APPENDIX H.3

FOUNDATION AND WASTE SETTLEMENT

Shaw® Shaw Environmental, Inc.

Client:	Clinton Landfill, Inc.
Project:	Clinton Landfill No. 3 Chemical Waste Unit
Proj. #:	128017
Calculated By: PCT	Date: 10/1/07
Checked By: JPV	Date: 10/1/07

TITLE: FOUNDATION AND WASTE SETTLEMENT

Problem Statement

Determine the consolidation settlement of the landfill foundation. The consolidation due to waste placement at critical locations is evaluated to determine the differential settlement between these locations. These calculations are performed to demonstrate that the leachate collection system will maintain a positive slope and the liner system will not be damaged due to differential settlement. These calculations demonstrate compliance with 329 IAC 10-15-8 (a)(9).

Given

- ❑ Drawings of the "Proposed Excavation Grades," the "Intermediate Top of Waste Grades," and "Proposed Final Grades," - Drawing Nos. D4, D11, and D12 contained in this application.
- ❑ Hydrogeologic Report, contained in this application.
- ❑ Appendix H.1 "Summary of geotechnical parameters" contained in this application.
- ❑ Microsoft Excel settlement calculation spreadsheets. (Refer to attached pages).
- ❑ Das, Braja M., *Principles of Geotechnical Engineering, Third Edition*. (Refer to attached pages).
- ❑ Coduto, Donald P., *Geotechnical Engineering Principles and Practices*. (Refer to attached pages).
- ❑ Yen, Bing C. and Brian Scanlon, *Sanitary Landfill Settlement Rates*. ASCE Journal of the Geotechnical Engineering Division. May, 1975. (Refer to attached pages).

Assumptions

Locations Analyzed

The greatest differential settlement of the bottom liner system is expected to occur between Points A and B which represent the location of the maximum and minimum waste height, respectively, over the highest gradient of the final contours and the lowest gradient of the leachate collection system in the Chemical Waste Unit. Point B is located near a leachate collection sump while point A is located approximately 333.6 feet east. The base elevation difference of these two points is controlled by the 0.60% gradient leachate pipe run.

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To analyze the differential settlement of the final cover, it was assumed that the largest differential settlement of the waste will occur at the edge of the landfill where the waste height is zero (Point C) and the Chemical Waste Unit peak elevation (Point A). The distance between points C and B is approximately 204 feet. Refer to the attached figures for locations of Points A, B, and C, and Table 1 for the elevations of these Points.

Table 1 - Elevations of Settlement Points

Location	Top of Final Landform Elevation (ft. MSL)	Top of Cohesive Soil Layer Elevation (ft. MSL)	Top of Leachate Drainage Layer Elevation (ft. MSL)	Top of MSW Elevation (ft. MSL)	Top of Chemical Waste Elevation (ft. MSL)	MSW Thickness (ft.)	Chemical Waste Thickness (ft.)
Point A	835.5	662.8	663.8	831.5	772.0	59.5	108.2
Point B	785.3	660.8	661.8	781.3	770.8	10.5	109.0
Point C	734.0	728.5	730.0	730.0	730.0	0.0	0.0

Note: Refer to attached figure for elevations at Points A, B, and C. Top of MSW elevation was determined by subtracting the final cover thickness (4 ft.) from the final landform elevation.

This analysis will calculate the settlement in the compressible layers beneath the leachate collection layer. The compressible geological units under the proposed liner system is the compacted clay fill/sub-base, and the Berry Clay / Radnor Till. The geologic units below the Berry Clay / Radnor Till Unit were assumed to be incompressible. Therefore it is assumed that settlement occurs only in these two units.

Initial Conditions

Table 2 summarizes the geology at the site prior to landfill construction. Unit weights were estimated from previous studies and laboratory testing performed on representative site soil materials. The potentiometric surface was conservatively assumed to occur at elevation 691.4 feet MSL, which respresents the highest water level measured on site (measured in Monitoring Well EX-4 on November 18, 2004).

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Table 2 - Stratigraphy of Geology Before Landfill					
Material	**Average Top Elevation (ft. MSL)**	**Average Bottom Elevation (ft. MSL)**	**Thickness (ft.)**	**Moist Unit Weight (pcf)**	**Saturated Unit Weight (pcf)**
Point A					
Tiskilwa Formation	724.0	670.0	54.0	135.0	140.0
Roxana Silt / Robein Member	670.0	660.0	10.0	100.0	110.0
Berry Clay / Radnor Till	660.0	483.0	177.0	140.0	148.0
Point B					
Tiskilwa Formation	705.0	670.0	35.0	135.0	140.0
Roxana Silt / Robein Member	670.0	660.0	10.0	100.0	110.0
Berry Clay / Radnor Till	660.0	483.0	177.0	140.0	148.0

Final Conditions

Table 3 summarizes the maximum waste height, the typical thickness of the final cover and landfill liner layers, and the average thickness of the geological units below the landfill liner. Also summarized are the assumed unit weights of each layer. Conservatively, the unit weight of in-place MSW is assumed to be 75 pcf, and the unit weight of in-place chemical waste is 90 pcf. The density of the compacted cohesive earth liner was based on results from previous studies and laboratory testing performed on sampled site soils. The compacted cohesive earth liner material will be constructed from the excavated Tiskilwa Formation and Berry Clay / Radnor Till soils.

Conservatively, the potentiometric surface of the foundation soils is assumed to be at the top of the leachate collection system of the proposed Chemical Waste Unit and all geologic units below the groundwater table are assumed to be saturated. The compacted cohesive earth liner and soil layers beneath the landfill were also assumed to be saturated.

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Table 3 - Stratigraphy of Geology After Landfill					
Material	**Average Top Elevation (ft. MSL)**	**Average Bottom Elevation (ft. MSL)**	**Thickness (ft.)**	**Moist Unit Weight (pcf)**	**Saturated Unit Weight (pcf)**
Point A					
Final Cover	835.5	831.5	4.0	128.0	134.0
MSW	831.5	772.0	59.5	75.0	75.0
Chemical Waste	772.0	663.8	108.2	90.0	90.0
Leachate Collection Layer	663.8	662.8	1.0	126.0	130.0
Compacted Cohesive Earth Liner	662.8	659.8	3.0	135.0	140.0
Berry Clay / Radnor Till	659.8	483.0	176.8	140.0	148.0
Point B					
Final Cover	785.3	781.3	4.0	128.0	134.0
MSW	781.3	770.8	10.5	75.0	75.0
Chemical Waste	770.8	661.8	109.0	90.0	90.0
Leachate Collection Layer	661.8	660.8	1.0	126.0	130.0
Compacted Cohesive Earth Liner	660.8	657.8	3.0	135.0	140.0
Berry Clay / Radnor Till	657.8	483.0	174.8	140.0	148.0

Foundation Settlement Calculations

Consolidation is divided into three categories: 1) immediate settlement, 2) primary consolidation settlement, and 3) secondary consolidation settlement. Immediate settlement is caused by the elastic deformation of soils without any change in the moisture content. However, immediate settlement is negligible for cohesive soils and therefore is not applicable. Primary consolidation in saturated cohesive 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. It occurs only in saturated cohesive soils and is the result of the plastic adjustment of soil fabrics. Primary and secondary consolidations are calculated for both the compacted cohesive earth liner and the Berry Clay / Radnor Till.

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Primary Settlement:

For overconsolidated clays, primary settlement is determined using the following equation.

$$S_P = \left[\frac{(C_r)}{1+e_o} H \log\left(\frac{\sigma'_c}{\sigma'_{zo}}\right) + \frac{(C_c)}{1+e_o} H \log\left(\frac{\sigma'_{z_f}}{\sigma'_c}\right) \right]$$

Where,

S_p = Primary Settlement, feet
C_c = Compression Index
C_r = Recompression Index
H = Thickness of the layer, feet
e_o = Initial void ratio = n/(1-n)
σ'_c = Preconsolidation stress, psf
σ'_o = Initial vertical effective stress, psf
σ'_f = Final vertical effective stress, psf

Values for void ratios, compression, and recompression indexes for all materials are summarized in Appendix H.1.

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 are summarized in Appendix H.1.

Waste Settlement Calculations

The waste settlement was calculated based on Terzaghi's theory of one-dimensional consolidation. The primary settlement is calculated incrementally for nine fill lifts of one cell within the Chemical Waste Unit. It is assumed that each lift of waste is approximately 20-feet thick. 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 settlement was calculated to determine how much of the primary settlement would occur following the construction of the final cover. The time of primary settlement was conservatively estimated for the final lift of MSW (Lift No. 9) following the placement of the final cover system. The primary settlement for the final lift was calculated to be 2.8 days. From this estimate we can conclude 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. The waste settlement calculations therefore focus on the post-construction 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 summed up to provide a total value for secondary settlement.

Calculations

Foundation Settlement

The equations listed above outline the method used to estimate the foundation settlement at Point A and B. The thickness of waste at Points A and B are 167.7 feet (MSW = 59.5 feet + Chemical Waste = 108.2 feet) and 119.5 feet (MSW = 10.5 feet + Chemical Waste = 109 feet), respectively. The final effective 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 cohesive earth liner was calculated as the weight of itself. The effective stress is calculated at the center of each geologic unit. Please see the attached spreadsheets for calculations.

Final Effective Stress:

The final effective stress is the effective stress following final cover placement and varies for Points A and B. The effective stress is calculated at the center of each layer or geologic unit. Please see

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attached spreadsheets for calculations.

The effective stress values for initial and final conditions, for each geologic unit are summarized below.

