APPENDIX III-D.5-4

LANDFILL FOUNDATION SETTLEMENT, WASTE SETTLEMENT, AND SOIL LINER STRAIN ANALYSES

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CB&I

CB&I Environmental & Infrastructure	**Client Name:** Rancho Viejo Waste Management, LLC			
	Project Name:	Pescadito Environmental Resource Center	**Project No.:**	148866
	Prepared by:	P.Thomas	**Date Prepared:**	02/24/2015
	Reviewed by:	Jesse P. Varsho, PE	**Date Reviewed:**	03/02/2015

TITLE: LANDFILL FOUNDATION SETTLEMENT, WASTE SETTLEMENT, AND SOIL LINER STRAIN ANALYSES

Problem Statement

Determine the consolidation settlement of 1) the landfill foundation, and 2) the waste; and determine the strain on the soil liner due to the foundation settlement. The consolidation due to waste placement at critical locations is evaluated to determine the differential settlement between these locations. The calculations are performed to demonstrate that the leachate collection system will maintain a positive slope, and the final cover system and soil liner will not be damaged due to differential settlement.

References

The referenced literature cited below is provided in the attached pages. Referenced site specific information is provided within the Application as stated below.

1. Mass excavation grades, liner grades, and final landform grades presented on plan drawings contained in Design Drawing Set of this Application.
2. Summary of Geotechnical Design Parameters contained in **Appendix III-D.5-1** of this Report.
3. The site Geology Report (dated 2015) contained in this Application — as it pertains to subsurface investigative data (i.e., potentiometric levels) refer to Appendix III-E.1 of the Geology Report.
4. Figures 1 and 2 presenting locations of analyzed settlement points (attached pages).
5. Microsoft Excel foundation and waste settlement calculation spreadsheets (attached pages).

6. Coduto, Donald P. (2001). “Foundation Design Principles and Practices.” Prentice-Hall, 2nd Edition, 2001.
7. Sharma, H.D., and Anirban, D. (2007). “Municipal Solid Waste Landfill Settlement: Postclosure Perspectives.” Journal of Geotechnical and Geoenvironmental Engineering, 133(6), 619-629.
8. Qian, X., Koerner, R.M., and Gray, D.H. (2002). “Geotechnical Aspects of Landfill Design and Construction. Prentice-Hall, 2001.

Assumptions

Locations Analyzed for Foundation Settlement

To analyze potential impacts due to differential settlement of the landfill liner / leachate collection system, locations of where the largest differential settlement would occur were evaluated. From this evaluation, the largest differential settlement of the landfill liner system / foundation is expected to occur in the South Unit landfill between foundation settlement points **F1** and **F2** (as shown on **Figure 1** in **Reference No. 4**) for the following reasons:

- Foundation settlement points F1 and F2 are located where the maximum and minimum waste column thicknesses occur, respectively; and
- Foundation settlement points F1 and F2 are located where the highest gradient for the final landform grades occurs, and the lowest gradient for the leachate collection system grades occurs.

Settlement point **F1** is located approximately **1,470 feet east** of settlement point **F2**. The base elevation difference of the two settlement points is controlled by the **0.50%** gradient leachate pipe run.

Table 1 on the following page provides the elevations of the foundation settlement points, and the elevations and thicknesses of the relevant landfill system layers. The foundation settlement point locations are presented on **Figure 1** (**Reference No. 4**).

The leachate collection system (LCS) grades will settle as the compacted low permeable soil liner settles. The analysis that follows in this section, calculates the settlement in the compressible layers beneath the LCS:

- The compacted low permeable soil liner (3-ft); and
- Native soils that lie 50-ft beneath the proposed landfill bottom (i.e., 50-ft below the compacted low permeable soil liner).

*Note, the native soils were determined to be overconsolidated (**Reference No. 2**) and the overburden pressure that will be due to the final landform (i.e., complete landfill build-out) at the point of maximum waste column thickness (approximately 380 feet) will be significantly less than the preconsolidation pressure that was calculated (**Reference No. 2**). Therefore the assumption that the native soils 50-ft beneath the landfill bottom will settle is conservative for the purposes of this settlement calculation.*

Locations Analyzed for Waste Settlement

To analyze potential impacts due to differential settlement on the final cover system, locations of where the largest differential settlement of the waste would occur were evaluated. From this evaluation, the largest differential settlement of waste is expected to occur between the point of maximum waste thickness and the point of minimum waste thickness (at the edge of the landfill) or:

- Maximum waste thickness of **380 feet** at waste settlement point **W1**, and
- Minimum waste thickness of **0 feet** at the edge of the landfill at waste settlement point **W2**.

The horizontal distance between the waste settlement points **W1** and **W2** is approximately **1,846 feet**. **Table 1** below provides the elevations of the waste settlement points, and the elevations and thicknesses of the relevant landfill system layers. The waste settlement point locations are presented on **Figure 2**. (**Reference No. 4**).

Table 1
Elevations of Material Layers
at Foundation and Waste Settlement Points

Settlement Point Locations	Elevation of Top of Final Landform / Final Cover	Final Cover Thickness	Waste Column Thickness	Elevation of Top of Protective Soil Cover	Protective Soil Cover Thickness	Elevation of Top of Compacted Low Permeable Soil Liner	Compacted Low Permeable Soil Liner Thickness
Foundation Settlement Points:							
F1	834 -ft.MSL	3 -ft	380	451 -ft.MSL	2 -ft	449 -ft.MSL	3 -ft
F2	642 -ft.MSL	3 -ft	195	444 -ft.MSL	2 -ft	442 -ft.MSL	3 -ft
Waste Settlement Points:							
W1	842 -ft.MSL	3 -ft	380	459 -ft.MSL	2 -ft	457 -ft.MSL	3 -ft
W2	552 -ft.MSL	3 -ft	0	549 -ft.MSL	2 -ft	547 -ft.MSL	3 -ft

Note:
Maximum waste column thickness of 380 feet (occuring near approximate center of landfill) was conservatively assumed in settlement calculations.

Initial Site Conditions

Table 2 on the following page summarizes the geologic site stratigraphy prior to landfill development. Native soils will be excavated down to mass excavation grades (i.e., bottom of compacted soil liner elevation) — specifically, to elevations **446-ft.MSL** and **439-ft.MSL** at points **F1** and **F2**, respectively. The average potentiometric surface was assumed to be at elevation **538 ft. MSL** (**Reference No. 3**).

Final Site Conditions

Table 2 on the following page summarizes the stratigraphy of the landfill system layers at the time of complete landfill build-out. Inside the landfill, the potentiometric surface is assumed to be at the top of the LCS drainage geocomposite or approximately 1 inch above the compacted low permeable soil liner. Materials that are below the assumed potentiometric surface are assumed to be saturated.

Table 2
Descriptions of Site Stratigraphy At Foundation Settlement Points (F1, F2)
BEFORE and AFTER Landfill Development

Geologic and Landfill System Layer Descriptions	Top Elevation of Layer	Thickness	Moist Unit Weight	Saturated Unit Weight
At Point F1: BEFORE Landfill Development				
Stratum II-III-IV (excavated, dry)	541 -ft.MSL	3 -ft	129 pcf	132 pcf
Stratum II-III-IV (excavated, saturated)	538 -ft.MSL	90 -ft	129 pcf	132 pcf
Stratum II-III-IV (compressible, saturated)	446 -ft.MSL	50 -ft	129 pcf	132 pcf
Stratum II-III-IV (incompressible, saturated)	396 -ft.MSL	-	-	-
At Point F1: AFTER Landfill Development				
Final Cover System	834 -ft.MSL	3 -ft	129 pcf	132 pcf
Waste Fill	831 -ft.MSL	380 -ft	65 pcf	65 pcf
Protective Soil Cover	451 -ft.MSL	2 -ft	129 pcf	132 pcf
Compacted Low Permeable Soil Liner	449 -ft.MSL	3 -ft	129 pcf	132 pcf
Stratum II-III-IV (compressible, saturated)	446 -ft.MSL	50 -ft	129 pcf	132 pcf
Stratum II-III-IV (incompressible, saturated)	396 -ft.MSL	-	-	-
At Point F2: BEFORE Landfill Development				
Stratum II-III-IV (excavated, dry)	540 -ft.MSL	2 -ft	129 pcf	132 pcf
Stratum II-III-IV (excavated, saturated)	538 -ft.MSL	96 -ft	129 pcf	132 pcf
Stratum II-III-IV (compressible, saturated)	439 -ft.MSL	50 -ft	129 pcf	132 pcf
Stratum II-III-IV (incompressible, saturated)	389 -ft.MSL	-	-	-
At Point F2: AFTER Landfill Development				
Final Cover	642 -ft.MSL	3 -ft	129 pcf	132 pcf
Waste	639 -ft.MSL	193 -ft	65 pcf	65 pcf
Protective Soil Cover	444 -ft.MSL	2 -ft	129 pcf	132 pcf
Compacted Low Permeable Soil Liner	442 -ft.MSL	3 -ft	129 pcf	132 pcf
Stratum II-III-IV (compressible, saturated)	439 -ft.MSL	50 -ft	129 pcf	132 pcf
Stratum II-III-IV (incompressible, saturated)	389 -ft.MSL	-	-	-

Liner / Foundation Settlement Equations

Consolidation is divided into three categories: 1) immediate settlement, 2) primary consolidation settlement, and 3) secondary settlement. Immediate settlement is caused by the elastic deformation of soils without any change in the moisture content. Primary consolidation in saturated fine-grained soils occurs due to the expulsion of water in response to an increase in effective stress. Following primary consolidation under a constant effective stress is secondary consolidation. Primary and secondary consolidations are calculated for the compacted low permeable soil liner. It was determined that the native soils below the low permeability soil liner are overconsolidated (**Reference No. 2**).

