APPENDIX H.4

BEARING CAPACITY OF LANDFILL FOUNDATION

Shaw® Shaw Environmental, Inc.

Client: Clinton Landfill, Inc.
Project: Clinton LF No. 3 Chemical Waste Unit
Proj. #: 128017
Calculated By: PCT Date: 9/26/07
Checked By: JPV Date: 9/27/07

TITLE: BEARING CAPACITY OF LANDFILL FOUNDATION

Problem Statement

Determine the factor of safety against bearing capacity failure of the landfill foundation. 35 Ill. Admin. Code Section 811.304 (c) requires that "the solid waste disposal unit shall be designed to achieve a safety factor against bearing capacity failure of at least: 2.0 under static conditions and 1.5 under seismic loadings."

Given

- ❑ Coduto, Donald P, *Foundation Design Principles and Practices*. Second Edition. (Refer to the attached pages).
- ❑ Appendix H.1 "Summary of Geotechnical Parameters" contained in this application.
- ❑ Caterpillar Performance Handbook. Edition 32. (Refer to attached pages).
- ❑ Hydrogeologic Report, contained in this application.
- ❑ Landfill design specifications for layer types and thicknesses from this application.
- ❑ Design grades for the mass liner grades and final landform contained in this application.

Assumptions

The following conservative assumptions were utilized in the analysis:

Scenarios

1. Compacted soil liner bearing capacity for the final landform (long-term-drained conditions)
2. Compacted soil liner bearing capacity under vehicle loading (short-term-undrained conditions)

Weakest Foundation Material

- ❑ The landfill is keyed into the Berry Clay and Radnor Till (Foundation Materials). Based on laboratory triaxial shear strength tests performed on representative site soil samples, the effective shear strength of this soil was determined to be a friction angle, ϕ', equal to 18 degrees and a cohesion, c', equal to 1,100 psf; and the total shear strength to be a friction angle, ϕ, equal to 0 degrees and a cohesion, c, equal to 6,000 psf.

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Landfill Properties

- The following unit weight values were conservatively utilized (refer to Appendix H.1):
  - Foundation soils - 148 pcf (saturated);
  - Compacted Cohesive Earth Liner and Compacted Fill / Sub-base - 140 pcf (saturated);
  - Leachate Collection System drainage layer - 130 pcf (saturated);
  - Chemical Waste - 90 pcf (moist);
  - MSW - 75 pcf (moist); and
  - Final Cover soils - 128 pcf (moist).

- The maximum waste thickness in the Chemical Waste Unit occurs at the northern portion of the Chemical Waste Unit, over the Chemical Waste Unit north sideslope and includes the MSW piggyback waste fill. This waste thickness was estimated to be approximately 167.6 feet which breaks down as follows:
  - 118.9 ft. of MSW + 48.7 ft. of Chemical Waste = 167.6 ft.

- At the peak waste height of the Chemical Waste fill, which occurs at the center of the Chemical Waste Unit, the maximum waste thickness is approximately 153.1 ft. This waste thickness breaks down as follows:
  - 13.1 ft. of MSW + 140 ft. of Chemical Waste = 153.1 ft.

- Two scenarios were evaluated: Scenario 1 evaluates the bearing capacity at the maximum waste height of 167.6 ft; and Scenario 2 evaluates the bearing capacity at the maximum waste height of 153.1 ft. The elevation and thickness of each layer used in these calculations are summarized below (refer to Design Drawings).

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Scenario 1 Summary of Average Thickness of Landfill Layers		
Layer	**Top Elevation (ft. MSL)**	**Thickness (ft.)**
Final Cover System	842.6	4.0
MSW	838.6	118.9
Chemical Waste	719.7	48.7
Leachate Collection System	671.0	1.0
Compacted Cohesive Earth Liner + Compacted Fill / Sub-base	670.0	10.0
Foundation Materials	660.0	-
Total Height of Landfill, H =		**182.6**

Scenario 2 Summary of Average Thickness of Landfill Layers		
Layer	**Top Elevation (ft. MSL)**	**Thickness (ft.)**
Final Cover System	827.1	4.0
MSW	823.1	13.1
Chemical Waste	810.0	140.0
Leachate Collection System	670.0	1.0
Compacted Cohesive Earth Liner + Compacted Fill / Sub-base	669.0	9.0
Foundation Materials	660.0	-
Total Height of Landfill, H =		**167.1**

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- The length and width of the smallest chemical waste cell is approximately 407 feet by 1,112 feet, respectively. To be conservative, only half of the cell width was used in the calculations (B = 203.5 feet).