Geologic Unit	Initial Effective Stress, psf		Final Effective Stress, psf	
	Point A	Point B	Point A	Point B
Cohesive Earth Liner	116.4	116.4	14,896.5	11,293.5
Berry Clay / Radnor Till	20,533.2	17,968.2	28,991.4	25,217.2

Primary Consolidation and Secondary Settlement:

The following summary tables summarize calculations completed in spreadsheets attached at the end of the document.

Settlement at Point A			
Geologic Unit	Primary Settlement (ft)	Secondary Settlement (ft)	Total Settlement (ft)
Cohesive Earth liner	0.07662	0.00315	0.07978
Berry Clay / Radnor Till	0.46659	0.18579	0.65238
Total	**0.54321**	**0.18894**	**0.73216**
Note: values shown above for the Berry Clay / Radnor Till Unit represent cumulative settlement in the entire 176.8-ft thick unit.			

Settlement at Point B			
Geologic Unit	Primary Settlement (ft)	Secondary Settlement (ft)	Total Settlement (ft)
Cohesive earth liner	0.07225	0.00315	0.07540
Berry Clay / Radnor Till	0.48767	0.18285	0.67052
Total	**0.55992**	**0.18600**	**0.74592**
Note: values shown above for the Berry Clay / Radnor Till Unit represent cumulative settlement in the entire174.8-ft thick unit.			

Total Settlement:

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Project: Clinton Landfill No. 3 Chemical Waste Unit

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The total settlement of the foundation soils is equal to the summation of the settlement of each layer or geologic unit. The elevation of the top of the compacted cohesive earth liner after settlement will be approximately 662.07 feet (El.662.8' - 0.73216') at Point A and approximately 660.05 feet (El.660.8' - 0.74592') at Point B.

Differential Settlement:

The differential settlement between Points A and B are calculated as follows:

$$S_{diff} = \frac{|S_{Pt.A} - S_{Pt.B}|}{Distance_{Pt.A/Pt.B}} \times 100\%$$

$$S_{diff} = \frac{|0.73216\ feet - 0.74592\ feet|}{333.6\ feet} \times 100\%$$

$$S_{diff} = 0.004\%$$

Slope of Leachate Collection System

The leachate collection system is designed with a slope of 0.60%. During waste placement and post-closure care, differential settlement will occur. The slope will be approximately 0.60% at the end of the post-closure care period.

$$Slope = \frac{Elev_{Pt.A} - Elev_{Pt.B}}{Distance_{Pt.A/Pt.B}} \times 100\%$$

$$Slope = \frac{662.07\ feet - 660.05\ feet}{333.6\ feet} \times 100\%$$

$$Slope = 0.605\%$$

<u>Waste Settlement</u>

At Point A, settlement is calculated to be approximately 10.8 feet:

S = (ΔS_p due to Final Cover Placement on Lift No.9) + (ΣS_s following Post-Construction, 100 yrs.)
S = (4.7 + 4.8) feet = 9.5 feet.

At Point A, settlement is calculated to be approximately 10.8 feet:

S = (ΔS_p due to Final Cover Placement on Lift No.9) + (ΣS_s following Post-Construction, 100 yrs.)
S = (6.3 + 2.2) feet = 8.5 feet

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Differential settlement between Points A and B was calculated to be 2.85 percent:

$$S_{diff} = \frac{S_{Pt.A} - S_{Pt.B}}{Distance_{Pt.C/Pt.D}} ' \ 100\%$$

$$S_{diff} = \frac{9.5 \text{ feet} - 0 \text{ feet}}{333.6 \text{ feet}} ' \ 100\%$$

$$S_{diff} = 2.85\%$$

Differential settlement between Points A and B was calculated to be 4.17 percent:

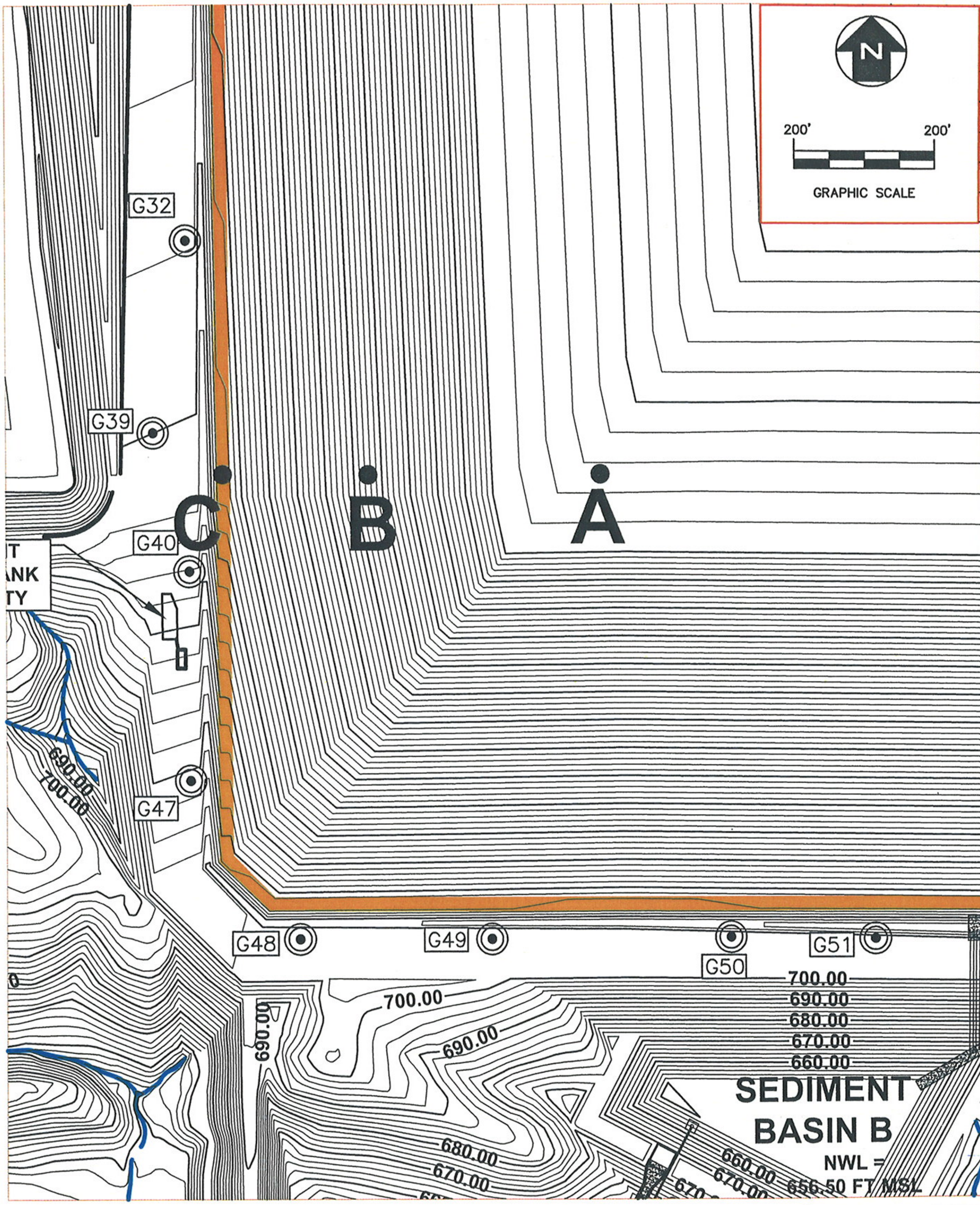
$$S_{diff} = \frac{S_{Pt.B} - S_{Pt.C}}{Distance_{Pt.C/Pt.D}} ' \ 100\%$$

$$S_{diff} = \frac{8.5 \text{ feet} - 0 \text{ feet}}{204 \text{ feet}} ' \ 100\%$$

$$S_{diff} = 4.17\%$$

Results

The estimated maximum differential settlement of the landfill foundation is approximately 0.004 ft/ft. This value is negligible and will not cause or contribute to the failure of the liner or leachate collection system. The slope of the leachate system will be approximately 0.60 percent at the end of the post-closure care period, which will allow for proper leachate drainage and collection.