Primary Settlement

For overconsolidated soils, where $\sigma'_o < \sigma'_f \leq \sigma'_p$, primary settlement is determined using the following equation:

$$S_p = \frac{C_r}{1+e_0} * H * \log\left(\frac{\sigma'_f}{\sigma'_o}\right)$$

Where,

S_p = Primary Settlement, feet
C_r = Recompression Index
H = Thickness of the layer, feet
e_o = Initial void ratio
σ'_o = Initial vertical effective stress, psf
σ'_f = Final vertical effective stress, psf

Consolidation parameters have been summarized in **Appendix III-D.5-1** of this Report (**Reference No. 2**).

Secondary Settlement

It is conservatively assumed that primary consolidation is complete subsequent to final cover placement. Secondary consolidation is calculated using the following equation.

$$S_s = \frac{C_\alpha}{1+e_p} * H * \log\left(\frac{T_2}{T_1}\right)$$

Where:

S_S = Secondary settlement, feet
C_α = Secondary compression index
H = Thickness of Layer, feet
e_p = Void Ratio at end of primary consolidation
= e_o (to be conservative)
T_1 = Time at start of secondary compression, years
T_2 = Time at end of observation period, years

Values of C_α used in the settlement analyses have been summarized in **Appendix III-D.5-1** of this Report (**Reference No. 2**).

Final Cover / Waste Settlement Equations

The waste settlement calculations are based on Terzaghi's theory of one-dimensional consolidation in which the primary settlement, time of primary settlement, and secondary settlement are evaluated. However waste will not experience primary consolidation in the manner of a saturated soil. Waste will undergo initial and primary compression. Both types of compression occur rapidly and are grouped together. The primary settlement is calculated incrementally for nineteen (19) fill lifts of waste and one lift for the final cover placement for one landfill cell. It is assumed that each lift of waste is 20-feet thick and each lift will take 3 months to complete. The estimate for primary settlement assumes that as each lift (or load) is placed large settlements will occur rapidly with no pore pressure build up.

The time of primary compression is estimated to be completed within 2 to 30 days following loading. From this estimate, we can assume that the final cover will only be subjected to the primary settlement from the final lift of the landfill plus secondary settlement that will occur during post-construction / post-closure. The waste settlement calculations focus on the post-closure settlement to evaluate the potential for damage to the final cover system.

The secondary settlement was calculated based on Terzaghi's time-settlement relationship. Because it is assumed that secondary settlement occurs by the self-weight of each fill lift, the secondary settlement is calculated for each lift individually, and then summed to provide a total value for secondary settlement.

Liner / Foundation Settlement Calculations

The equations presented on the previous page were used to estimate the foundation settlement at Points F1 and F2. The thickness of waste at points **F1** and **F2** are **380 feet** and **195 feet**, respectively. The final effective overburden stress and settlement vary accordingly.

Initial Effective Stress. The initial effective stress of the in-situ materials is the average effective stress prior to excavation and waste placement. The initial effective stress for the compacted low permeable soil liner was calculated as the weight of itself. The effective stress is calculated at the center of each geologic unit / layer (please refer to the attached spreadsheets for calculations, provided as **Reference No. 5**).

Final Effective Stress. The final effective stress is the effective stress following final cover placement and varies for settlement points F1 and F2. The effective stress is calculated at the center of each geologic unit / layer (please refer to the attached spreadsheets for calculations, provided as **Reference No. 5**). The effective stress values for initial and final conditions, for each geologic / landfill layer are summarized on **Tables 3** and **4** on the following page.

Table 3
Initial and Final Effective Stresses

Geologic Unit / Landfill Layer	Initial Effective Stress		Final Effective Stress	
	Point F1	Point F2	Point F1	Point F2
Compacted Low Permeable Soil Liner	104.4 psf	104.4 psf	25,226.7 psf	13,245.7 psf
Stratum II-III-IV	8,530.2 psf	8,679.6 psf	27,304.5 psf	15,020.5 psf

Primary and Secondary Consolidation Settlement

Table 4 below summarizes the calculated settlement at foundation settlement points F1 and F2. Detailed spreadsheets providing a breakdown of the calculations are provided in the attached pages (**Reference No. 5**).

Table 4
Liner / Foundation Settlement

Landfill Layer	Primary Settlement	Secondary Settlement	TOTAL Settlement
Settlement at Point F1:			
Compacted Low Permeable Soil Liner	0.265559595 -ft	0.007467012 -ft	0.273026607 -ft
Stratum II-III-IV	0.938148023 -ft	0.124450206 -ft	1.062598229 -ft
TOTAL:	1.203707618 -ft	0.131917218 -ft	1.335624836 -ft
Settlement at Point F2:			
Compacted Low Permeable Soil Liner	0.234127669 -ft	0.007467012 -ft	0.241594681 -ft
Stratum II-III-IV	0.442355799 -ft	0.124450206 -ft	0.566806004 -ft
TOTAL:	0.676483468 -ft	0.131917218 -ft	0.808400685 -ft

Total Liner / Foundation Settlement. The total settlement of the foundation soils is equal to the summation of the settlement of each geologic unit. The elevation of the top of the compacted low permeability soil liner after settlement will be approximately:

- At Settlement Point F1: (EL. 449-ft MSL) - (1.335624836-ft) = EL. 447.664-ft MSL
- At Settlement Point F2: (EL. 442-ft MSL) - (0.808400685-ft) = EL. 441.192-ft MSL

Differential Settlement

The differential settlement between Points F1 and F2 are calculated as follows:

$$S_{diff} = \frac{|S_{pt.F1} - S_{pt.F2}|}{Horizontal\ Distance_{pt.F1/pt.F2}} \times 100\%$$

$$S_{diff} = \frac{|1.335624836\ ft - 0.808400685\ ft|}{1{,}470\ ft} = \mathbf{0.03586}\%$$

Slope of Leachate Collection System

The leachate collection system (LCS) is designed with a **slope of 0.50%** (slope along LCS collection pipe). During waste placement and post-closure care, differential settlement will occur. At the end of the post-closure care period, the final slope between points **F1** and **F2** will be:

$$Slope_{diff} = \frac{Elev_{pt.F1} - Elev_{pt.F2}}{Horizontal\ Distance_{pt.F1/pt.F2}} \times 100\%$$

$$Slope_{diff} = \frac{(447.664\ ft - 441.192\ ft)}{1{,}470\ ft} \times 100\% = \mathbf{0.44027}\%$$

Compacted Low Permeable Soil Liner Strain

The maximum strain (ε) the compacted low permeable soil liner will experience from the foundation settlement will be equal to **0.0001646%** which is deemed within acceptable limits for a compacted clay soil, and therefore the soil liner integrity will not be compromised due to cracking (**Reference No. 8**).

$$\varepsilon_{F1,F1} = \frac{\left|\left(L_{F1,F2}\right)_{Final} - \left(L_{F1,F2}\right)_{Initial}\right|}{\left(L_{F1,F2}\right)_{Initial}} \times 100\%$$

$$\left(L_{F1,F2}\right)_{Initial} = \sqrt{(El.449ft - El.442ft)^2 + (1{,}470ft)^2} = 1470.016667ft$$

$$\left(L_{F1,F2}\right)_{Final} = \sqrt{(El.447.664ft - El.441.192ft)^2 + (1{,}470ft)^2} = 1470.014247ft$$

$$\varepsilon_{F1,F2} = \frac{|(1470.014247ft) - (1470.016667ft)|}{(1470.016667ft)} \times 100\%$$

$$\varepsilon_{F1,F2} = \mathbf{0.0001646}\%$$

A summary of the differential settlement, soil liner strain, and the initial and final LCS slopes between the foundation settlement point locations analyzed (i.e., F1 and F2) is presented below on **Table 5**.

Table 5
Summary of Foundation Differential Settlement,
Initial and Final LCS Slopes, and Soil Liner Strain

Location	Foundation Differential Settlement	Initial LCS Slope	Final LCS Slope	Compacted Low Permeable Soil Liner Strain
Between Settlement Points F1 and F2	0.03586%	0.5%	0.44027%	0.0001646%

Final Cover / Waste Settlement Calculations

The calculated settlement at settlement point **W1** is calculated to be approximately **48.02 feet** (refer to attached spreadsheets in **Reference No. 5**):

$$S_{pt.W1} = (\Delta S_p due\ to\ Final\ Cover\ Placement) + (\ \sum S_s\ following\ post\ construction, 30yrs.)$$

$$S_{pt.W1} = (2.16ft\ + 45.86ft) = \mathbf{48.02}\boldsymbol{ft}$$

Differential settlement between points **W1** and **W2** was calculated using a value of **48.02 feet**. At point **W2**, settlement is **0 feet**; therefore, the differential settlement between Points **W1** and **W2** is approximately **2.60 percent**:

$$S_{diff} = \frac{|S_{pt.W1} - S_{pt.W2}|}{Distance_{pt.W1/pt.W2}} \times 100\%$$

$$S_{diff} = \frac{|48.02\ ft - 0.00\ ft|}{1{,}846\ ft} = \mathbf{2.60}\%$$

Results

Foundation Settlement

The estimated maximum differential settlement of the landfill foundation is approximately 0.0003586 ft/ft. This settlement value is deemed negligible and will not cause failure of the liner or leachate collection system. The slope of the leachate collection system at the end of the post-closure care period will be approximately 0.44% which will allow for proper leachate drainage and collection.

Waste Settlement

The estimated maximum differential settlement of the landfill final slopes due to waste settlement is approximately 0.0260 ft/ft. This value is considered to be negligible and will not cause or contribute to the failure of the final cover system.

