compacted cover soil, the bearing capacity factors, N_q, and N_γ, calculated using Equations (5a) and (5b) are 18.4 and 22.4, respectively.

q_{ult} = 0.5(120 pcf) (22 in./12 in.) (22.4) (1 ft^2 / 144 in^2) = 17.1 psi

The factor of safety for bearing capacity of the soil is calculated as the ratio of the ultimate bearing capacity, q_{ult}, to the applied ground pressure, q_{eqp}, of the construction equipment. Table 5 summarizes the ultimate bearing capacity of the ground and the calculated factor of safety against bearing capacity failure.

Table 5-Summary of calculated factor of safety against bearing capacity failure

Equipment	Standard Shoe Width, B (inches)	q_{ult}(1) (psi)	Ground Pressure, q_{eqp}, (psi)	Factor of safety, (q_{ult}/q_{eqp})
CAT D6R	22	17.1	8.82	1.94

NOTES:

(1) Soil unit weight assumed to be 120 pcf.

SUMMARY

Based on the analysis presented here, the typical construction equipment operating with a minimum of one foot of cover soil will not compromise the geomembrane puncture resistance or cause a bearing capacity failure of the overlying soil. Other vehicles with equal or lower ground pressures may also operate safely.

REFERENCES

Caterpillar Performance Handbook, 32 edition, Oct. 2001.

"Foundations and Earth Structures Design Manual 7.2", Department of the Navy, Naval Facilities Engineering Command, Alexandria, Virginia, May 1982.

Geosynthetics Research Institute, GM13, 1999.

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

FIGURE

High Density Polyethylene Super Gripnet® Liner

agru america

Product Data

Property	Test Method	Values			
Thickness (min. ave.), mil (mm)	ASTM D5994*	50 (1.25)	60 (1.5)	80 (2.0)	100 (2.5)
Thickness (lowest indiv.), mil (mm)	ASTM D5994*	50 (1.25)	54 (1.35)	72 (1.8)	90 (2.25)
*The thickness values may be changed due to project specifications (i.e., absolute minimum thickness)					
Drainage Stud Height (min. ave.), mil (mm)	ASTM D7466	130 (3.30)	130 (3.30)	130 (3.30)	130 (3.30)
Friction Spike Height (min. ave.), mil (mm)	ASTM D7466	175 (4.45)	175 (4.45)	175 (4.45)	175 (4.45)
Density, g/cc, minimum	ASTM D792, Method B	0.94	0.94	0.94	0.94
Tensile Properties (ave. both directions)	ASTM D6693, Type IV				
Strength @ Yield (min. ave.), lb/in width (N/mm)	2 in/minute	110 (19.3)	132 (23.1)	176 (30.8)	220 (38.5)
Elongation @ Yield (min. ave.), % (GL=1.3in)	5 specimens in each direction	13	13	13	13
Strength @ Break (min. ave.), lb/in width (N/mm)		110 (19.3)	132 (23.1)	176 (30.8)	220 (38.5)
Elongation @ Break (min. ave.), % (GL=2.0in)		200	200	200	200
Tear Resistance (min. ave.), lbs. (N)	ASTM D1004	38 (169)	40 (178)	53 (236)	64 (285)
Puncture Resistance (min. ave.), lbs. (N)	ASTM D4833	80 (356)	90 (400)	120 (534)	150 (667)
Carbon Black Content (range in %)	ASTM D4218	2 - 3	2 - 3	2 - 3	2 - 3
Carbon Black Dispersion (Category)	ASTM D5596	Only near spherical agglomerates			
	for 10 views: 9 views in Cat. 1 or 2, and 1 view in Cat. 3				
Stress Crack Resistance (Single Point NCTL), hours	ASTM D5397, Appendix	300	300	300	300
Oxidative Induction Time, minutes	ASTM D3895, 200°C, 1 atm O_2	≥100	≥100	≥100	≥100
Melt Flow Index, g/10 minutes	ASTM D1238, 190°C, 2.16kg	≤1.0	≤1.0	≤1.0	≤1.0
Oven Aging	ASTM D5721	80	80	80	80
with HP OIT, (% retained after 90 days)	ASTM D5885, 150°C, 500psi O_2				
UV Resistance	GRI GM11	20hr. Cycle @ 75°C/4 hr. dark condensation @ 60°C			
with HP OIT, (% retained after 1600 hours)	ASTM D5885, 150°C, 500psi O_2	50	50	50	50

These product specifications meet or exceed GRI's GM13

Supply Information (Standard Roll Dimensions)

Thickness		Width		Length		Area (approx.)		Weight (average)*	
mil	mm	ft	m	ft	m	ft^2	m^2	lbs	kg
50	1.25	23	7	300	91.435	6,900	640.05	2,800	1,270.06
60	1.5	23	7	300	91.435	6,900	640.05	2,900	1,315.42
80	2.0	23	7	300	91.435	6,900	640.05	3,100	1,406.14
100	2.5	23	7	300	91.435	6,900	640.05	4,000	1,814.40

Notes:

All rolls are supplied with two slings. All rolls are wound on a 6 inch core. Special lengths are available on request. All roll lengths and widths have a tolerance of ±1%

**The weight values may change due to project specifications (i.e. absolute minimum thickness or special roll lengths) or shipping requirements (i.e. international containerized shipments).*

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Figure 1 Specification of Super Gripnet Geomembrane