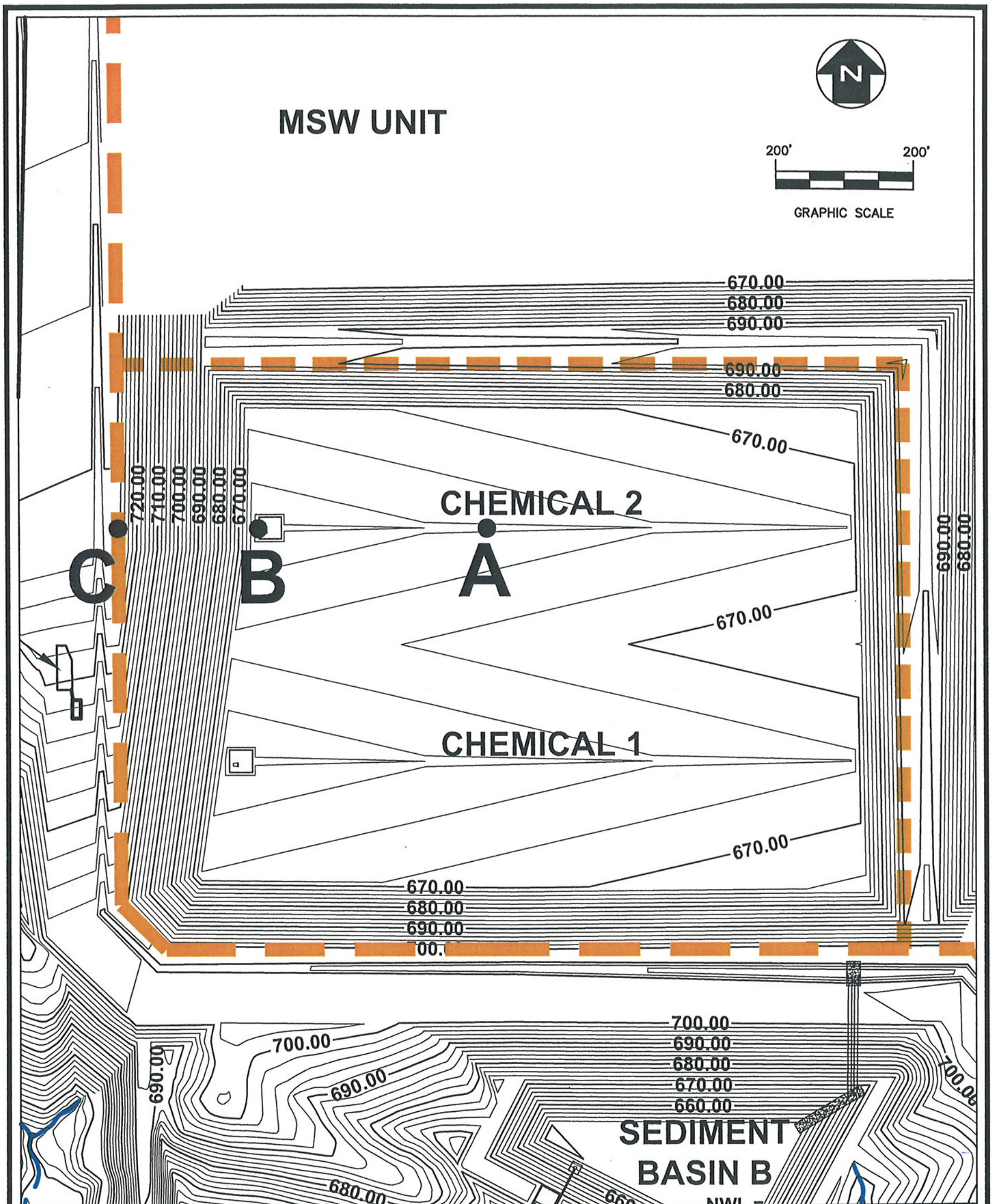


Shaw® Shaw Environmental, Inc.

CLINTON LF. NO. 3 CHEMICAL WASTE UNIT
DEWITT COUNTY, ILLINOIS

SETTLMENT POINT LOCATIONS
SHOWN ON PROPOSED
FINAL LANDFORM GRADES DRAWING

APPROVED BY: DAM	PROJ. NO.: 128017	DATE: OCT. 2007



CLINTON LF. NO. 3 CHEMICAL WASTE UNIT
DEWITT COUNTY, ILLINOIS

SETTLEMENT POINT LOCATIONS SHOWN ON PROPOSED MASS LINER GRADES DRAWING

Shaw® Shaw Environmental, Inc.

APPROVED BY:	DAM	PROJ. NO.:	128017	DATE:	OCT. 2007

Stress concentrations through cross section of a Landfill

Company Name	Shaw Environmental, Inc.
Project Name	Clinton Landfill No. 3 Chemical Waste Unit
Project Number	128017
Date	9/27/2007
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

Point A

Unit	Classification	Interval	Thickness (ft)	Relative Density (%)	Unit Weights (pcf)		Mid-Layer Stresses (psf)		Bottom-Layer Stresses (psf)	
					λ soil	λ bouyant	σ' (effective)	σ (total)	σ' (effective)	σ (total)
Example	EX	0-2	2		0	0	0.00	0.00	0.00	0.00
Tiskilwa Formation (Excavated / Above W.T.)	CL	EL. 724-691.4	32.6		135	135	2,200.50	2,200.50	4,401.00	4,401.00
Tiskilwa Formation (Excavated / Below W.T.)	CL	EL. 691.4-670	21.4		140	77.6	5,231.32	5,899.00	6,061.64	7,397.00
Roxana Silt and Robein Member (Excavated / Below W.T.)	OL	EL. 670-660	10		110	47.6	6,299.64	7,947.00	6,537.64	8,497.00
Berry Clay and Radnor Till (Excavated / Below W.T.)	CL	EL. 660-659.8	0.2		148	85.6	6,546.20	8,511.80	6,554.76	8,526.60
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 659.8-630	29.8		148	85.6	7,830.20	10,731.80	9,105.64	12,937.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 630-600	30		148	85.6	10,389.64	15,157.00	11,673.64	17,377.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 600-570	30		148	85.6	12,957.64	19,597.00	14,241.64	21,817.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 570-540	30		148	85.6	15,525.64	24,037.00	16,809.64	26,257.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 540-510	30		148	85.6	18,093.64	28,477.00	19,377.64	30,697.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 510-483	27		148	85.6	20,533.24	32,695.00	21,688.84	34,693.00
Mahomet Sand Member	SP	EL.483-								

W.T. assumed = El.691.4 (November 2004 at EX-4)

Compacted Cohesive Earth Liner Proposed at EL. 662.8'-659.8'

Stress concentrations through cross section of a Landfill

Company Name	Shaw Environmental, Inc.
Project Name	Clinton Landfill No. 3 Chemical Waste Unit
Project Number	128017
Date	9/27/2007
Units	English

Cross Section after Landfill

Point A

Unit	Classification	Interval	Thickness (ft)	Unit Weights (pcf)		Mid-Layer Stresses (psf)		Bottom-Layer Stresses (psf)	
				λ soil	λ bouyant	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	CL	EL. 835.5-831.5	4	128	128	256.00	256.00	512.00	512.00
MSW	-	EL. 831.5-772	59.5	75	75	2,743.25	2,743.25	4,974.50	4,974.50
Chemical Waste	-	EL. 772-663.8	108.2	90	90	9,843.50	9,843.50	14,712.50	14,712.50
Leachate Collection Layer	SP	EL. 663.8-662.8	1	130	67.6	14,746.30	14,777.50	14,780.10	14,842.50
Compacted Cohesive Earth Liner	CL	EL.662.8-659.8	3	140	77.6	14,896.50	15,052.50	15,012.90	15,262.50
Berry Clay and Radnor Till	CL	EL.659.8-630	29.8	148	85.6	16,288.34	17,467.70	17,563.78	19,672.90
Berry Clay and Radnor Till	CL	EL. 630-600	30	148	85.6	18,847.78	21,892.90	20,131.78	24,112.90
Berry Clay and Radnor Till	CL	EL. 600-570	30	148	85.6	21,415.78	26,332.90	22,699.78	28,552.90
Berry Clay and Radnor Till	CL	EL. 570-540	30	148	85.6	23,983.78	30,772.90	25,267.78	32,992.90
Berry Clay and Radnor Till	CL	EL. 540-510	30	148	85.6	26,551.78	35,212.90	27,835.78	37,432.90
Berry Clay and Radnor Till	CL	EL. 510-483	27	148	85.6	28,991.38	39,430.90	30,146.98	41,428.90
Mahomet Sand Member	SP	EL.483-		148	85.6				

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	Shaw Environmental, Inc.	Units	English
Project Name	Clinton Landfill No. 3 Chemical Waste Unit	Life of Landfill (yrs)	45
Project Number	128017	Post-closure care period (yrs)	100
Date	9/27/2007	Total Settlement (ft)	0.73216

Method for Non-Cohesive Soils
Mark X in the correct box

Classical	X
Peck	

L

Point A		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	Cα	σ'p	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 Cohesive Earth Liner	CL	C	EL.662.8-659.8	3			0.32	0.10	0.016	0.0040	-	116.40	14,896.50	0.07662295	0.00315261	0.07977557
Berry Clay and Radnor Till	CL	C	EL.659.8-630	29.8			0.32	0.10	0.016	0.0040	35,000	7,830.20	16,288.34	0.11490301	0.03131596	0.14621897
Berry Clay and Radnor Till	CL	C	EL. 630-600	30			0.32	0.10	0.016	0.0040	35,000	10,389.64	18,847.78	0.09405807	0.03152614	0.12558421
Berry Clay and Radnor Till	CL	C	EL. 600-570	30			0.32	0.10	0.016	0.0040	35,000	12,957.64	21,415.78	0.07934836	0.03152614	0.11087449
Berry Clay and Radnor Till	CL	C	EL. 570-540	30			0.32	0.10	0.016	0.0040	35,000	15,525.64	23,983.78	0.06867932	0.03152614	0.10020545
Berry Clay and Radnor Till	CL	C	EL. 540-510	30			0.32	0.10	0.016	0.0040	35,000	18,093.64	26,551.78	0.06057007	0.03152614	0.09209621
Berry Clay and Radnor Till	CL	C	EL. 510-483	27			0.32	0.10	0.016	0.0040	35,000	20,533.24	28,991.38	0.04902919	0.02837352	0.07740271
Mahomet Sand Member	SP	N	EL.483-													

$\sum(\text{Settlement})_{\text{Liner}} =$	0.07662295	0.00315261	0.07977557
$\sum(\text{Settlement})_{\text{Berry/Radnor}} =$	0.46658802	0.18579402	0.65238204
Totals =	0.54321097	0.18894664	0.73215761

Stress concentrations through cross section of a Landfill

Company Name	Shaw Environmental, Inc.
Project Name	Clinton Landfill No. 3 Chemical Waste Unit
Project Number	128017
Date	9/27/2007
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