Reference No. 4

Figures 1 and 2

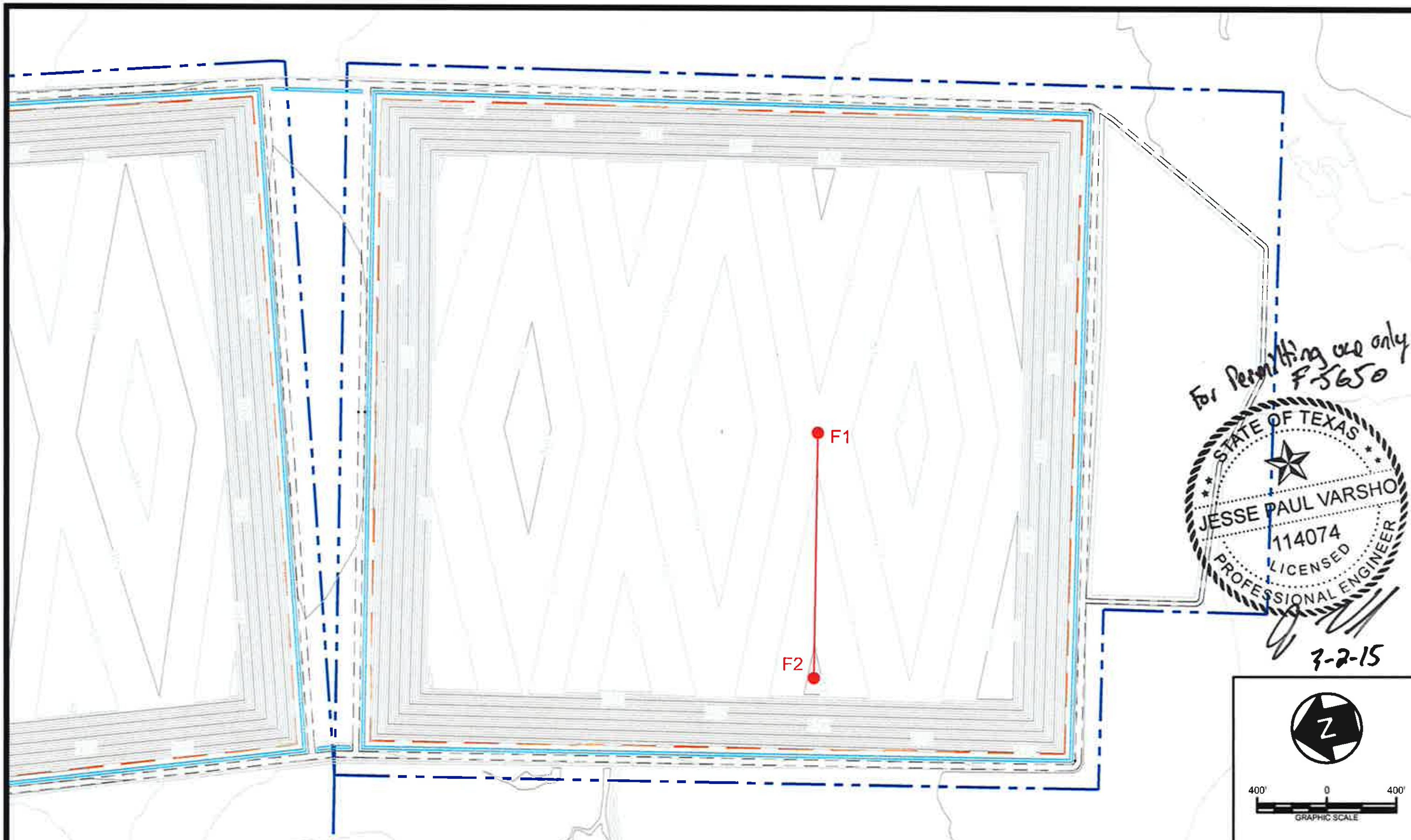

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FIGURE 1
LOCATION OF FOUNDATION SETTLEMENT POINTS SHOWN ON TOP OF MASS EXCAVATION GRADES

DRAWN BY:	MTE	APPROVED BY:	PCT	PROJ. NO.:	148866	DATE:	MARCH 2015

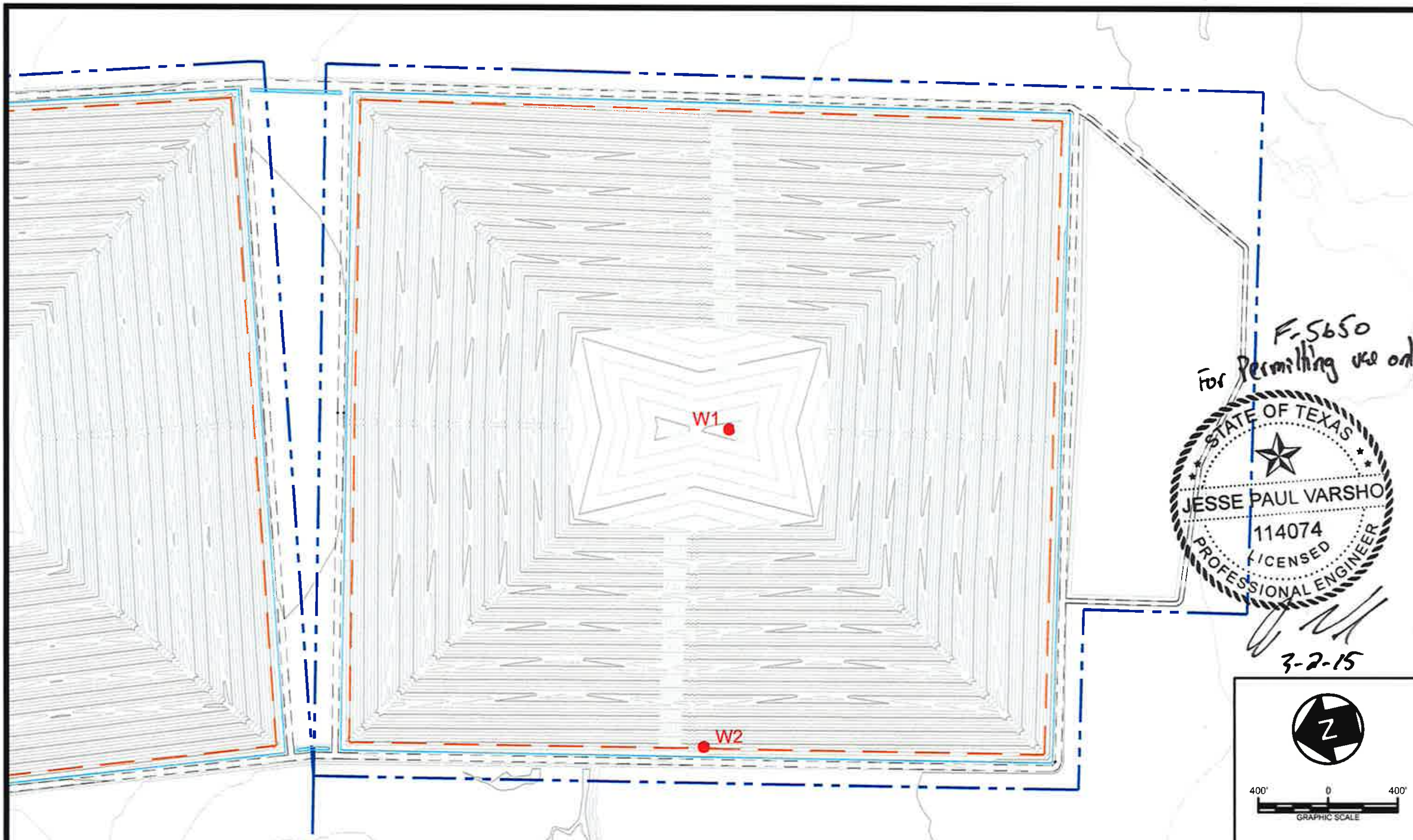

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FIGURE 2
LOCATION OF WASTE SETTLEMENT POINTS SHOWN ON TOP OF FINAL LANDFILL GRADES

DRAWN BY:	MTE	APPROVED BY:	PCT	PROJ. NO.:	148866	DATE:	MARCH 2015

Reference No. 5

Foundation and Waste Settlement Calculation Spreadsheets

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Stress concentrations through cross section of a Landfill

Company Name	CB&I
Project Name	Pescadito Landfill - South Unit
Project Number	148866
Date	2/12/2015
Units	English

Make sure that the cross sections for both the before and after landfill line up at the bottom geological units under the landfill liner.

Cross Section before landfill development
Settlement Point F1

Unit	Classification	Interval	Thickness (ft)	Relative Density (%)	Unit Weights (pcf) γsat	Unit Weights (pcf) γbuoyant	Mid-Layer Stresses (psf) σ' (effective)	Mid-Layer Stresses (psf) σ (total)	Bottom-Layer Stresses (psf) σ' (effective)	Bottom-Layer Stresses (psf) σ (total)
Example	EX	0-2	2		0	0	0.00	0.00	0.00	0.00
Stratum II-III-IV (excavated, dry)	CH	El. 541-538	3		129	129	193.50	193.50	387.00	387.00
Stratum II-III-IV (excavated, saturated)	CH	El. 538-446	92		132	69.6	3,588.60	6,459.00	6,790.20	12,531.00
Stratum II-III-IV (compressible, saturated)	CH	El. 446-396	50		132	69.6	8,530.20	15,831.00	10,270.20	19,131.00
Stratum II-III-IV (incompressible, saturated)	CH	El. 396-								

Stress concentrations through cross section of a Landfill

Company Name	CB&I
Project Name	Pescadito Landfill - South Unit
Project Number	148866
Date	2/12/2015
Units	English

Cross Section after Landfill
Settlement Point F-1

				Unit Weights (pcf)		Mid-Layer Stresses (psf)		Bottom-Layer Stresses (psf)	
Unit	Classification	Interval	Thickness (ft)	γsat	γbuoyant	σ' (effective)	σ (total)	σ' (effective)	σ (total)
Example	EX	0-2	2	0	0	0.00	0.00	0.00	0.00
Final Cover	CH	El. 834-831	3.083	129	129	198.85	198.85	397.71	397.71
Waste	-	El. 831-451	380	65	65	12,747.71	12,747.71	25,097.71	25,097.71
Protective Cover Soil	CH	El. 451-449	2	129	129	25,226.71	25,226.71	25,355.71	25,355.71
Compacted Low Permeable Soil Liner	CH	El. 449-446	3	132	69.6	25,460.11	25,553.71	25,564.51	25,751.71
Stratum II-III-IV (compressible, saturated)	CH	El. 446-396	50	132	69.6	27,304.51	29,051.71	29,044.51	32,351.71
Stratum II-III-IV (incompressible, saturated)	CH	El. 396-							