Horizontal Acceleration

- From Appendix H.1, the maximum horizontal acceleration is approximately 0.0981 g.

Bearing Capacity Equation for Static Conditions

- Karl Terzaghi's bearing capacity equation for square footings is used to calculate bearing capacity of landfill foundation for static conditions. Due to the size and depth of the landfill, the equation is overly conservative for landfills.

$$q_{ult} = 1.3cN_c + S'_{zD}N_q + 0.4g'BN_g$$

Where,

q_{ult}	= Ultimate bearing capacity, psf
c, c'	= Cohesion of soil, psf
σ'_{zD}	= Vertical effective stress
γ'	= Buoyant unit weight of soil, pcf
B	= Width of foundation, feet
N_c, N'_q, N_γ	= Nondimensional factors, functions of ϕ
ϕ, ϕ'	= Soil friction angle, degrees

For Short - Term Loading Conditions :

$$f = 0^\circ \text{ ®} \; N_c = 5.7, N_q = 1.0, N_g = 0.0$$

For Long - Term Loading Conditions :

$$f = 18^\circ \text{ ®} \; N_c = 15.5, N_q = 6.0, N_g = 3.3$$

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Bearing Capacity Equation for Seismic Conditions

- For seismic conditions, the total stress on the structural backfill is equal to the effective overburden stress and the increase in stress due to overturning moment, σ_M, which is calculated using the following equation.

$$\sigma_M = \frac{Mc}{I}$$

$$M = B * L * H * \gamma\left(\frac{H}{2}\right)(Horiz.Accel.)$$

$$I = \frac{LB^3}{12}$$

Where,

M = Overturning moment
c = Distance from center
I = Moment of Inertia
B = Width of foundation
L = Length of foundation
H = Height of landfill

Factor of Safety

- For both static and seismic conditions, the factor of safety, FS, is calculated using the following equation:

$$FS = \frac{q_{ult}}{\sigma_v'}$$

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Scenario 1 Calculations

Calculate ultimate bearing capacity, q_{ult} on the Foundation Materials. Conservatively assume that the vertical effective stress (σ'_{zD}) is zero.

Short-Term Loading Conditions

$$q_{ult} = 1.3cN_c + s_{zD}N_q + 0.4g\,BN_g$$
$$q_{ult} = (1.3)(6,000)(5.7) + (0)(1.0) + (0.4)(148.0 - 62.4)(203.5)(0.0)$$
$$q_{ult} = 44,460 \text{ psf}$$

Long-Term Loading Conditions

$$q_{ult} = 1.3cN_c + s'_{zD}N_q + 0.4g'\,BN_g$$
$$q_{ult} = (1.3)(1,100)(15.5) + (0)(6.0) + (0.4)(148 - 62.4)(203.5)(3.3)$$
$$q_{ult} = 45,159 \text{ psf}$$

Compacted Soil Liner Bearing Capacity under Final Landform Loading

Calculate the effective overburden stress (σ'_v) due to waste and soil load for the worst case conditions.

Scenario 1 Effective Overburden Stress, σ'_v, on the Foundation Materials From Final Landform			
Layer	**Thickness, t (ft)**	**Density, γ (pcf)**	**σ'_v = (t) x (γ) (psf)**
Final Cover	4.0	128	512.0
MSW	118.9	75	8,917.5
Chemical Waste	48.7	90	4,383.0
Leachate Drainage Layer	1.0	130	130.0
Compacted Cohesive Earth Liner + Compacted Fill / Sub-base	10.0	(140-62.4) = 77.6	776.0
Total Thickness =	**182.6**	**Σ(σ'_v) =**	**14,718.5**
Weighted Average γ'_v =		**80.6 pcf**	