Point A

Unit	Classification	Interval	Thickness (ft)	Relative Density (%)	Unit Weights (pcf) λ soil	Unit Weights (pcf) λ bouyant	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
Tiskilwa Formation (Excavated / Above W.T.)	CL	EL. 724-691.4	32.6		135	135	2,200.50	2,200.50	4,401.00	4,401.00
Tiskilwa Formation (Excavated / Below W.T.)	CL	EL. 691.4-670	21.4		140	77.6	5,231.32	5,899.00	6,061.64	7,397.00
Roxana Silt and Robein Member (Excavated / Below W.T.)	OL	EL. 670-660	10		110	47.6	6,299.64	7,947.00	6,537.64	8,497.00
Berry Clay and Radnor Till (Excavated / Below W.T.)	CL	EL. 660-659.8	0.2		148	85.6	6,546.20	8,511.80	6,554.76	8,526.60
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 659.8-630	29.8		148	85.6	7,830.20	10,731.80	9,105.64	12,937.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 630-600	30		148	85.6	10,389.64	15,157.00	11,673.64	17,377.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 600-570	30		148	85.6	12,957.64	19,597.00	14,241.64	21,817.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 570-540	30		148	85.6	15,525.64	24,037.00	16,809.64	26,257.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 540-510	30		148	85.6	18,093.64	28,477.00	19,377.64	30,697.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 510-483	27		148	85.6	20,533.24	32,695.00	21,688.84	34,693.00
Mahomet Sand Member	SP	EL.483-								

W.T. assumed = El.691.4 (November 2004 at EX-4)

Compacted Cohesive Earth Liner Proposed at EL. 662.8'-659.8'

Stress concentrations through cross section of a Landfill

Company Name	Shaw Environmental, Inc.
Project Name	Clinton Landfill No. 3 Chemical Waste Unit
Project Number	128017
Date	9/27/2007
Units	English

Cross Section <u>after</u> Landfill

Point A

				Unit Weights (pcf)		Mid-Layer Stresses (psf)		Bottom-Layer Stresses (psf)	
Unit	Classification	Interval	Thickness (ft)	λ soil	λ bouyant	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	CL	EL. 835.5-831.5	4	128	128	256.00	256.00	512.00	512.00
MSW	-	EL. 831.5-772	59.5	75	75	2,743.25	2,743.25	4,974.50	4,974.50
Chemical Waste	-	EL. 772-663.8	108.2	90	90	9,843.50	9,843.50	14,712.50	14,712.50
Leachate Collection Layer	SP	EL. 663.8-662.8	1	130	67.6	14,746.30	14,777.50	14,780.10	14,842.50
Compacted Cohesive Earth Liner	CL	EL.662.8-659.8	3	140	77.6	14,896.50	15,052.50	15,012.90	15,262.50
Berry Clay and Radnor Till	CL	EL.659.8-630	29.8	148	85.6	16,288.34	17,467.70	17,563.78	19,672.90
Berry Clay and Radnor Till	CL	EL. 630-600	30	148	85.6	18,847.78	21,892.90	20,131.78	24,112.90
Berry Clay and Radnor Till	CL	EL. 600-570	30	148	85.6	21,415.78	26,332.90	22,699.78	28,552.90
Berry Clay and Radnor Till	CL	EL. 570-540	30	148	85.6	23,983.78	30,772.90	25,267.78	32,992.90
Berry Clay and Radnor Till	CL	EL. 540-510	30	148	85.6	26,551.78	35,212.90	27,835.78	37,432.90
Berry Clay and Radnor Till	CL	EL. 510-483	27	148	85.6	28,991.38	39,430.90	30,146.98	41,428.90
Mahomet Sand Member	SP	EL.483-		148	85.6				

Stress concentrations through cross section of a Landfill

Company Name	Shaw Environmental, Inc.
Project Name	Clinton Landfill No. 3 Chemical Waste Unit
Project Number	128017
Date	9/27/2007
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

Point B

Unit	Classification	Interval	Thickness (ft)	Relative Density (%)	Unit Weights (pcf)		Mid-Layer Stresses (psf)		Bottom-Layer Stresses (psf)	
					λ soil	λ bouyant	σ' (effective)	σ (total)	σ' (effective)	σ (total)
Example	EX	0-2	2		0	0	0.00	0.00	0.00	0.00
Tiskilwa Formation (Excavated / Above W.T.)	CL	EL. 705-691.4	13.6		135	135	918.00	918.00	1,836.00	1,836.00
Tiskilwa Formation (Excavated / Below W.T.)	CL	EL. 691.4-670	21.4		140	77.6	2,666.32	3,334.00	3,496.64	4,832.00
Roxana Silt and Robein Member (Excavated / Below W.T.)	OL	EL. 670-660	10		110	47.6	3,734.64	5,382.00	3,972.64	5,932.00
Berry Clay and Radnor Till (Excavated / Below W.T.)	CL	EL. 660-657.8	2.2		148	85.6	4,066.80	6,094.80	4,160.96	6,257.60
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 657.8-630	27.8		148	85.6	5,350.80	8,314.80	6,540.64	10,372.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 630-600	30		148	85.6	7,824.64	12,592.00	9,108.64	14,812.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 600-570	30		148	85.6	10,392.64	17,032.00	11,676.64	19,252.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 570-540	30		148	85.6	12,960.64	21,472.00	14,244.64	23,692.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 540-510	30		148	85.6	15,528.64	25,912.00	16,812.64	28,132.00
Berry Clay and Radnor Till (In-Place / Below W.T.)	CL	EL. 510-483	27		148	85.6	17,968.24	30,130.00	19,123.84	32,128.00
Mahomet Sand Member	SP	EL.483-								

W.T. assumed = El.691.4 (November 2004 at EX-4)
Compacted Cohesive Earth Liner Proposed at EL. 660.8'-657.8'

Stress concentrations through cross section of a Landfill

Company Name	Shaw Environmental, Inc.
Project Name	Clinton Landfill No. 3 Chemical Waste Unit
Project Number	128017
Date	9/27/2007
Units	English

Cross Section <u>after</u> Landfill

Point B

Unit	Classification	Interval	Thickness (ft)	Unit Weights (pcf)		Mid-Layer Stresses (psf)		Bottom-Layer Stresses (psf)	
				λ soil	λ bouyant	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	CL	EL. 785.3-781.3	4	128	128	256.00	256.00	512.00	512.00
MSW	-	EL. 781.3-770.8	10.5	75	75	905.75	905.75	1,299.50	1,299.50
Chemical Waste	-	EL. 770.8-661.8	109	90	90	6,204.50	6,204.50	11,109.50	11,109.50
Leachate Collection Layer	SP	EL. 661.8-660.8	1	130	67.6	11,143.30	11,174.50	11,177.10	11,239.50
Compacted Cohesive Earth Liner	CL	EL.660.8-657.8	3	140	77.6	11,293.50	11,449.50	11,409.90	11,659.50
Berry Clay and Radnor Till	CL	EL. 657.8-630	27.8	148	85.6	12,599.74	13,716.70	13,789.58	15,773.90
Berry Clay and Radnor Till	CL	EL. 630-600	30	148	85.6	15,073.58	17,993.90	16,357.58	20,213.90
Berry Clay and Radnor Till	CL	EL. 600-570	30	148	85.6	17,641.58	22,433.90	18,925.58	24,653.90
Berry Clay and Radnor Till	CL	EL. 570-540	30	148	85.6	20,209.58	26,873.90	21,493.58	29,093.90
Berry Clay and Radnor Till	CL	EL. 540-510	30	148	85.6	22,777.58	31,313.90	24,061.58	33,533.90
Berry Clay and Radnor Till	CL	EL. 510-483	27	148	85.6	25,217.18	35,531.90	26,372.78	37,529.90
Mahomet Sand Member	SP	EL.483-		148	85.6				

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	Shaw Environmental, Inc.	Units	English
Project Name	Clinton Landfill No. 3 Chemical Waste Unit	Life of Landfill (yrs)	45
Project Number	128017	Post-closure care period (yrs)	100
Date	9/27/2007	Total Settlement (ft)	0.74592

Method for Non-Cohesive Soils

Mark X in the correct box

Classical	X
Peck	

Point B		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)	Primary Settlment	Secondary Settlement	Settlement
Unit	Classification	C or N	Interval	Thickness (ft)	LL	N60	e_o	Cc	Cr	Cα	σ'p	σ' (intial)	σ' (final)			
Example	EX	C	0-2	2			0	0	0	0	-	1.00	1.00	0	0	0.000000
Compacted Cohesive Earth Liner	CL	C	EL.660-657	3			0.32	0.10	0.016	0.0040	-	116.40	11,293.50	0.07225002	0.00315261	0.07540263
Berry Clay and Radnor Till	CL	C	EL. 657-630	27			0.32	0.10	0.016	0.0040	35,000	5,350.80	12,599.74	0.12172676	0.02837352	0.15010028
Berry Clay and Radnor Till	CL	C	EL. 630-600	30			0.32	0.10	0.016	0.0040	35,000	7,824.64	15,073.58	0.10354620	0.03152614	0.13507233
Berry Clay and Radnor Till	CL	C	EL. 600-570	30			0.32	0.10	0.016	0.0040	35,000	10,392.64	17,641.58	0.08356785	0.03152614	0.11509399
Berry Clay and Radnor Till	CL	C	EL. 570-540	30			0.32	0.10	0.016	0.0040	35,000	12,960.64	20,209.58	0.07015667	0.03152614	0.10168280
Berry Clay and Radnor Till	CL	C	EL. 540-510	30			0.32	0.10	0.016	0.0040	35,000	15,528.64	22,777.58	0.06049969	0.03152614	0.09202583
Berry Clay and Radnor Till	CL	C	EL. 510-483	27			0.32	0.10	0.016	0.0040	35,000	17,968.24	25,217.18	0.04817159	0.02837352	0.07654511
Mahomet Sand Member	SP	N	EL.483-													