Settlement Analysis for the base of a Landfill

Enter data into the necessary white cells
Data must be entered into all the columns that contain comments

Company Name	CB&I	Units	English	Method for Non-Cohesive Soils Mark X in the correct box	
		Life of Landfill (yrs)	30	Classical	
Project Name	Pescadito Landfill - South Unit	Post-closure care period + Life of Landfill (yrs)	60	Peck	
Project Number	148866				
Date	2/12/2015	Total Settlement (ft)	1.33562		

Settlement Point F1		Cohesion or Non-Cohesion			Liquid Limit	Corrected Standard Pentration Count	Void Ratio	Compression Index	Recompresion Index	Secondary Compression Index	Preconsolidation Stress (psf)	Mid-Layer Stresses (psf)	Mid-Layer Stresses (psf)			
Unit	Classification	C or N	Interval	Thickness (ft)	LL	N60	e_o	Cc	Cr	Ca	σ'c	σ' (intial)	σ' (final)	Primary Settlment	Secondary Settlement	Settlement
Example	EX	C	0-2	2			0	0	0	0	-	1.00	1.00	0	0	0.000000
Compacted Low Permeable Soil Liner	CH	C	El. 449-446	3	58		0.64	0.0609	0.0609	0.0136		104.40	25,226.71	0.265559595	0.007467012	0.273026607
Stratum II-III-IV (compressible, saturated)	CH	C	El. 446-396	50	58		0.64	0.4240	0.0609	0.0136	114,763.00	8,530.20	27,304.51	0.938148023	0.124450206	1.062598229
Stratum II-III-IV (incompressible, saturated)	CH	C	El. 396-													

$Settlement_{LINER}$ =	0.265559595	0.007467012	0.273026607
$Settlement_{SUBGRADE}$ =	0.938148023	0.124450206	1.062598229
Totals =	**1.203707618**	**0.131917218**	**1.335624836**

Note:

The compression index (Cc) for the low permeable soil liner was set equal to the recompression index (Cr) since there is no preconsolidation stress.

Stress concentrations through cross section of a Landfill

Company Name	CB&I
Project Name	Pescadito Landfill - South Unit
Project Number	148866
Date	2/12/2015
Units	English

Make sure that the cross sections for both the before and after landfill line up at the bottom geological units under the landfill liner.

Cross Section <u>before</u> landfill
Settlement Point F2

				Relative	Unit Weights (pcf)		Mid-Layer Stresses (psf)		Bottom-Layer Stresses (psf)	
Unit	Classification	Interval	Thickness (ft)	Density (%)	γsat	γbuoyant	σ' (effective)	σ (total)	σ' (effective)	σ (total)
Example	EX	0-2	2		0	0	0.00	0.00	0.00	0.00
Stratum II-III-IV (excavated, dry)	CH	El. 540-538	2		129	129	129.00	129.00	258.00	258.00
Stratum II-III-IV (excavated, saturated)	CH	El. 538-439	96		132	69.6	3,598.80	6,594.00	6,939.60	12,930.00
Stratum II-III-IV (compressible, saturated)	CH	El. 439-389	50		132	69.6	8,679.60	16,230.00	10,419.60	19,530.00
Stratum II-III-IV (incompressible, saturated)	CH	El. 389-								

Stress concentrations through cross section of a Landfill

Company Name	CB&I
Project Name	Pescadito Landfill - South Unit
Project Number	148866
Date	2/12/2015
Units	English

Cross Section after development of landfill
Settlement Point F2

Unit	Classification	Interval	Thickness (ft)	Unit Weights (pcf) γsat	Unit Weights (pcf) γbuoyant	Mid-Layer Stresses (psf) σ' (effective)	Mid-Layer Stresses (psf) σ (total)	Bottom-Layer Stresses (psf) σ' (effective)	Bottom-Layer Stresses (psf) σ (total)
Example	EX	0-2	2	0	0	0.00	0.00	0.00	0.00
Final Cover	CH	EL. 642-639	3.083	129	129	198.85	198.85	397.71	397.71
Waste	-	El. 639-444	193	65	65	6,670.21	6,670.21	12,942.71	12,942.71
Protective Cover Soil	CH	El. 444-442	1	129	129	13,007.21	13,007.21	13,071.71	13,071.71
Compacted Low Permeable Soil Liner	CH	El. 442-439	3	132	69.6	13,176.11	13,269.71	13,280.51	13,467.71
Stratum II-III-IV (compressible, saturated)	CH	El. 439-389	50	132	69.6	15,020.51	16,767.71	16,760.51	20,067.71
Stratum II-III-IV (incompressible, saturated)	CH	El. 389-							

Settlement Point F2

Settlement Analysis for the base of a Landfill

Enter data into the necessary white cells
Data must be entered into all the columns that contain comments

Company Name	CB&I	Life of Landfill (yrs)	30	Classical: X
Project Name	Pescadito Landfill - South Unit	Post-closure care period + Life of Landfill (yrs)	60	Peck:
Project Number	148866	Units	English	Method for Non-Cohesive Soils — Mark X in the correct box
Date	2/12/2015	Total Settlement (ft)	0.80840	

Settlement Point F2		Cohesion or Non-Cohesion			Liquid Limit	Corrected Standard Pentration Count	Void Ratio	Compression Index	Recompresion Index	Secondary Compression Index	Preconsolidation Stress (psf)	Mid-Layer Stresses (psf)	Mid-Layer Stresses (psf)			
Unit	Classification	C or N	Interval	Thickness (ft)	LL	N60	e_o	Cc	Cr	Ca	σ'c	σ' (intial)	σ' (final)	Primary Settlment	Secondary Settlement	Settlement
Example	EX	C	0-2	2			0	0	0	0	-	1.00	1.00	0	0	0.000000
Compacted Low Permeable Soil Liner	CH	C	El. 442-439	3	58		0.64	0.0609	0.0609	0.0136		104.40	13,176.11	0.234127669	0.007467012	0.241594681
Stratum II-III-IV (compressible, saturated)	CH	C	El. 439-389	50	58		0.64	0.4204	0.0609	0.0136	114,763.00	8,679.60	15,020.51	0.442355799	0.124450206	0.566806004
Stratum II-III-IV (incompressible, saturated)	CH	C	El. 389-													

$\text{Settlement}_{\text{LINER}}$ =	0.234127669	0.007467012	0.241594681
$\text{Settlement}_{\text{SUBGRADE}}$ =	0.442355799	0.124450206	0.566806004
Totals =	**0.676483468**	**0.131917218**	**0.808400685**

Note:

The compression index (Cc) for the low permeable soil liner was set equal to the recompression index (Cr) since there is no preconsolidation stress.

Pescadito Landfill - Primary Waste Settlement Calculation
February 2015

Waste Settlement Calculations
(Page 1 of 2)

Given:	
Primary Settlement Eqtn.	$S_p = H \times C'_c(\log(\sigma'_{zo} + \sigma'_{zf}) / \sigma'_{zo}))$
	$C'_c =$ 0.25 $H_{waste} =$ height of waste fill lift Maximum waste height of cell = 380 feet Cell is divided into nineteen (19) lifts at 20 feet each $\gamma_{waste\ (pcf)} = 65$ Each lift takes 3 months to complete
Final Cover	$H_{final\ cover}$ (ft) = 3 $\gamma_{final\ cover}$ (pcf) = 129 Assume 3 months to complete construction of final cover
Stresses	σ'_{zo} = initial effective stress (psf) σ'_{zf} = final effective stress (psf)
Other Information	Each lift takes 3 months to complete (conservative) Life of landfill is assumed to be 30 years

Mid-Lift Stresses (psf)

Placement of Lift (mos.)	Lift No.	Depth of Fill Lift (ft)	Total Depth of Fill (ft)	Lift 1		Lift 2		Lift 3		Lift 4		Lift 5		Lift 6		Lift 7		Lift 8		Lift 9		Lift 10	
				σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}
3	1	20	20	650	650	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	2	20	40	650	1,300	650	650	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	3	20	60	650	1,950	650	1,300	650	650	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	4	20	80	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-	-	-	-	-	-	-	-	-
15	5	20	100	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-	-	-	-	-	-	-
18	6	20	120	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-	-	-	-	-
21	7	20	140	650	4,550	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-	-	-
24	8	20	160	650	5,200	650	4,550	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-
27	9	20	180	650	5,850	650	5,200	650	4,550	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-
30	10	20	200	650	6,500	650	5,850	650	5,200	650	4,550	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300	650	650
33	11	20	220	650	7,150	650	6,500	650	5,850	650	5,200	650	4,550	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300
33	12	20	240	650	7,800	650	7,150	650	6,500	650	5,850	650	5,200	650	4,550	650	3,900	650	3,250	650	2,600	650	1,950
33	13	20	260	650	8,450	650	7,800	650	7,150	650	6,500	650	5,850	650	5,200	650	4,550	650	3,900	650	3,250	650	2,600
33	14	20	280	650	9,100	650	8,450	650	7,800	650	7,150	650	6,500	650	5,850	650	5,200	650	4,550	650	3,900	650	3,250
33	15	20	300	650	9,750	650	9,100	650	8,450	650	7,800	650	7,150	650	6,500	650	5,850	650	5,200	650	4,550	650	3,900
33	16	20	320	650	10,400	650	9,750	650	9,100	650	8,450	650	7,800	650	7,150	650	6,500	650	5,850	650	5,200	650	4,550
33	17	20	340	650	11,050	650	10,400	650	9,750	650	9,100	650	8,450	650	7,800	650	7,150	650	6,500	650	5,850	650	5,200
33	18	20	360	650	11,700	650	11,050	650	10,400	650	9,750	650	9,100	650	8,450	650	7,800	650	7,150	650	6,500	650	5,850
33	19	20	380	650	12,350	650	11,700	650	11,050	650	10,400	650	9,750	650	9,100	650	8,450	650	7,800	650	7,150	650	6,500
33	final cover	3.000	383	650	12,544	650	11,894	650	11,244	650	10,594	650	9,944	650	9,294	650	8,644	650	7,994	650	7,344	650	6,694