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Factor of Safety against bearing capacity failure, static conditions, FS:

$$F.S._{static} = \frac{q_{ult}}{s_v} = \frac{44,460}{14,718.5} = 3.02$$

Seismic Conditions

First, calculate the increase in stress due to the overturning moment, σ_M.

$$M = BLHg_{weighted}\left(\frac{H}{2}\right)(\text{Horz.Accel.}) = (203.5)(1,112)(182.6)(80.6)\left(\frac{182.6}{2}\right)(0.0981) = 2.98\text{x}10^{10}\,\text{lb} * \text{ft}$$

$$c = \frac{B}{2} = \frac{407}{2} = 203.5\,\text{ft}$$

$$I = \frac{LB^3}{12} = \frac{(1,112)(203.5)^3}{12} = 7.809\text{x}10^8\,\text{ft}^4$$

$$s_M = \frac{Mc}{I} = \frac{(2.98\text{x}10^{10})(203.5)}{7.809\text{x}10^8} = 7,765.8\,\text{psf}$$

Factor of Safety against bearing capacity failure, seismic conditions, FS

$$F.S._{seismic} = \frac{q_{ult}}{s_v + s_m} = \frac{44,460}{14,718.5 + 7,765.8} = 1.98$$

Compacted Soil Liner Bearing Capacity under Vehicle Loading

Calculate the effective overburden stress (σ'_v) due to the placement of the leachate collection system, clay liner and loading by a vehicle (compactor). Conservatively assume that the vehicle load does not attenuate with depth.

Assume loading by CAT 826G compactor (Caterpillar Performance Handbook, Ed. 32)

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:

Weight of the Vehicle (W_{eq}):

$$W_{eq} = 73{,}370 \text{ lb}$$

Contact Pressure (P):

$$P = \frac{73{,}370 \text{ lb}}{(4 \text{ drums} \times \text{Contact Area of Drums})}$$

$$P = \frac{73{,}370 \text{ lb}}{\left(4 \text{ drums} \times \left(3.92 \text{ ft} \times (1/3) \times 6.0 \text{ ft}\right)\right)}$$

$$P = 2{,}340 \text{ psf}$$

Scenario 1 Effective Overburden Stress, σ'_v, on Foundation Materials from Vehicle Load			
Layer	**Thickness, t (ft)**	**Density, γ (pcf)**	**σ'_v = (t) x (γ) (psf)**
Vehicle Load	-	2,340	2,340
Drainage Material	1.0	130	130
Compacted Cohesive Earth Liner + Compacted Fill / Sub-base	10.0	(140-62.4) = 77.6	776
Total Thickness =	**11**	**Σ (σ'_v) =**	**3,246**

Factor of Safety against bearing capacity failure, vehicle loading, FS:

$$F.S._{seismic} = \frac{q_{ult}}{s_v} = \frac{44{,}460}{3{,}246} = 13.70$$

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Scenario 2 Calculations

Calculate ultimate bearing capacity, q_{ult} on the Foundation Materials. Conservatively assume that the vertical effective stress (σ'_{zD}) is zero.

Short-Term Loading Conditions

$$q_{ult} = 1.3cN_c + s_{zD}N_q + 0.4g\,BN_g$$
$$q_{ult} = (1.3)(6,000)(5.7) + (0)(1.0) + (0.4)(148.0 - 62.4)(203.5)(0.0)$$
$$q_{ult} = 44,460 \text{ psf}$$

Long-Term Loading Conditions

$$q_{ult} = 1.3cN_c + s'_{zD}N_q + 0.4g'\,BN_g$$
$$q_{ult} = (1.3)(1,100)(15.5) + (0)(6.0) + (0.4)(148 - 62.4)(203.5)(3.3)$$
$$q_{ult} = 45,159 \text{ psf}$$

Compacted Soil Liner Bearing Capacity under Final Landform Loading

Calculate the effective overburden stress (σ'_v) due to waste and soil load for the worst case conditions.