	Primary Settlment	Secondary Settlement	Settlement
$\sum(\text{Settlement})_{\text{Liner}}$ =	0.07225002	0.00315261	0.07540263
$\sum(\text{Settlement})_{\text{Berry/Radnor}}$ =	0.48766876	0.18285158	0.67052035
Totals =	0.55991878	0.18600420	0.74592298

Clinton Landfill No. 3 Chemical Waste Unit
Primary Settlement of Waste at Point A
September 27, 2007

Given:	
Primary Settlement Eqtn.	$S_p = [H \bullet C_c(\log(\sigma'_{zo} + \sigma'_{zf}) / \sigma'_{zo})]$
MSW	C_c = 0.351 H_{waste} = 1 lift of waste fill = 20 ft Maximum MSW waste height = 59.5 feet Cell is divided into 3 lifts *(2 lifts at 20-ft. and final lift at 19.5-ft.)* γ_{waste} = 75 pcf Each lift takes 4 months to complete
Chemical Waste	C_c = 1.13 H_{waste} = 1 lift of waste fill = 20 ft Maximum chemical waste height = 108.2 feet Cell is divided into 6 lifts *(5 lifts at 20-ft. and final lift at 8.2-ft.)* γ_{waste} = 90 pcf Each lift takes 44 months to complete
Final Cover	$H_{final\ cover}$ = 4 ft $\gamma_{final\ cover}$ = 134 pcf Assume 6 months to complete construction of final cover
Stresses	σ'_{zo} = initial effective stress (psf) σ'_{zf} = final effective stress (psf)
Other Information	Life of Clinton Landfill No. 3 is 45 years Each lift of chemical waste takes 2 years (24 months) to complete Life of one cell in Chemical Waste Unit is 22 years Each lift of MSW takes 4 months to complete Life of portion of MSW piggyback over one Chemical Waste Unit is 1 year

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

Reference:
Coduto, D.P., *Geotechnical Engineering Principles and Practices,* 1998, pp.435-446.

Fill Type	Placement of Lift (mos.)	Lift No.	Depth of Fill Lift (ft)	Total Depth of Fill (ft)	Mid-Lift Stresses (psf) Lift 1 σ'_{zo}	Lift 1 σ'_{zf}	Lift 2 σ'_{zo}	Lift 2 σ'_{zf}	Lift 3 σ'_{zo}	Lift 3 σ'_{zf}	Lift 4 σ'_{zo}	Lift 4 σ'_{zf}	Lift 5 σ'_{zo}	Lift 5 σ'_{zf}	Lift 6 σ'_{zo}	Lift 6 σ'_{zf}	Lift 7 σ'_{zo}	Lift 7 σ'_{zf}	Lift 8 σ'_{zo}	Lift 8 σ'_{zf}	Lift 9 σ'_{zo}	Lift 9 σ'_{zf}	Lift 10 σ'_{zo}	Lift 10 σ'_{zf}	Total Primary Settlement "S_p" (ft)	Incremental Primary Settlement "S_p" (ft)
Chem. Waste	44	1	20	20	900	900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	
	44	2	20	40	900	1,800	900	900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.8	6.8
	44	3	20	60	900	2,700	900	1,800	900	900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17.6	10.8
	44	4	20	80	900	3,600	900	2,700	900	1,800	900	900	0	0	0	0	0	0	0	0	0	0	0	0	31.2	13.6
	44	5	20	100	900	4,500	900	3,600	900	2,700	900	1,800	900	900	0	0	0	0	0	0	0	0	0	0	47.0	15.8
	44	6	8.2	108.2	900	4,869	900	3,969	900	3,069	900	2,169	900	1,269	369	369	0	0	0	0	0	0	0	0	55.2	8.2
MSW	4	7	20	128.2	900	5,619	900	4,719	900	3,819	900	2,919	900	2,019	369	1,119	750	750	0	0	0	0	0	0	72.4	17.2
	4	8	20	148.2	900	6,369	900	5,469	900	4,569	900	3,669	900	2,769	369	1,869	750	1,500	750	750	0	0	0	0	86.3	14.0
	4	9	19.5	167.7	900	7,100	900	6,200	900	5,300	900	4,400	900	3,500	369	2,600	750	2,231	750	1,481	731	731	0	0	98.8	12.5
Final Cover	6	Cover	4	171.7	900	7,368	900	6,468	900	5,568	900	4,668	900	3,768	369	2,868	750	2,499	750	1,749	731	999	268	268	103.5	4.7
																										ΣS_p =103.5

Clinton Landfill No. 3 Chemical Waste Unit
Primary Settlement of Waste at Point B
September 27, 2007

Shaw® Shaw Environmental, Inc.

Given:	
Primary Settlement Eqtn.	$S_p = [H \bullet C_c(\log(\sigma'_{zo} + \sigma'_{zf}) / \sigma'_{zo}))]$
MSW	C_c = 0.351 H_{waste} = 1 lift of waste fill = 20 ft Maximum MSW waste height = 10.5 feet Cell has only 1 lift *at 10.5-ft.* γ_{waste} = 75 pcf Lift takes 4 months to complete
Chemical Waste	C_c = 1.13 H_{waste} = 1 lift of waste fill = 20 ft Maximum chemical waste height = 109 feet Cell is divided into 6 lifts *(5 lifts at 20-ft. and final lift at 9-ft.)* γ_{waste} = 90 pcf Each lift takes 44 months to complete
Final Cover	$H_{final\ cover}$ = 4 ft $\gamma_{final\ cover}$ = 134 pcf Assume 6 months to complete construction of final cover
Stresses	σ'_{zo} = initial effective stress (psf) σ'_{zf} = final effective stress (psf)
Other Information	Life of Clinton Landfill No. 3 is 45 years Each lift of chemical waste takes 2 years (44 months) to complete Life of cell in Chemical Waste Unit is 22 years One lift of MSW takes 4 months to complete

Notes:

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

Reference:

Coduto, D.P., *Geotechnical Engineering Principles and Practic*

Fill Type	Placement of Lift (mos.)	Lift No.	Depth of Fill Lift (ft)	Total Depth of Fill (ft)	Lift 1 σ'_{zo}	Lift 1 σ'_{zf}	Lift 2 σ'_{zo}	Lift 2 σ'_{zf}	Lift 3 σ'_{zo}	Lift 3 σ'_{zf}	Lift 4 σ'_{zo}	Lift 4 σ'_{zf}	Lift 5 σ'_{zo}	Lift 5 σ'_{zf}	Lift 6 σ'_{zo}	Lift 6 σ'_{zf}	Lift 7 σ'_{zo}	Lift 7 σ'_{zf}	Lift 8 σ'_{zo}	Lift 8 σ'_{zf}	Total Primary Settlement "S_p" (ft)	Incremental Primary Settlement "S_p" (ft)
Chem. Waste	44	1	20	20	900	900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	
	44	2	20	40	900	1,800	900	900	0	0	0	0	0	0	0	0	0	0	0	0	6.8	6.8
	44	3	20	60	900	2,700	900	1,800	900	900	0	0	0	0	0	0	0	0	0	0	17.6	10.8
	44	4	20	80	900	3,600	900	2,700	900	1,800	900	900	0	0	0	0	0	0	0	0	31.2	13.6
	44	5	20	100	900	4,500	900	3,600	900	2,700	900	1,800	900	900	0	0	0	0	0	0	47.0	15.8
	44	6	9	109	900	4,905	900	4,005	900	3,105	900	2,205	900	1,305	405	405	0	0	0	0	55.9	8.9
MSW	4	7	10.5	119.5	900	5,299	900	4,399	900	3,499	900	2,599	900	1,699	405	799	394	394	0	0	65.9	10.1
Final Cover	6	Cover	4	123.5	900	5,567	900	4,667	900	3,767	900	2,867	900	1,967	405	1,067	394	662	268	268	72.2	6.3
																						ΣS_p =72.2

Shaw Environmental, Inc.