Placement of Lift (mos.)	Lift No.	Depth of Fill Lift (ft)	Total Depth of Fill (ft)	Lift 11		Lift 12		Lift 13		Lift 14		Lift 15		Lift 16		Lift 17		Lift 18		Lift 19		Lift 20		Total Primary Settlement "S_p" (ft)	Incremental Primary Settlement "S_p" (ft)
				σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}	σ'_{zo}	σ'_{zf}		
3	1	20	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	
6	2	20	40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.51	1.51
9	3	20	60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.89	2.39
12	4	20	80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.90	3.01
15	5	20	100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10.40	3.49
18	6	20	120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14.29	3.89
21	7	20	140	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18.51	4.23
24	8	20	160	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	23.03	4.52
27	9	20	180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	27.80	4.77
30	10	20	200	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	32.80	5.00
33	11	20	220	650	650	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	38.01	5.21
33	12	20	240	650	1,300	650	650	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	43.40	5.40
33	13	20	260	650	1,950	650	1,300	650	650	-	-	-	-	-	-	-	-	-	-	-	-	-	-	48.97	5.57
33	14	20	280	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-	-	-	-	-	-	-	-	-	54.70	5.73
33	15	20	300	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-	-	-	-	-	-	-	60.58	5.88
33	16	20	320	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-	-	-	-	-	66.60	6.02
33	17	20	340	650	4,550	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-	-	-	72.76	6.15
33	18	20	360	650	5,200	650	4,550	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-	-	-	79.03	6.28
33	19	20	380	650	5,850	650	5,200	650	4,550	650	3,900	650	3,250	650	2,600	650	1,950	650	1,300	650	650	-	-	85.43	6.39
33	final cover	3.000	383	650	6,044	650	5,394	650	4,744	650	4,094	650	3,444	650	2,794	650	2,144	650	1,494	650	844	194	194	87.58	2.16 (Σ S_p = 75.76)

Notes:
Incremental settlement is the difference of the total primary settlement number and the previous total primary settlement number.

48.02

Pescadito Landfill - Secondary Waste Settlement Calculation
February 2015

Given:	
Waste	**Secondary Settlement Eqtn:** $S_s = [(C'_\alpha) * (H_o) * (\log(t_2 / t_1))]$
	C'_α = 0.051
	Maximum height of cell = 380 ft. (waste) + 3 ft. (cover) = 383 ft.
	Waste is placed in nineteen (19) lifts at 20 ft. each
	H_o = height of lifts 1-19 = 20 feet
	Assume 3 months to complete each lift: t_1 = 0.25 yrs
Final Cover	**Secondary Settlement Eqtn:** $S_s = [(C_\alpha) / (1+e_o)] * (H_o) * (\log(t_2 / t_1))]$
	e_o = 0.064
	C_α = 0.0136
	H_o = height of final cover = 3 feet
	Assume 3 months to complete construction of final cover
Other Information	Landfill life conservatively assumed = 30 years
	Post Closure monitoring period = 30 years
	t_1 = time of pseudo-primary settlement to occur after completion of fill (years)
	t_2 = time after placed fill and post-closure (years) = (30 + 30 - ($\sum t_x$))

Lift No.	(A) Total Time in Months to Complete Filling of Lifts	(B) Total Time in Years to Complete Filling of Lifts ($\sum t_x$)	(C) t_1 (yrs)	(D) t_2 (yrs)	t_2 / t_1	S_s (ft)
1	3	0.25	0.25	59.75	239	2.426
2	6	0.50	0.25	59.50	238	2.424
3	9	0.75	0.25	59.25	237	2.422
4	12	1.00	0.25	59.00	236	2.420
5	15	1.25	0.25	58.75	235	2.418
6	18	1.50	0.25	58.50	234	2.417
7	21	1.75	0.25	58.25	233	2.415
8	24	2.00	0.25	58.00	232	2.413
9	27	2.25	0.25	57.75	231	2.411
10	30	2.50	0.25	57.50	230	2.409
11	33	2.75	0.25	57.25	229	2.407
12	36	3.00	0.25	57.00	228	2.405
13	39	3.25	0.25	56.75	227	2.403
14	42	3.50	0.25	56.50	226	2.401
15	45	3.75	0.25	56.25	225	2.399
16	48	4.00	0.25	56.00	224	2.397
17	51	4.25	0.25	55.75	223	2.395
18	54	4.50	0.25	55.50	222	2.393
19	57	4.75	0.25	55.25	221	2.391
final cover	60	5.00	0.25	55.00	220	0.090
					$\sum$ Settlement =	**45.86**

Notes:

(A) = 3 months + time for filling previous lifts
(B) = Col.(A) / 12
(C) = (3 mos.) x (1 yr./12mos.) = 0.25
(D) = 30 + 30 - Col.(B)

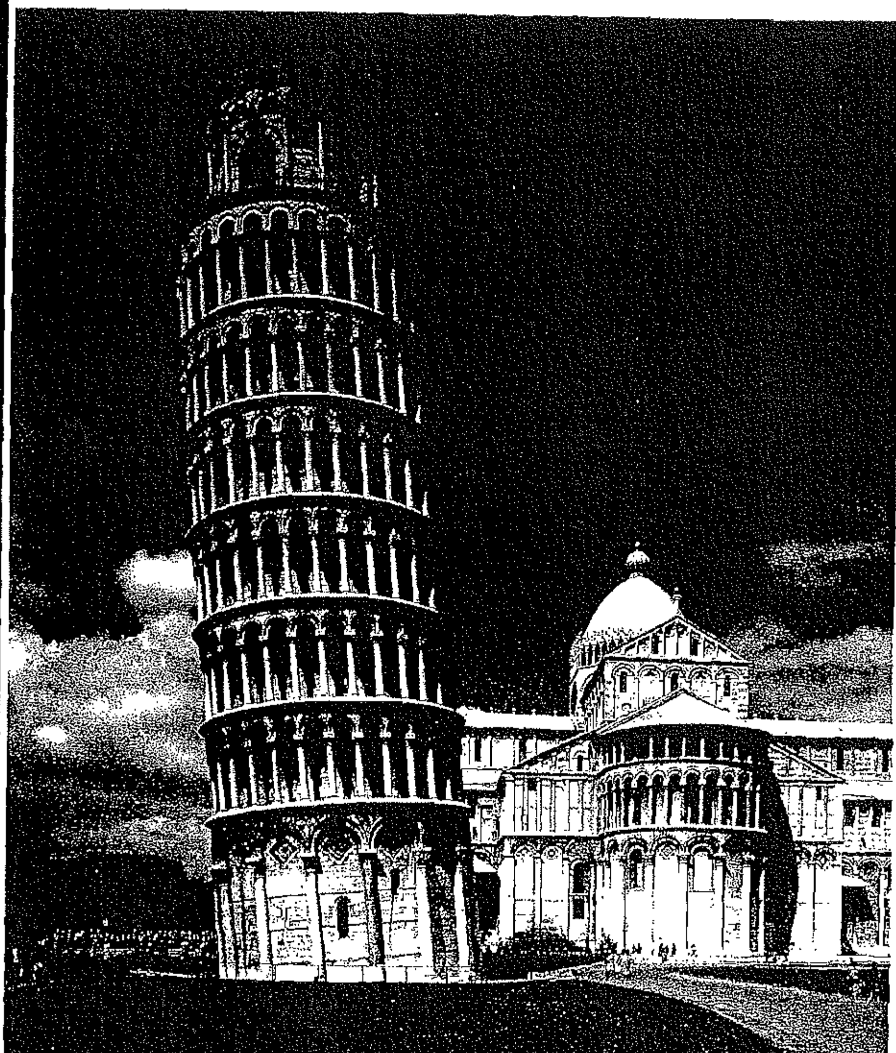
Reference No. 6

Consolidation Equations for Soils
(Coduto)

SECOND EDITION

FOUNDATION DESIGN

Principles and Practices



DONALD P. CODUTO

TABLE 3.5 CLASSIFICATION OF SOIL COMPRESSIBILITY

$\frac{C_c}{1+e_0}$ or $\frac{C_r}{1+e_0}$	Classification
0–0.05	Very slightly compressible
0.05–0.10	Slightly compressible
0.10–0.20	Moderately compressible
0.20–0.35	Highly compressible
> 0.35	Very highly compressible

Table 3.5 gives a classification of soil compressibility based on $C_c / (1+e_0)$ for normally consolidated soils or $C_r / (1+e_0)$ for overconsolidated soils.

Overconsolidation Margin and Overconsolidation Ratio

The σ_c' values from the laboratory only represent the preconsolidation stress at the sample depth. To estimate σ_c' at other depths in the same strata (i.e., in a soil strata with the same geologic origin), compute the *overconsolidation margin*, σ_m', at the sample depth using:

$$\boxed{\sigma_m' = \sigma_c' - \sigma_{z0}'} \tag{3.23}$$

The overconsolidation margin should be approximately constant in a strata with common geologic origins, so we can estimate the preconsolidation stress at other depths in that strata by using Equation 3.23 with σ_{z0}' at the desired depth. In normally consolidated soils, $\sigma_m' = 0$. Table 3.6 presents typical ranges of σ_m'.

Another useful parameter is the *overconsolidation ratio* or OCR:

$$\boxed{\text{OCR} = \frac{\sigma_c'}{\sigma_{z0}'}} \tag{3.24}$$

TABLE 3.6 TYPICAL RANGES OF OVERCONSOLIDATION MARGINS

Overconsolidation Margin, σ_m'		
(kPa)	(lb/ft^2)	Classification
0	0	Normally consolidated
0–100	0–2000	Slightly overconsolidated
100–400	2000–8000	Moderately overconsolidated
> 400	> 8000	Heavily overconsolidated

fills can be considered to be overconsolidated, as can soils that have clear geologic evidence of preloading, such as glacial tills. Therefore, many settlement analyses simply consider the compressibility of such soils to be zero. If it is unclear whether a soil is normally consolidated or overconsolidated, it is conservative to assume it is normally consolidated.

Very few consolidation tests have been performed on gravelly soils, but the compressibility of these soils is probably equal to or less than those for sand, as listed in Table 3.7.