Scenario 2 Effective Overburden Stress, σ'_v, on the Foundation Materials From Final Landform			
Layer	**Thickness, t (ft)**	**Density, γ (pcf)**	**σ'_v = (t) x (γ) (psf)**
Final Cover	4.0	128	512.0
MSW	13.1	75	982.5
Chemical Waste	140.0	90	12,600.0
Leachate Drainage Layer	1.0	130	130.0
Compacted Cohesive Earth Liner + Compacted Fill / Sub-base	9.0	(140-62.4) = 77.6	698.4
Total Thickness =	**167.1**	**$\Sigma(\sigma'_v)$ =**	**14,922.9**
Weighted Average γ'_v =		**89.3**	

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Factor of Safety against bearing capacity failure, static conditions, FS:

$$F.S._{static} = \frac{q_{ult}}{s_v} = \frac{44,460}{14,929.9} = 2.98$$

Seismic Conditions

First, calculate the increase in stress due to the overturning moment, σ_M.

$$M = BLHg_{weighted}\left(\frac{H}{2}\right)(\text{Horz.Accel.}) = (203.5)(1,112)(167.1)(89.3)\left(\frac{167.1}{2}\right)(0.0981) = 2.767x10^{10}\,\text{lb} * \text{ft}$$

$$c = \frac{B}{2} = \frac{407}{2} = 203.5\,\text{ft}$$

$$I = \frac{LB^3}{12} = \frac{(1,112)(203.5)^3}{12} = 7.809x10^8\,\text{ft}^4$$

$$s_M = \frac{Mc}{I} = \frac{(2.767x10^{10})(203.5)}{7.809x10^8} = 7,210.7\,\text{psf}$$

Factor of Safety against bearing capacity failure, seismic conditions, FS:

$$F.S._{seismic} = \frac{q_{ult}}{s_v + s_m} = \frac{44,460}{14,922.9 + 7,210.7} = 2.01$$

Compacted Soil Liner Bearing Capacity under Vehicle Loading

Calculate the effective overburden stress (σ'_v) due to the placement of the leachate collection system, clay liner and loading by a vehicle (compactor). Conservatively assume that the vehicle load does not attenuate with depth.

Assume loading by CAT 826G compactor (Caterpillar Performance Handbook, Ed. 32)

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Weight of the Vehicle (W_{eq}):

$$W_{eq} = 73,370 \text{ lb}$$

Contact Pressure (P):

$$P = \frac{73,370 \text{ lb}}{(4 \text{ drums} \cdot \text{Contact Arean of Drums})}$$

$$P = \frac{73,370 \text{ nlb}}{(4 \text{ drums} \cdot (3.92 \text{ ft} \cdot (1/3) \cdot 6.0 \text{ ft}))}$$

$$P = 2,340 \text{ psf}$$

Scenario 2 Effective Overburden Stress, σ'_v, on Foundation Materials from Vehicle Load			
Layer	**Thickness, t (ft)**	**Density, γ (pcf)**	**σ'_v = (t) x (γ) (psf)**
Vehicle Load	-	2,340	2,340
Drainage Material	1.0	130	130
Compacted Cohesive Earth Liner + Compacted Fill / Sub-base	9.0	(140-62.4) = 77.6	698.4
Total Thickness =	**10**	$\Sigma (\sigma'_v)$ =	**3,168.4**

Factor of Safety against bearing capacity failure, vehicle loading, FS:

$$F.S._{seismic} = \frac{q_{ult}}{s_v} = \frac{44,460}{3,168.4} = 14.03$$

Results

The Clinton Landfill No. 3 / Chemical Waste Unit has been designed to achieve a minimum factor of safety against bearing capacity failure of 2.0 under static conditions and 1.5 under seismic conditions. A summary of the determined factors of safety against bearing capacity failure of the landfill foundation is presented in the following table.

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Factors of Safety Against Bearing Capacity Failure Summary			
Scenario 1			
Conditions	**Calculated FS**	**Required FS**	**Compliance**
Static	3.02	2.0	✓
Seismic	1.98	1.5	✓
Vehicle Loading	13.70	2.0	✓
Scenario 2			
Conditions	**Calculated FS**	**Required FS**	**Compliance**
Static	2.98	2.0	✓
Seismic	2.01	1.5	✓
Vehicle Loading	14.03	2.0	✓

Scale 1:2585.8

Clinton Landfill No. 3 / Chemical Waste Unit
Bearing Capacity of Landfill Foundation
Scenarios 1 and 2 Locations