Clinton Landfill No. 3 Chemical Waste Unit
Secondary Settlement of Waste at Point A
September 27, 2007

Given:	
Chemical Waste	**Secondary Settlement Eqtn:** $S_s = [(C_\alpha) / (1+e_o)] \bullet (H_o) \bullet (\log (t_2 / t_1))]$ $e_o = 4.747$ $C_\alpha = 0.0565$ Maximum height of chemical waste = 108.2 ft. Cell is divided into 6 lifts H_o = 20 ft (= 1 lift); with exception of final lift (H=8.2 ft) Each lift takes 44 months to complete
MSW	**Secondary Settlement Eqtn:** $S_s = [(C_\alpha) \bullet (H_o) \bullet (\log (t_2 / t_1))]$ $e_o = 0.671$ $C_\alpha = 0.0217$ Maximum height of MSW = 59.5 ft. (waste) Cell is divided into 3 lifts H_o = 20 ft (= 1 lift); with exception of final lift (H=19.5 ft) Each lift takes 4 months to complete
Final Cover	**Secondary Settlement Eqtn:** $S_s = [(C_\alpha) / (1+e_o)] \bullet (H_o) \bullet (\log (t_2 / t_1))]$ $e_o = 0.32$ $C_\alpha = 0.004$ Final Cover is 4-feet thick ($H_{fc} = 4$) Assume 6 months to complete construction of final cover
Other Information	Life of Clinton Landfill No. 3 is 45 years Life of cell (chemical waste + MSW) is 23 years + 6 months for final cover placement (23.5 yrs.) Post Closure monitoring period = 100 years t_1 = time of pseudo-primary settlement to occur after completion of fill (years) t_2 = time after completion of fill (years) = (t_1 + 100)

	Lift No.	Lift Thickness (ft.)	Time in Months to Complete Filling of Each Lift	(A) Cumulative Time in Months to Complete Filling of Lifts	(B) Cumulative Time in Years to Complete Filling of Lifts	(C) t_1 (yrs)	(D) t_2 (yrs)	t_2 / t_1	S_s (ft)
Chemical Waste	1	20	44	44	3.67	3.67	119.83	33	0.298
	2	20	44	88	7.33	3.67	116.17	32	0.295
	3	20	44	132	11.00	3.67	112.50	31	0.292
	4	20	44	176	14.67	3.67	108.83	30	0.290
	5	20	44	220	18.33	3.67	105.17	29	0.287
	6	8.2	44	264	22.00	3.67	101.50	28	0.116
MSW	7	20	4	268	22.33	0.33	101.17	304	1.077
	8	20	4	272	22.67	0.33	100.83	303	1.077
	9	19.5	4	276	23.00	0.33	100.50	302	1.077
final cover	Cover	4	6	282	23.50	0.50	100.00	200	0.028
								Σ Settlement =	**4.84**

Notes:

(A) = # months + time for filling previous lifts

(B) = Col.(A) / 12

(C) = (# mos.per lift) x (1 yr./12mos.)

(D) = 100 + 23.5 - Col.(B)

Secondary settlement equation for waste taken from reference below.

Values for "e_o" and "$C\alpha$ " determined from laboratory test data and published literature (see Appendix H.1)

Reference:

Yee, K., Menard Geosystems, Lumpur, K., *Upgrading of Existing Landfills by Dynamic Consolidation - A Geotechnical Aspect*, Technical Paper in Master Builders Journal, Sept.1999.

Clinton Landfill No. 3 Chemical Waste Unit
Secondary Settlement of Waste at Point B
September 27, 2007

Shaw® Shaw Environmental, Inc.

Given:	
Chemical Waste	**Secondary Settlement Eqtn:** $S_s = [(C_\alpha) / (1+e_o)] \bullet (H_o) \bullet (\log (t_2 / t_1))]$ e_o = 4.747 C_α = 0.0565 Maximum height of chemical waste = 109 ft. Cell is divided into 6 lifts H_o = 20 ft (= 1 lift); with exception of final lift (H=9 ft) Each lift takes 44 months to complete
MSW	**Secondary Settlement Eqtn:** $S_s = [(C_\alpha) \bullet (H_o) \bullet (\log (t_2 / t_1))]$ e_o = 0.671 C_α = 0.0217 Maximum height of MSW = 10.5 ft. (waste) Cell has one lift of MSW H_o = 10.5 ft (= 1 lift) Lift takes 4 months to complete
Final Cover	**Secondary Settlement Eqtn:** $S_s = [(C_\alpha) / (1+e_o)] \bullet (H_o) \bullet (\log (t_2 / t_1))]$ e_o = 0.32 C_α = 0.004 Final Cover is 4-feet thick (H_{fc} = 4) Assume 6 months to complete construction of final cover
Other Information	Life of Clinton Landfill No. 3 is 45 years Life of cell (chemical waste + MSW) is 22.33 years + 6 months for final cover placement (total time = 22.83 yrs.) Post Closure monitoring period = 100 years t_1 = time of pseudo-primary settlement to occur after completion of fill (years) t_2 = time after completion of fill (years) = (t_1 + 100)

	Lift No.	Lift Thickness (ft.)	Time in Months to Complete Filling of Each Lift	(A) Cumulative Time in Months to Complete Filling of Lifts	(B) Cumulative Time in Years to Complete Filling of Lifts	(C) t_1 (yrs)	(D) t_2 (yrs)	t_2 / t_1	S_s (ft)
Chemical Waste	1	20	44	44	3.67	3.67	119.17	33	0.297
	2	20	44	88	7.33	3.67	115.50	32	0.295
	3	20	44	132	11.00	3.67	111.83	31	0.292
	4	20	44	176	14.67	3.67	108.17	30	0.289
	5	20	44	220	18.33	3.67	104.50	29	0.286
	6	9	44	264	22.00	3.67	100.83	28	0.127
MSW	7	10.5	4	268	22.33	0.33	100.50	302	0.565
final cover	Cover	4	6	274	22.83	0.50	100.00	200	0.028
								Σ Settlement =	**2.18**

Notes:

(A) = # months + time for filling previous lifts

(B) = Col.(A) / 12

(C) = (# mos.per lift) x (1 yr./12mos.)

(D) = 100 + 23.5 - Col.(B)

Secondary settlement equation for waste taken from reference below.

Values for "e_o" and "$C\alpha$ " determined from laboratory test data and published literature (see Appendix H.1)

Reference:

Yee, K., Menard Geosystems, Lumpur, K., *Upgrading of Existing Landfills by Dynamic Consolidation - A Geotechnical Aspect*, Technical Paper in Master Builders Journal, Sept.1999.

Clinton Landfill No. 3 Chemical Waste Unit
Time of Primary Settlement for <u>Final Lift of Waste (MSW)</u> at Point A
September 27, 2007

Find:
The total time ("t") for primary settlement of one waste lift (20-ft) to occur.

Given:
- Assume worst case scenario: Lift No. 9 will require the longest time for primary settlement to occur, therefore evaluate time "t" for Lift No.9.
- Terzaghi's theory of one-dimensional consolidation, related equations, and relationship between degree of consolidation ("U") and time ("T_v").
- Degree of consolidation "U" = 100%.

$T_v = [(c_v \bullet t) / H_{dr}^2]$

where,
T_v = time factor
c_v = coefficient of consolidation
t = for primary settlement to occur
H_{dr}^2 = length of drainage path (single drainage = 19.5 ft., double drainage = 9.75 ft.)

$U = [\,(1 - 10^{-((0.085+T_v)/0.933)}) \times 100\%]$

Solving for T_v with U = 100% ⟶ $T_v = 3.7$

$c_v = [((2.30) \bullet \sigma'_z \bullet k) / \gamma_w) \bullet ((1+e_o) / C_c)]$

where,
σ'_z = vertical effective stress = 999 psf
k= hydraulic conductivity of waste = 3.28×10^{-5} ft/sec
γ_w = density of water = 62.4 pcf
e_o = void ratio of waste = 0.671
C_c = compression index = 0.351

Solving for c_v ⟶ $c_v = 0.00575$

With T_v and c_v solved for, we can now solve for time "t":
for single drainage ⟶ $t = [((3.7) \times (19.5)^2 / (0.00575)) \times (1 / (24 \times 3600))] = 2.83$ days
for double drainage ⟶ $t = [((3.7) \times (9.75)^2 / (0.00575)) \times (1 / 3600)] = 17$ hours

<u>Reference</u>:
Coduto, D.P., *Geotechnical Engineering Principles and Practices,* 1998, pp.424-442.

Clinton Landfill No. 3 Chemical Waste Unit
Time of Primary Settlement for <u>Final Lift of Chemical Waste</u> at Point A
September 27, 2007

Find:
The total time ("t") for primary settlement of final chemical waste lift (8.2-ft) to occur.

Given:
- Evaluate time "t" for Lift No.6.
- Terzaghi's theory of one-dimensional consolidation, related equations, and relationship between degree of consolidation ("U") and time ("T_v").
- Degree of consolidation "U" = 100%.

$T_v = [(c_v \bullet t) / H_{dr}^2]$

where,
T_v = time factor
c_v = coefficient of consolidation
t = for primary settlement to occur
H_{dr}^2 = length of drainage path (single drainage = 8.2 ft., double drainage = 4.1 ft.)

$U = [\,(1 - 10^{-((0.085+T_v)/0.933)}) \times 100\%]$

Solving for T_v with U = 100% $\longrightarrow$ $T_v = 3.7$

$c_v = [((2.30) \bullet \sigma'_z \bullet k) / \gamma_w) \bullet ((1+e_o) / C_c)]$

where,
σ'_z = vertical effective stress = 1,119 psf
k= hydraulic conductivity of chemical waste = 2.4×10^{-4} ft/sec
γ_w = density of water = 62.4 pcf
e_o = void ratio of chemical waste = 4.747
C_c = compression index = 1.13