Another characteristic of sands and gravels is their high hydraulic conductivity, which means any excess pore water drains very quickly. Thus, the rate of consolidation is very fast, and typically occurs nearly as fast as the load is applied. Therefore, if the load is caused by a fill, the consolidation of these soils may have little practical significance.

Another way to assess the compressibility of sands is to use in-situ tests. We will discuss these test methods in Chapter 4, and will apply them to sand compressibility in Chapter 7. This method is especially useful for settlements due to loads on foundations.

Consolidation Settlement Predictions

The purpose of performing consolidation tests is to define the stress–strain properties of the soil and thus allow us to predict consolidation settlements in the field. We perform this computation by projecting the laboratory test results (as contained in the parameters C_c, C_r, e_0, and σ_c') back to the field conditions.

For simplicity, the discussions of consolidation settlement predictions in this chapter consider only the case of one-dimensional consolidation, and we will be computing only the ultimate consolidation settlement. *One-dimensional consolidation* means only vertical strains occur in the soil (i.e., $\epsilon_x = \epsilon_y = 0$). This is a reasonable assumption when computing settlements due to the weight of fills, but is not quite true for settlements due to loads on foundations. We will return to this issue in Chapter 7. The *ultimate consolidation settlement* is the value of δ_c at the end of the consolidation process.

Normally Consolidated Soils ($\sigma_{z0}' \approx \sigma_c'$)

If $\sigma_{z0}' \approx \sigma_c'$, the soil is, by definition, normally consolidated. Thus, the initial and final conditions are as shown in Figure 3.10, and the compressibility is defined by C_c, the slope of the virgin curve.

To compute the ultimate consolidation settlement, we divide the soil into layers, compute the settlement of each layer, and sum as follows:

$$\boxed{\delta_c = \Sigma \frac{C_c}{1 + e_0} H \log \left(\frac{\sigma_{zf}'}{\sigma_{z0}'} \right)} \tag{3.25}$$

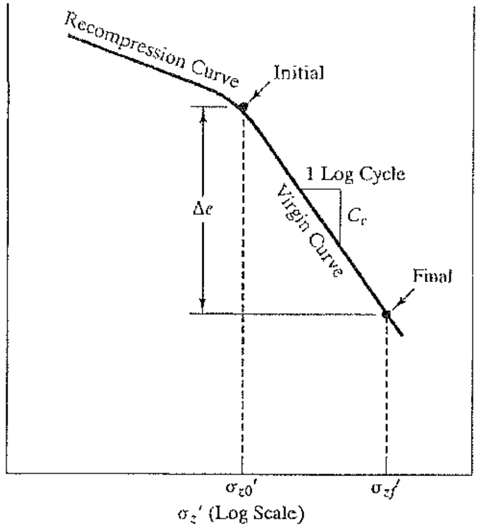


Figure 3.10 Consolidations of normally consolidated soils.

Where:

δ_c = ultimate consolidation settlement at the ground surface
C_c = compression index
e_0 = initial void ratio
H = thickness of soil layer
σ_{z0}' = initial vertical effective stress
σ_{zf}' = final vertical effective stress

When using Equation 3.25, compute σ_{z0}' and σ_{zf}' at the midpoints of each layer.

Overconsolidated Soils — Case I ($\sigma_{z0}' < \sigma_{zf}' \leq \sigma_c'$)

If both σ_{z0}' and σ_{zf}' do not exceed σ_c', the entire consolidation process occurs on the recompression curve as shown in Figure 3.11. The analysis is thus identical to that for normally consolidated soils except we use the recompression index, C_r instead of the compression index, C_c:

$$\boxed{\delta_c = \Sigma \frac{C_r}{1 + e_0} H \log\left(\frac{\sigma'_{zf}}{\sigma'_{z0}}\right)} \tag{3.26}$$

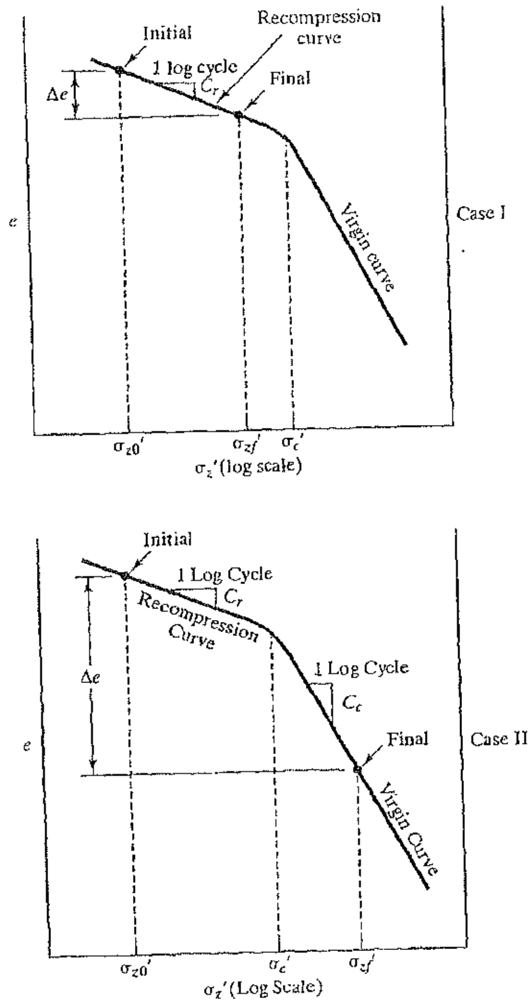


Figure 3.11 Consolidation of overconsolidated soils.

Overconsolidated Soils — Case II ($\sigma_{z0}' < \sigma_c' < \sigma_{zf}'$)

If the consolidation process begins on the recompression curve and ends on the virgin curve, as shown in Figure 3.11, then the analysis must consider both C_c and C_r:

$$\boxed{\delta_c = \Sigma\left[\frac{C_r}{1+e_0} H \log\left(\frac{\sigma_c'}{\sigma_{z0}'}\right) + \frac{C_c}{1+e_0} H \log\left(\frac{\sigma_{zf}'}{\sigma_c'}\right)\right]} \tag{3.27}$$

This condition is quite common, since many soils that might appear to be normally consolidated from a geologic analysis actually have a small amount of overconsolidation (Mesri, Lo, and Feng, 1994).

Ultimate Consolidation Settlement Analysis Procedure

Use the following procedure to compute δ_c caused by the weight of extensive fills:

1. Beginning at the original ground surface, divide the soil profile into strata, where each stratum consists of a single soil type with a common geologic origin. For example, one stratum may consist of a dense sand, while another might be a soft-to-medium clay. Continue downward with this process until you have passed through all of the compressible strata (i.e., until you reach bedrock or some very hard soil). For each stratum, identify the unit weight, γ. Note: Boring logs usually report the dry unit weight, γ_d, and moisture content, w, but we can compute γ from this data using Equation 3.3. Also define the location of the groundwater table.
2. Each clay or silt stratum must have results from at least one consolidation test (or at least estimates of these results). Using the techniques described earlier, determine if each stratum is normally consolidated or overconsolidated, then assign values for $C_c/(1+e_0)$ and/or $C_r/(1+e_0)$. For each overconsolidated stratum, compute σ_m' using Equation 3.23 and assume it is constant throughout that stratum. For normally consolidated soils, set $\sigma_m' = 0$.
3. For each sand or gravel stratum, assign a value for C_c / $(1+e_0)$ or C_r / $(1+e_0)$ based on the information in Table 3.7.
4. For any very hard stratum, such as bedrock or glacial till, that is virtually incompressible compared to the other strata, assign $C_c = C_r = 0$.
5. Working downward from the original ground surface (i.e., do not consider any proposed fills), divide the soil profile into horizontal layers. Begin a new layer whenever a new stratum is encountered, and divide any thick strata into multiple layers. When performing computations by hand, each strata should have layers no more than 2 to 5 m (5 to 15 ft) thick. Thinner layers are especially appropriate near the ground surface, because the strain is generally larger there. Computer-based computations can use much thinner layers throughout the entire depth, and achieve slightly more precise results.

Reference No. 7

Consolidation Equations for Waste
(Sharma / Anirban)

Municipal Solid Waste Landfill Settlement: Postclosure Perspectives

Hari D. Sharma, F.ASCE[1]; and Anirban De, M.ASCE[2]

Abstract: This paper presents settlement mechanisms and the methods for estimating settlements of municipal solid waste landfills, including bioreactor landfills. Based on results of field monitoring and data in published literature, coefficients of secondary compression for solid waste due to self-weight and external load are estimated. Special considerations are given to bioreactor landfills. Uses of these coefficients for long-term settlement estimation and their application to postclosure maintenance and development plans are discussed. Four case histories illustrating the use of these coefficients are presented. Methods of landfill treatment to reduce settlements are also presented.

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CE Database subject headings: Solid wastes; Municipal wastes; Landfills; Waste management.

Introduction

The composition of waste, both in the municipal solid waste (MSW) and hazardous waste landfills, is heterogeneous. According to the Code of Federal Regulations 257.2 a MSW landfill may receive household waste and any other type of Resource Conservation and Recovery Act Subtitle D waste, such as, commercial solid waste, nonhazardous sludge, and industrial solid waste. Data regarding the composition of MSW, collected from actual landfills are presented by Bouazza et al. (1996) and Sharma (2000). The very heterogeneous nature of MSW makes the estimation and prediction of landfill settlement difficult.

Increasiug pressure of new development on available real estate is leading to a worldwide trend to construct over former landfill sites. This, in turn, is making it imperative to obtain reasonably accurate predictions of landfill settlements, as desigu inputs for structures proposed at the site.

Methods of Settlement Estimation

Processes Responsible for Waste Settlement

The mechanism of waste settlement is complex and can be attributed to the following main processes (Sowers 1973; Edil et al. 1990; Sharma and Reddy 2004):

1. Physical and mechanical processes: These include the reorientation of particles, movement of the fine materials into larger voids, and collapse of void spaces.
2. Chemical (physicochemical) process: This includes corrosion, combustion, and oxidation.
3. Dissolution process: This consists of dissolving soluble substances by percolating liquids and then forming leachate.
4. Biological decomposition (biochemical decay): The organics in the refuse will decompose with time, controlled by temperature, humidity, and percentage of organics and uutrients in the waste.

