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Part III, Appendix III-D.5-4

Landfill Foundation Settlement, Waste Settlement, and Soil Liner Strain Analyses

APPENDIX III-D.5-4

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

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Appendix III-D.5-4, Landfill Foundation Settlement, Waste Settlement, and Liner Strain Analyses

- Updated calculations to match new landfill geometry

APTIM	**Client Name:** Rancho Viejo Waste Management, LLC		
	Project Name: Pescadito Environmental Resource Center	**Project No.:**	155145~~148866~~
	~~Prepared~~ Modified by: ~~P.Thomas~~O. Covert	**Date ~~Prepared~~Modified:**	8/1/17~~02/24/2015~~
	Reviewed by: ~~Jesse P. Varsho, PE~~ P. Thomas	**Date Reviewed:**	~~03/02/2015~~8/7/17

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 poin~~ts~~ F1 is located over the maximum waste column over the leachate collection pipe and point F2 is ~~are~~ located where the ~~maximum and~~ minimum waste column thicknes~~es~~ occurs over the leachate collection pipe~~, respectively~~; and
- Foundation settlement poin~~ts~~ F1 is located just south of the maximum elevation for the final landform and point F2 ~~are located where the highest gradient for the final landform grades occurs, and~~ is located where the lowest ~~gradient~~ elevation for the leachate collection system grades occurs.

Settlement point **F1** is located approximately **~~1,470~~ 214 feet ~~east~~ west** of settlement point **F2**. The base elevation difference of the two settlement points is controlled by the **0.50%** gradient leachate pipe run (see

Drawing No. III-D.3-1).

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~~ 241 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~~ 241 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~~553 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~~ 703 -ft.MSL	3 -ft	~~380~~241	~~451~~ 459 -ft.MSL	2 -ft	~~449~~ 457 -ft.MSL	3 -ft
F2	~~642~~659 -ft.MSL	3 -ft	~~195~~198	~~444~~ 458 -ft.MSL	2 -ft	~~442~~456 -ft.MSL	3 -ft
Waste Settlement Points:							
W1	~~842~~ 703 -ft.MSL	3 -ft	~~380~~241	459 -ft.MSL	2 -ft	457 -ft.MSL	3 -ft
W2	~~552~~ 575 -ft.MSL	3 -ft	0	~~549~~ 572 -ft.MSL	2 -ft	~~547~~ 570 -ft.MSL	3 -ft

Note:
Maximum waste column thickness of ~~380~~ 241 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~~454-ft.MSL** and **~~439~~453-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~~ 555 -ft.MSL	~~3~~ 17 -ft	129 pcf	132 pcf
Stratum II-III-IV (excavated, saturated)	538 -ft.MSL	~~90~~84 -ft	129 pcf	132 pcf
Stratum II-III-IV (compressible, saturated)	454~~446~~ -ft.MSL	50 -ft	129 pcf	132 pcf
Stratum II-III-IV (incompressible, saturated)	~~396~~ 404 -ft.MSL	-	-	-
At Point F1: AFTER Landfill Development				
Final Cover System	703~~834~~ -ft.MSL	3 -ft	129 pcf	132 pcf
Waste Fill	~~831~~ 700 -ft.MSL	~~380~~ 241 -ft	65 pcf	65 pcf
Protective Soil Cover	~~451~~459 -ft.MSL	2 -ft	129 pcf	132 pcf
Compacted Low Permeable Soil Liner	~~449~~ 457 -ft.MSL	3 -ft	129 pcf	132 pcf
Stratum II-III-IV (compressible, saturated)	~~446~~454 -ft.MSL	50 -ft	129 pcf	132 pcf
Stratum II-III-IV (incompressible, saturated)	~~396~~ 404 -ft.MSL	-	-	-
At Point F2: BEFORE Landfill Development				
Stratum II-III-IV (excavated, dry)	~~540~~ 556-ft.MSL	~~2~~ 18 -ft	129 pcf	132 pcf
Stratum II-III-IV (excavated, saturated)	538 -ft.MSL	~~96~~ 85 -ft	129 pcf	132 pcf
Stratum II-III-IV (compressible, saturated)	~~439~~ 453 -ft.MSL	50 -ft	129 pcf	132 pcf
Stratum II-III-IV (incompressible, saturated)	~~389~~ 403 -ft.MSL	-	-	-
At Point F2: AFTER Landfill Development				
Final Cover	~~642~~ 659-ft.MSL	3 -ft	129 pcf	132 pcf
Waste	~~639~~ 656 -ft.MSL	~~193~~ 198 -ft	65 pcf	65 pcf
Protective Soil Cover	~~444~~458 -ft.MSL	2 -ft	129 pcf	132 pcf
Compacted Low Permeable Soil Liner	~~442~~ 456 -ft.MSL	3 -ft	129 pcf	132 pcf
Stratum II-III-IV (compressible, saturated)	~~439~~ 453 -ft.MSL	50 -ft	129 pcf	132 pcf
Stratum II-III-IV (incompressible, saturated)	~~389~~ 403 -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 $\Phi'_o < \Phi'_f \leq \Phi'_p$, 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 **380 241 feet** and **195 198 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~~16,191.7 psf	~~13,245.7~~13,630.1 psf
Stratum II-III-IV	~~8,530.2~~ 9,779.4psf	~~8,679.6~~9,978.0 psf	~~27,304.5~~18,269.5 psf	~~15,020.5~~ 15,474.5 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	~~0.2655595950~~0.244101422 -ft	~~0.0074670120~~0.018588267 -ft	~~0.2730266070~~0.262689689 -ft
Stratum II-III-IV	~~0.9381480230~~0.503937507 -ft	~~0.1244502060~~0.309804455 -ft	~~1.062598229~~ 0.813741962-ft
TOTAL:	**~~1.2037076180~~0.748038929 -ft**	**~~0.1319172180~~0.3289392722 -ft**	**~~1.335624836~~ 1.076431652-ft**
Settlement at Point F2:			
Compacted Low Permeable Soil Liner	~~0.2341276690~~0.235767069 -ft	~~0.0074670120~~0.018588267 -ft	~~0.2415946810~~0.254355336 -ft
Stratum II-III-IV	~~0.4423557990~~0.353931844 -ft	~~0.1244502060~~0.309804455 -ft	~~0.5668060040~~0.663736299 -ft
TOTAL:	**~~0.6764834680~~0.589698913 -ft**	**~~0.1319172180~~0.328392722 -ft**	**~~0.8084006850~~0.918091636 -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~~457-ft MSL) - (~~1.335624836~~1.076431652-ft) = **EL. ~~447.664~~455.924-ft MSL**
- At Settlement Point F2: (EL. ~~442~~456-ft MSL) - (~~0.808400685~~0.918091636-ft) = **EL. ~~441.192~~455.082-ft MSL**