Solving for c_v $\longrightarrow$ $c_v = 0.0569$

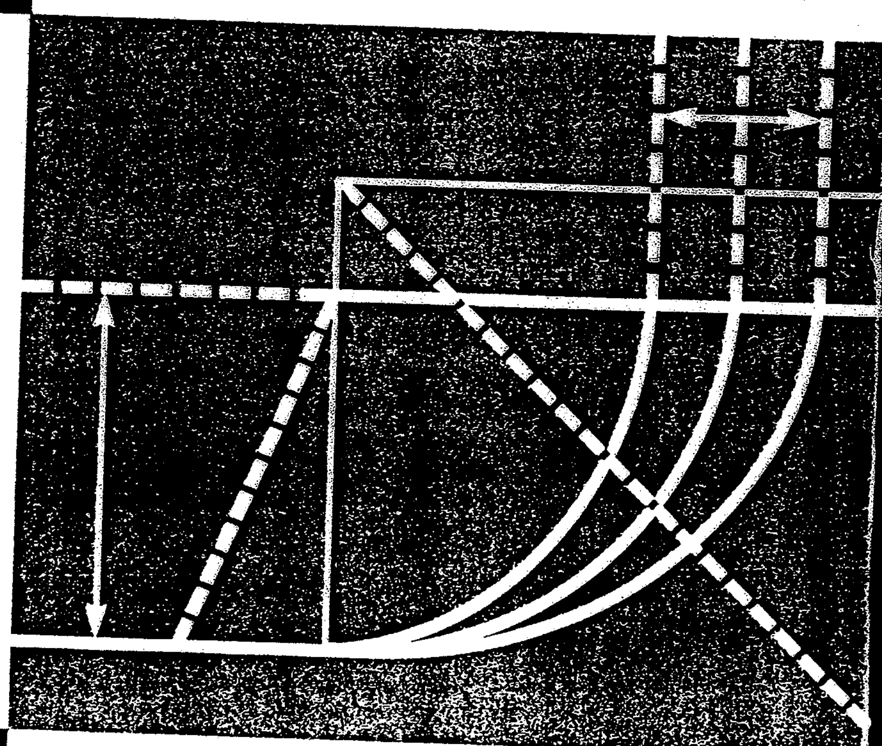
With T_v and c_v solved for, we can now solve for time "t":
for single drainage $\longrightarrow$ $t = [((3.7) \times (8.2)^2 / (0.0569))]$ = 1.2 hours
for double drainage $\longrightarrow$ $t = [((3.7) \times (4.1)^2 / (0.0569))]$ = 18 minutes

Reference:
Coduto, D.P., *Geotechnical Engineering Principles and Practices,* 1998, pp.424-442.

BRAJA M. DAS

Principles of Geotechnical Engineering

Third Edition



where V_{v0} and V_{v1} are the initial and final void volumes, respectively. From the definition of void ratio,

$$\Delta V_v = \Delta e V_s \tag{8.16}$$

where Δe = change of void ratio. But

$$V_s = \frac{V_0}{1 + e_O} = \frac{AH}{1 + e_O} \tag{8.17}$$

where e_O = initial void ratio at volume V_0. Thus, from Eqs. (8.14), (8.15), (8.16), and (8.17),

$$\Delta V = SA = \Delta e V_s = \frac{AH}{1 + e_O} \Delta e$$

or

$$S = H \frac{\Delta e}{1 + e_O} \tag{8.18}$$

For normally consolidated clays that exhibit a linear e-log p (Figure 8.12) relationship,

$$\Delta e = C_c[\log(p_O + \Delta p) - \log p_O] \tag{8.19}$$

where C_c = slope of the e-log p plot and is defined as the compression index. Substitution of Eq. (8.19) in Eq. (8.18) gives

$$\boxed{S = \frac{C_c H}{1 + e_O} \log\left(\frac{p_O + \Delta p}{p_O}\right)} \tag{8.20}$$

For a thicker clay layer, it is more accurate if the layer is divided into a number of sublayers and calculations for settlement are made separately for each sublayer. Thus, the total settlement for the entire layer can be given as

$$S = \sum \left[\frac{C_c H_i}{1 + e_O} \log\left(\frac{p_{O(i)} + \Delta p_{(i)}}{p_{O(i)}}\right)\right]$$

where H_i = thickness of sublayer i
$p_{O(i)}$ = initial average effective overburden pressure for sublayer i
$\Delta p_{(i)}$ = increase of vertical pressure for sublayer i

In overconsolidated clays (Figure 8.13), for $p_O + \Delta p \leq p_c$ field e-log p variation will be along the line cb, the slope of which will be approximately equal to that for the laboratory rebound curve. The slope of the rebound curve, C_s, is referred to as the *swell index*, so

$$\Delta e = C_s[\log(p_O + \Delta p) - \log p_O] \tag{8.21}$$

From Eqs. (8.18) and (8.21),

$$S = \frac{C_s H}{1 + e_O} \log \left(\frac{p_O + \Delta p}{p_O} \right) \quad (8.22)$$

If $p_O + \Delta p > p_c$, then

$$S = \frac{C_s H}{1 + e_O} \log \frac{p_c}{p_O} + \frac{C_c H}{1 + e_O} \log \left(\frac{p_O + \Delta p}{p_c} \right) \quad (8.23)$$

However, if the e-log p curve is given, it is possible simply to pick Δe off the plot for the appropriate range of pressures. This figure may be substituted into Eq. (8.18) for the calculation of settlement, S.

8.8 COMPRESSION INDEX (C_c)

The compression index for the calculation of field settlement caused by consolidation can be determined by graphic construction (as shown in Figure 8.12) after obtaining laboratory test results for void ratio and pressure.

Terzaghi and Peck (1967) suggested the following empirical expressions for compression index:

For undisturbed clays:

$$C_c = 0.009(LL - 10) \quad (8.24)$$

For remolded clays:

$$C_c = 0.007(LL - 10) \quad (8.25)$$

where LL = liquid limit, in percent.

In the absence of laboratory consolidation data, Eq. (8.24) is often used for an approximate calculation of primary consolidation in the field.

Several other correlations for the compression index are also available now. They have been developed by tests on various clays. Some of these correlations are given in Section E.2 (Appendix E).

The secondary compression index can be defined from Figure 8.22 as

$$C_\alpha = \frac{\Delta e}{\log t_2 - \log t_1} = \frac{\Delta e}{\log (t_2/t_1)} \tag{8.30}$$

where C_α = secondary compression index
Δe = change of void ratio
t_1, t_2 = time

The magnitude of the secondary consolidation can be calculated as

$$S_s = C'_\alpha H \log\left(\frac{t_{s2}}{t_{s1}}\right) \tag{8.31}$$

where

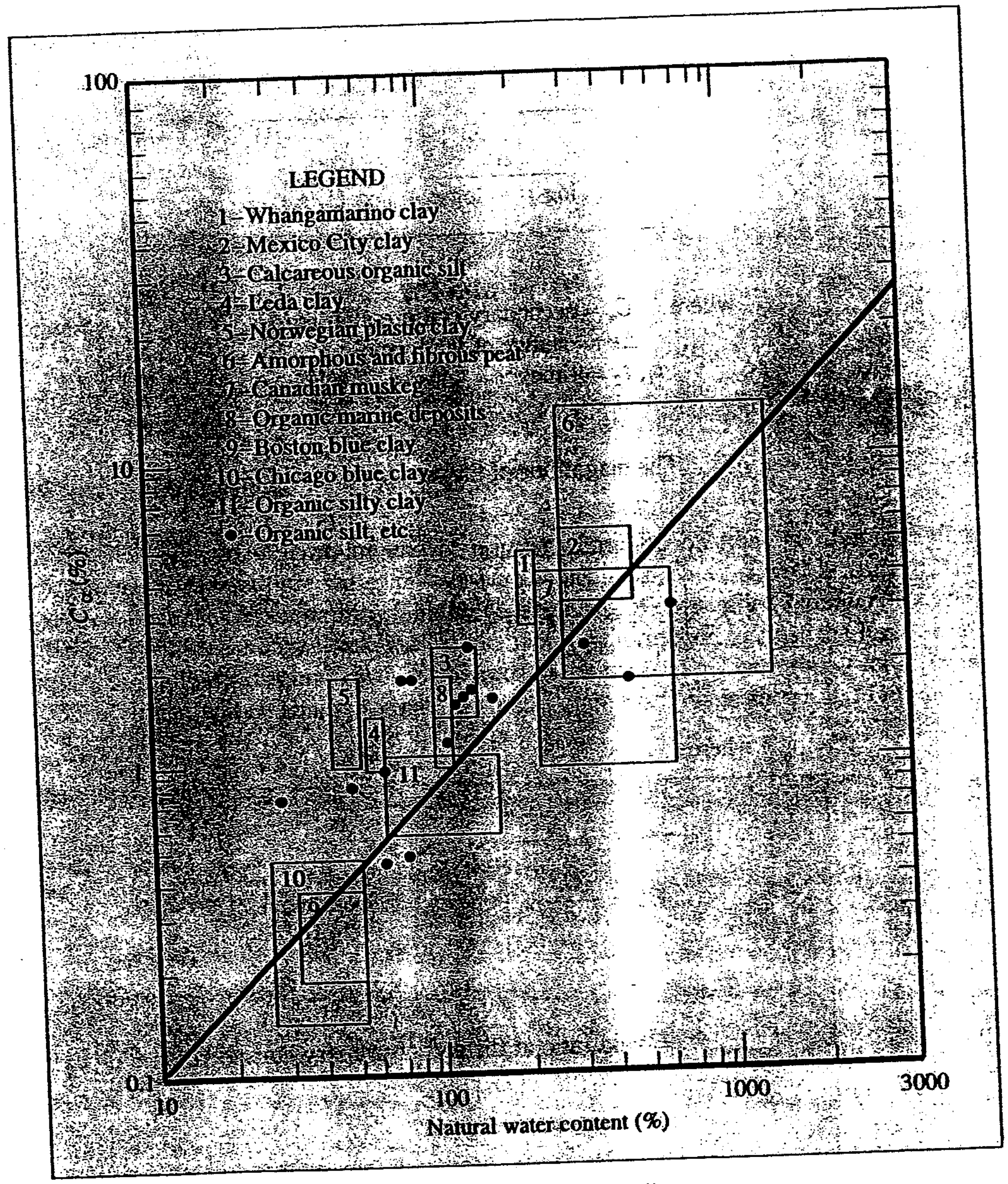
$$C'_\alpha = \frac{C_\alpha}{1 + e_p} \tag{8.32}$$

e_p = void ratio at the end of primary consolidation (Figure 8.22)
H = thickness of clay layer

The general magnitudes of C'_α as observed in various natural deposits are given in Figure 8.23.