Settlement Estimation Methods for MSW Landfills

Numerous settlement estimation methods for MSW have been proposed in the literature (Sowers 1973; Dodt et al. 1987; Edil et al. 1990, Ling et al. 1998; Park et al. 2002). Brief discussions of some of the more significaut methods are presented below.

Sowers Method

Sowers (1973) used equations similar to those used for primary and secondary consolidation of soils to estimate settlements of waste landfills. Total settlement (ΔH) is divided into primary (short-term) settlement (ΔH_p) and secondary or long-term settlement (ΔH_s). The following equations are used to estimate the settlement

$$\Delta H = \Delta H_p + \Delta H_s \tag{1}$$

$$\boxed{\Delta H_p = H C_{ce} \log \frac{p_0 + \Delta p}{p_0}} \tag{2}$$

$$\Delta H_s = H_1 C_\alpha \log \frac{t_2}{t_1} \tag{3}$$

where, H=initial thickness of waste (before load placement); H_1=thickness of waste at the beginning of the secondary settlement (i.e., thickness at $t=t_1$); $C_{ce}=C_c/(1+e_0)$, where C_c=compression index and e_0=void ratio; C_α=secondary com-

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pression index; p_0=initial overburden pressure; Δp=incremental pressure; t_1=starting time for secondary compression; and t_2=ending time for secondary compression.

Rheological Model

Edil et al. (1990) proposed a method based on the rheological model of Gibson and Lo (1961) to estimate total settlement (ΔH) based on the following equation:

$$\Delta H = H(\Delta p)[a + b\{1 - \exp(-\lambda/b)t\}] \tag{4}$$

where H=initial height of waste; Δp=change in pressure; a=primary compression parameter; b=secondary compression parameter; λ/b=rate of secondary compression, and t=time since load application.

Power Creep Model

The power creep model, as proposed by Edil et al. (1990), uses the following:

$$\Delta H = H\Delta pm(t/t_r)^n \tag{5}$$

expression for settlement (ΔH) estimation where H and Δp are as defined earlier; m=reference compressibility; n=compression rate; t_r=reference time; and t=time since load applicatiou.

Hyperbolic Function Model

Ling et al. (1998) applied the hyperbolic function to predict long-term settlements at three landfill sites. They used the following expression to relate settlement with time:

$$S = \frac{t}{1/\rho_0 + t/S_{\mathrm{ult}}} \tag{6}$$

where t=time interval of interest; S=settlement occurring in time interval, t; ρ_0=rate of settlement at the beginning of the time interval; and S_{ult}=ultimate settlement. The values of ρ_0 and S_{ult} may be obtained through a regression analysis conducted on the t/S versns t relationship.

Ling et al. (1998) found that the hyperbolic function method provided a good prediction of long-term settlement in comparison with the logarithmic and the power function methods.

Comments on Different Methods

Park et al. (2002) evaluated the effects of waste decomposition on long-term settlement predictions for MSW landfills. They proposed separating long-term field compression behavior of MSW into two phases—the first dominated by mechanical processes of compression and the second dominated by decomposition. According to Park et al. (2002), the power creep method did not provide good predictions of long-term waste settlement. They noted that inclusion of accelerated logarithmic compression due to decomposition was necessary in order to successfully predict long-term settlement of MSW landfills.

Babu and Fox (1997) suggested that dividing settlements into primary and secondary components may not be realistic for landfills. They recommended evaluating total settlement behavior, while considering methods for landfill stabilization.

The rheological model, the power creep model, and the hyperbolic model do not require separation of settlement into primary and secondary components. However, these methods need further field verifications and, from a practical application point of view, are more involved than the Sowers method. At the present time, due to its simplicity and familiarity of consolidation based approach by practicing engineers, the Sowers method is widely used in the practice. This method has, therefore, been used to interpret the data from the case histories presented in this paper. It is likely that some of the other methods will gain acceptance in practice in the future, as additional documented case histories become available.

Time for Completion of Primary Settlement

Most of the initial refuse settlement, also called primary settlement, is due to physical and mechanical mechanisms. Secondary or long-term settlement, primarily due to physicochemical and biochemical decay, occurs under constant load after the completion of primary settlement. Primary settlement of municipal solid waste typically occurs within the first four months after load placement (Sowers 1973; Bjarngard and Edgers 1990; Sharma 2000; NAVFAC 1983). Thus, the value of t_1 in Eq. (3) can be between 1 and 4 months. In practice a value of 3–4 months is used for t_1 in Eqs. (7) and (8), as presented in the following. Settlement estimates for postclosure end use projects typically require calculations for ΔH_s made after about 15 to 20 years or longer following waste placement. In such cases, where t_2 is approximately say 20 years, the value of ΔH_s is not very sensitive to the choice of t_1 between three or 4 months.

Categories of Secondary Settlement

The secondary settlement, ΔH_s in a MSW landfill can be grouped into the following two categories, based on the type of loading applied:

1. Settlement under self-weight: This type of settlement is caused by the load imposed due to the weight of waste material on the underlying waste layers. The loading mechanism is different from an externally imposed load (such as either due to a structure or an earthen fill, discussed in the next section). The externally imposed load does not have a secondary settlement component due to its self weight. On the coutrary, in the case of waste self-weight, the overlying waste material itself also undergoes settlement.

   As discussed earlier, the primary settlement of waste typically occurs during the first one to 4 months after waste placement. Thus, all of the primary settlement is generally over by the time a landfill is closed. The time required for primary settlement to complete depends on the nature of the material in the landfill. Some ground improvement techniques used to pretreat landfill waste material prior to construction over closed landfills tend to reduce the time required to complete primary settlement. This is discussed in further details later in this paper.

   For long-term settlement estimation, such as, for postclosure development, the time-dependent secondary settlement (ΔH_s), due to self-weight can be expressed by the following equation:

$$\boxed{\Delta H_s = \Delta H_{(\mathrm{SW})} = C_{\alpha(\mathrm{SW})} H_1 \log \frac{t_2}{t_1}} \tag{7}$$

   where $\Delta H_{(\mathrm{SW})}$=settlement at time t_2 after fill placement; t_1=time for primary settlement, as discussed earlier; t_2=time of interest, since the self-weight was applied; H_1=thickness of refuse fill at the end of the primary settlement; and $C_{\alpha(\mathrm{SW})}$=coefficient of secondary compression due to self-weight. Typical values for $C_{\alpha(\mathrm{SW})}$ range between 0.1 and 0.4 (NAVFAC 1983).

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Table 2. Recommended Values of C_α Parameters

C_α under external load, $C_{\alpha(EL)}$	Overall range of C_α	0.01–0.07
	With pretreatment using DDC[a]	0.014
	With pretreatment using RC[b]	0.03
	With pretreatment using preload/surcharge loading	0.045
C_α under self-weight, $C_{\alpha(SW)}$	Fresh waste	0.014–0.06
	Waste undergoing active decomposition	0.1–0.34
C_α for bioreactor landfills under self-weight, $C_{\alpha(\text{Bioreactor})SW}$		0.1–0.34

[a]DDC=deep dynamic compaction.
[b]RC=roller compaction.

dergoing active decomposition, and already-decomposed waste.

As noted previously, the value of C_α for bioreactor landfill under self-weight $[C_{\alpha(\text{Bioreactor})SW}]$ lies within the range recommended for settlement under self-weight in older landfills, where leachate recirculation is not practiced. This is believed to be due to the accelerated rate of waste decomposition and associated settlement that occurs in bioreactor landfills, where leachate recirculation is practiced. It should be noted that the data for older landfills is applicable to landfills where waste placement occurred more than 10 years ago, whereas the bioreactor landfill data were obtained from an ongoing study approximately seven year after waste placement. Table 2 summarizes the recommended C_α values for various conditions.

As discussed previously, external loads are typically applied during or after closure of a landfill. Therefore, data for $C_{\alpha(EL)}$ are generally available for and applicable to waste undergoing active decomposition.

Postclosure Maintenance and Development Perspectives

Postclosure Maintenance

After a landfill is closed, state and federal regulations require that a postclosure maintenance program be prepared and executed for 30 years. As a part of this program the landfill final surface grades must be maintained so that surface runoff is drained and final cover erosion is minimized. Therefore, the final cover on the top deck of the landfill is generally graded to between 2 and 5%.

As discussed earlier, landfill settlements can continue for many years after closure. The differential settlement may result in (1) grade reversals causing surface water ponding and (2) cracks in the final cover system. Excessive differential settlements can cause tensile stresses to develop in the compouents of the final cover system. Low hydraulic conductivity soil components in the cover system are most susceptible to cracking under tensile stresses. Flexible membrane liners, such as geomembranes are less vulnerable; however they can fail when the tensile strains exceed their allowable limits. For example, tensile strains at failure in clayey soils are between 0.1 and 4 percent, in geosynthetic clay liners are between 1 and 10%, and in high density polyethylene geomembranes is in excess of 15% (LaGatta et al. 1997).

Morris and Woods (1990) cite case histories where settlements have caused surface water ponding and cracks resulting in ponded water infiltrating through the cracks resulting in increased leachate generation. Sharma et al. (1999) cite a case where landfill surface cracks caused by settlements created potential for increased leachate due to infiltration of surface water through the cracks. It is, therefore, important to estimate the landfill settlements for the entire postclosure period and at different locations on the landfill surface. Surface grading and periodic maintenance (i.e., regrading and settlement crack repair) can then be planned and performed to minimize the impact of postclosure settlements on leachate generation.

Leachate recirculation in bioreactor landfill results in enhanced rate of waste decomposition, because of which the time rate of secondary compression is accelerated. Thus, surface grades will be observed to change relatively early after closure, requiring remedial maintenance, compared with landfills where leachate is not recirculated. However, enhanced rate of decomposition will also cause the total final settlement to be achieved relatively early in bioreactor landfills, such that structures constructed over bioreactor landfills after most of the secondary compression is completed, will likely experience less settlement-related impacts.