Differential Settlement

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

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

$$S_{diff} = \frac{|\cancel{1.335624836}1.076431652\ ft - \cancel{0.808400685}0.918091636\ ft|}{\cancel{1,470}214\ ft} = \mathbf{0.07399\cancel{0.03586}\%}$$

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:

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

$$Slope_{diff} = \frac{(\cancel{447.664}455.924\ ft - \cancel{441.192}455.082\ ft)}{\cancel{1,470}214\ ft} \times 100\%$$

$$= \mathbf{0.39346\cancel{0.44027}\%}$$

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~~0.0003178%** 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**).

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

$$(L_{F1,F2})_{Initial} = \sqrt{(El.457\cancel{449}ft - El.\cancel{442}456ft)^2 + (\cancel{1,470}214ft)^2}$$

$$= \cancel{1470.016667}214.002336ft$$

$$(L_{F1,F2})_{Final} = \sqrt{(El.\,447.664\,455.924ft - El.\,441.192\,455.082ft)^2 + (1,470\,214ft)^2}$$

$$= 1470.014247\,214.001656ft$$

$$\varepsilon_{F1,F2} = \frac{|(1470.014247\,214.001656ft) - (1470.016667\,214.002336ft)|}{(1470.016667\,214.002336ft)} \times 100\%$$

$$\varepsilon_{F1,F2} = 0.0001646\,0.0003178\%$$

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~~0.07399%	0.5%	~~0.44027~~0.39346%	~~0.0001646~~0.0003178%

Final Cover / Waste Settlement Calculations

The calculated settlement at settlement point **W1** is calculated to be approximately **~~48.02~~27.54 feet** (refer to attached spreadsheets in **Reference No. 5**):

$$S_{pt.W1} = (\Delta S_p\, due\ to\ Final\ Cover\ Placement) + (\ 3S_s\ following\ post\ construction, 30yrs.)$$

$$S_{pt.W1} = (2.161.10ft + 45.8626.44ft) = 27.5448.02ft$$

Differential settlement between points **W1** and **W2** was calculated using a value of **~~48.02~~27.54 feet**. At point **W2**, settlement is **0 feet**; therefore, the differential settlement between Points **W1** and **W2** is approximately **~~2.60~~4.98 percent**:

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

$$S_{diff} = \frac{|48.0227.54\ ft - 0.00\ ft|}{1{,}846553\ ft} = 2.604.98\%$$

Results

Foundation Settlement

The estimated maximum differential settlement of the landfill foundation is approximately ~~0.0003586~~0.0007399 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~~0.39% 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~~0.0498 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

New Figures to replace existing

New Spreadsheet provided

Reference No. 5

Foundation and Waste Settlement Calculation Spreadsheets

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Appendix III-D.5-4, Landfill Foundation Settlement, Waste Settlement, and Liner Strain Analyses

- Updated calculations to match new landfill geometry