Postclosure Developments

In many urban areas, where real estate is very expensive, postclosure developments on closed landfills have been done. A few examples of postclosure developments on top of closed landfills are: Parks, golf courses, and buildings. Most of these developments are planned over closed MSW landfills.

Parks and Golf Course Developments

These would require placing general fills for maintaining grades and planting trees, regrading for access roads and constructing certain utility lines. All these would require information on postclosure settlement estimates. These settlements estimates will require information on both $C_{\alpha(SW)}$ and $C_{\alpha(EL)}$. These coefficients can be obtained for the site specific landfill under specific environmental conditions by instituting a settlement monitoring program as a part of predesign activity. A predicted settlement contour map for the site can then be prepared and used when preparing facility design and operations plan.

Building Development over Closed Landfills

There are many cases where buildings have been successfully constructed on closed landfills. Long-term settlements due to refuse self-weight and external loads (due to regrading and foundation loads) generally result in differential settlements that may result in tilting of building support system, ponding of water in parking lots, cracking of slabs supported on ground, breakage in utility lines and down-drag forces on piles that support heavy building loads. Again, as in the case of parks and golf course developments, a settlement monitoring program for the specific landfill should be instituted so that $C_{\alpha(SW)}$ and $C_{\alpha(EL)}$ can be estimated. Settlement contour maps for different time periods, e.g., 10, 20, 30 years, etc. (depending on building design life and civil/structural engineering requirements) should then be prepared. These settlement contour maps can then be used for building and

Reference No. 8

Strain Equation for Soil Liner
(Qian / Koerner / Gray)

GEOTECHNICAL ASPECTS *of* LANDFILL DESIGN *and* CONSTRUCTION

Xuede Qian · Robert M. Koerner · Donald H. Gray

The preceding table is generalized because there are many individual products in each of the specification areas. In general, the materials and products categorized in Table 11.7 have been successful in preventing or greatly reducing erosion losses on slopes. Considerable research activity is focused at present on adapting the USLE's variables to the various erosion-control materials and products. It is important to note that the performance of rolled erosion control products (RECPs) is limited by the effectiveness of their attachment to the ground surface. Insufficient use of point attachments (such as pins, pegs, and staples) can allow rills and small gullies to form at the ground interface between attachment points. Burying a blanket or mat at periodic intervals in shallow trenches dug on contours across a sloping surface can minimize this problem. [See Gray and Sotir (1996) for further discussion of this problem and for a description of various biotechnical groundcover alternatives for erosion control.]

11.5 EFFECTS OF SETTLEMENT AND SUBSIDENCE

Two types of settlement are of concern with respect to landfill covers: total settlement and differential settlement. Total settlement of the surface of a cover is the total downward movement of a fixed point on the surface. Total settlement of municipal solid waste can be enormous. As seen in Figure 11.21, total settlement of 10 to 15% of the thickness is generally to be expected, and 20 to 30% also is possible. The contours of the final cover must take such anticipated settlement into account.

Differential settlement is even more insidious and problematic. Differential settlement is always measured between two points and is defined as the difference between the total settlements at these two points; that is,

$$\Delta Z_{i,i+1} = Z_{i+1} - Z_i \tag{11.5}$$

where $\Delta Z_{i,i+1}$ = differential settlement between points i and $i + 1$,
Z_i = total settlement of point i.
Z_{i+1} = total settlement of point $i + 1$.

Distortion is defined as the differential settlement between two points divided by the distance along the ground surface between the two points, or

$$\psi_{i,i+1} = \frac{\Delta Z_{i,i+1}}{L_{i,i+1}} \tag{11.6}$$

where $\psi_{i,i+1}$ = distortion between points i and $i+1$,
$\Delta Z_{i,i+1}$ = differential settlement between points i and $i+1$,
$L_{i,i+1}$ = distance between points i and $i+1$.

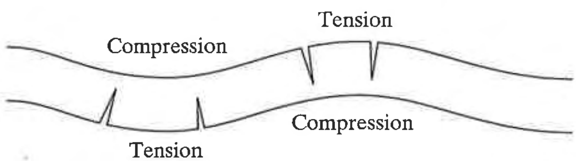

FIGURE 11.21 Tension Cracking of Landfill Cover due to Differential Settlement

Excessive differential settlement of underlying waste can damage a cover system. If differential settlement occurs, tensile strains develop in cover materials as a result of bending stresses and/or elongation. Tensile strain is defined as the amount of stretching of an element divided by the original length of the element, written as

$$\varepsilon_{i,i+1} = \frac{(L_{i,i+1})_{\text{Fnl}} - (L_{i,i+1})_{\text{Int}}}{(L_{i,i+1})_{\text{Int}}} \times 100\% \tag{11.7}$$

where $\varepsilon_{i,i+1}$ = tensile strain between points i and $i+1$,
$(L_{i,i+1})_{\text{Int}}$ = distance between points i and $i+1$ in their initial positions,
$(L_{i,i+1})_{\text{Fnl}}$ = distance between points i and $i+1$ in their post-settlement positions.

When the cover settles differentially, some part of it will be subjected to tension and will undergo tensile strain. Tensile strains are of concern because the larger the stretching (tensile strain), the greater the possibility that the soil will crack and that a geomembrane or geosynthetic clay liner will rupture.

Bending stresses—stresses that occur when an object is bent—result when covers settle differentially; part of the bent cover is in tension and part is in compression. Bending stresses are of concern because the tensile stresses associated with bending may be large enough to cause the soil to crack (Figure 11.21). Geomembranes can withstand far larger tensile strains without failing than soils (recall Figure 11.6). Geomembranes have the ability to elongate (stretch) a great deal without rupturing or breaking. On the contrary, compacted clay is very weak in tension; it cracks at tensile strain of less than 1%. Geosynthetic clay liners are intermediate between these two extremes.

Gilbert and Murphy (1987) discuss the prediction and mitigation of subsidence damage to the landfill covers. Gilbert and Murphy developed a relationship between tensile strain in a cover and distortion. This relationship is shown in Figure 11.22. As the distortion increases, the tensile strain in the cover soils increases.

Minor cracking to topsoil or drainage layers as a result of tensile stresses is of little concern. However, cracking of a hydraulic barrier, such as a layer of low hydraulic con-

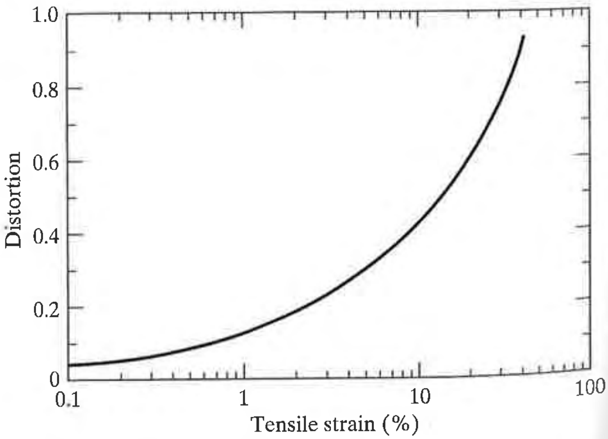

FIGURE 11.22 Relationship between Distortion and Tensile Strain in a Cover (Gilbert and Murphy, 1987)

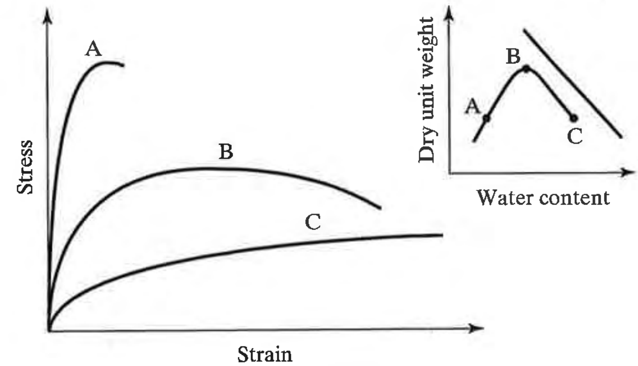

FIGURE 11.23 Relationship between Shearing Characteristics of Compacted Soils and Conditions of Compaction (USEPA, 1991)

ductivity soil, is of great concern because the hydraulic integrity of the barrier layer is compromised if it is cracked. The amount of strain that a low hydraulic conductivity, compacted soil can withstand prior to cracking depends significantly upon the water content of the soil. As shown in Figure 11.23, soils compacted wet of optimum are more ductile than soils compacted dry of optimum. For cover systems, ductile soils that can withstand significant strain without cracking are preferred. For this reason, as well as the hydraulic conductivity consideration, it is preferable to compact low hydraulic conductivity soil layers wet of optimum. The soil must then be kept safe from drying out and cracking. One way of accomplishing this is to cover the clay with a geomembrane that acts as a vapor trap in addition to its own intrinsic barrier capabilities.

Gilbert and Murphy (1987) summarize information concerning tensile strain at failure for compacted, clayey soils. The available data show that such soils can withstand maximum tensile strains of 0.1 to 1%. If the lower limit (0.1%) is used for design, the maximum allowable value of distortion is approximately 0.05%.

EXAMPLE 11.2

A circular depression with a radius (R) of 10 feet (3 m) develops in a landfill cover with a compacted clay liner as the barrier. The maximum allowable distortion (ψ) is 0.05%. What is the maximum allowable settlement at the center of the depression to avoid cracking from excessive tensile strain?

Solution: The maximum allowable differential settlement,

$$
\begin{aligned}
\Delta Z &= \psi \cdot R \\
&= 0.05 \times 10 \\
&= 0.5 \text{ ft} = 6 \text{ inches (150 mm)}
\end{aligned}
$$

Therefore, settlement at center of depression $\leq$ 6 inches (150 mm).

Some wastes (such as loose municipal solid waste or unconsolidated sludge of varying thickness) are so compressible that constructing a cover system above the waste will almost certainly produce distortions that are far larger than 0.05. The hydraulic integrity of a low hydraulic conductivity layer of compacted soil is likely to