Secondary consolidation settlement is more important than primary consolidation in organic and highly compressible inorganic soils. In overconsolidated inorganic clays, the secondary compression index is very small and of less practical significance.

There are several factors that might affect the magnitude of secondary consolidation, some of which are not very clearly understood (Mesri, 1973). The ratio of secondary to primary compression for a given thickness of soil layer is dependent on the ratio of the stress increment (Δp) to the initial effective stress (p). For small $\Delta p/p$ ratios, the secondary-to-primary compression ratio is larger.



▼ **FIGURE 8.23** C'_α for natural soil deposits (after Mesri, 1973)

▼ EXAMPLE 8.6

Refer to Example 8.4. Assume that the primary consolidation will be complete in 3.5 years. Estimate the secondary consolidation that would occur from 3.5 years to 10 years after the load application. Given $C_\alpha = 0.022$, what is the total consolidation settlement after 10 years?

So, for a given overburde: _ ——, p, the void ratio in the field can be estimated if the liquid limit and the specific gravity of the soil solid are known.

E.2 CORRELATION FOR COMPRESSION INDEX

Several correlations for the compression index are available now. They have been developed by testing various clays. Some of these correlations are given in Table E.1. It is important to realize that they are for estimation purposes only.

TABLE E.1 Correlations for Compression Index, C_c*

Equation	Reference	Region of applicability
$C_c = 0.007(LL - 7)$	Skempton (1944)	Remolded clays
$C_c = 0.01w_N$		Chicago clays
$C_c = 1.15(e_O - 0.27)$	Nishida (1956)	All clays
$C_c = 0.30(e_O - 0.27)$	Hough (1957)	Inorganic cohesive soil: silt, silty clay, clay
$C_c = 0.0115w_N$		Organic soils, peats, organic silt, and clay
$C_c = 0.0046(LL - 9)$		Brazilian clays
$C_c = 0.75(e_O - 0.5)$		Soils with low plasticity
$C_c = 0.208e_O + 0.0083$		Chicago clays
$C_c = 0.156e_O + 0.0107$		All clays

* After Rendon-Herrero (1980)
Note: e_O = *in situ* void ratio; w_N = *in situ* water content

REFERENCES

Hough, B. K. (1957). *Basic Soils Engineering*. New York: Ronald Press.

Nagaraj, T., and Murty, B. R. S. (1985). "Prediction of the Preconsolidation Pressure and Recompression Index of Soils," *Geotechnical Testing Journal*, Vol. 8, No. 4, 199–202.

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GEOTECHNICAL ENGINEERING

Principles and Practices

DONALD P. CODUTO

TABLE 11.3 TYPICAL CONSOLIDATION PROPERTIES OF SATURATED NORMALLY CONSOLIDATED SANDY SOILS AT VARIOUS RELATIVE DENSITIES (Adapted from Burmister, 1962)

Soil Type	$C_c/(1+e_0)$		
	D_r = 20%	D_r = 60%	D_r = 100%
Medium to coarse sand, some fine gravel (SW)	-	-	-
Medium to coarse sand (SW/SP)	0.008	0.005	0.002
Fine to coarse sand (SW)	0.009	0.005	0.002
Fine to medium sand (SW/SP)	0.010	0.006	0.003
Fine sand (SP)	0.013	0.008	0.003
Fine sand with trace fine to coarse silt (SP-SM)	-	-	-
Find sand with little fine to coarse silt (SM)	0.014	0.009	0.003
Fine sand with some fine to coarse silt (SM)	-	-	-

For saturated overconsolidated sands, $C_r/(1+e_0)$ is typically about one-third of the values listed in Table 11.3, which makes such soils nearly incompressible. Compacted 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 11.3.

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. Thus, if the load is due to a fill, the consolidation of these soils may have little practical significance.

However, there are at least two cases where consolidation of coarse-grained soils can be very important and needs more careful consideration:

1. Loose sandy soils subjected to dynamic loads, such as those from an earthquake. They can experience very large and irregular settlements that can cause serious damage. Kramer (1996) discusses methods of evaluating this problem.

secondary compression and occurs under a constant effective stress. We don't fully understand the physical basis for secondary compression, but it appears to be due to particle rearrangement, creep, and the decomposition of organics. Highly plastic clays, organic soils, and sanitary landfills are most likely to have significant secondary compression. However, secondary compression is negligible in sands and gravels.

The *secondary compression index*, C_α, defines the rate of secondary compression. It can be defined either in terms of either void ratio or strain:

$$C_\alpha = -\frac{de}{d\log t} \tag{11.26}$$

$$\frac{C_\alpha}{1+e_p} = \frac{d\epsilon_z}{d\log t} \tag{11.27}$$

where:
C_α = secondary compression index
e = void ratio
e_p = void ratio at end of consolidation settlement (can use $e_p = e_0$ without introducing much error)
ϵ_z = vertical strain
t = time

Design values are normally determined while conducting a laboratory consolidation test. The consolidation settlement occurs very rapidly in the lab (because of the short drainage distance), so it is not difficult to maintain one or more of the load increments beyond the completion of consolidation settlement. The change in void ratio after this point can be plotted against log time to determine C_α.

Another way of developing design values of C_α is to rely on empirical data that relates it to the compression index, C_c. This data is summarized in Table 11.4.

TABLE 11.4 EMPIRICAL CORRELATION BETWEEN C_α AND C_c (Terzaghi, Peck, and Mesri, 1996)

Material	C_α/C_c
Granular soils, including rockfill	0.02 ± 0.01
Shale and mudstone	0.03 ± 0.01
Inorganic clays and silts	0.04 ± 0.01
Organic clays and silts	0.05 ± 0.01
Peat and muskeg	0.06 ± 0.01

UPGRADING OF EXISTING LANDFILLS BY DYNAMIC CONSOLIDATION A GEOTECHNICAL ASPECT

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ABSTRACT: In recent years, the scarcity of land space available for new urban development has prompted a renewed interest from local authorities in the end use of various landfills or in the extension of the life of existing landfills. Rehabilitation of closed landfills for urban developments has received considerable interest. Likewise, the extension of landfill life to allow for more waste storage is also receiving equal attention. In both cases, ground improvement is required.

Dynamic consolidation (also known as dynamic compaction) is a ground improvement technique. The process involves dropping heavy weights (15ton - 20tons) on to the surface of the fill from a considerable height (15m - 20m) following a selected grid pattern. These high-energy impacts produce sufficient compaction effort to reduce void space, increase density and reduce long-term settlement of the fill. By increasing the density, it increases the storage capacity of the landfill. Beside, it also increases the bearing capacity. Reducing the long-term settlement, roads, parking bays and lighter structures can be designed on shallow foundations on closed landfills.

In this paper, the subject of settlement of waste fills is addressed. A case study concerning a housing development over a landfill is also presented.

1.0 INTRODUCTION

Landfilling is one of the most economic and feasible means of disposing municipal solid waste in Malaysia and other countries in Southeast Asia. In the past, the disposal of waste fills was carried out by uncontrolled dumping into ex-mining ponds and low-lying areas close to housing estates. With increasing scarcity of land in urban areas, it is increasingly difficult to find new landfill sites for future dumping. This has prompted the local authorities and privatized companies (operators of landfill) to find solution to extend the life of the landfill to allow for more waste storage.

Typical landfills may occupy an area ranging from several acres to hundreds of acres. Settlement estimation is a topic of concern. om the operator's viewpoint, landfill capacity will be increased if most settlement occurs during the stage of filling. Jnfortunately, the landfill settlement continues over an extended period of time with a final settlement that can be as large as 30%-40% of the initial fill height (H.I.Ling, et.al. 1998). Hence, it is imperative that a solution is needed to increase the rate of settlement to recover the additional space.

Dynamic consolidation is a good method of compacting refuse and waste fill. This technique involves dropping heavy weights (15 – 20 tons) on to the surface of the fill from a height of 10 to 20m following a selected grid pattern. The high-energy impacts produce shock waves that propagate to great depths (figure 1). As a result, the density of the waste fill is increased and hence, the storage capacity of the landfill is also increased.

With the increase in the density of the waste fill, the overall bearing capacity is improved. The long-term settlement is reduced and hence, the differential settlement is also reduced which is important for the integrity of the cover system when the landfill is closed. In the past such landfills have been considered suitable only for green areas. With the increasing scarcity of land in urban areas, it is making it necessary to build structures above such fills. Charles et.al. (1981) report several case histories of construction on old refuse tips, which include construction of a 2-storey hospital, roads and highways. Welsh (1983) cites a roadway site with 6m to 12m of waste fills. MÀnard (1984) cites a case for a warehouse designed with floor loads of 20 kN/m^2 and spread footing with 145 kN/m^2 with 6m to 17m of refuse waste. There are many other recorded and published case studies on such developments (e.g. Aziz & Mohd. Raihan (992), Downie & Treharne (1979), Faisal, K.Yee & Varaksin (1997), Fryman & Baker (1987), Lewis & Langer (1994), Mappleback & Fraser (1993), Steinberg & Lukas (1984), etc.).

In this paper, the subject of settlement of waste fills and rehabilitation of landfill for housing development is presented. Only the geotechnical aspect is covered. The related environmental issue has been intentionally left out due to space constraint.

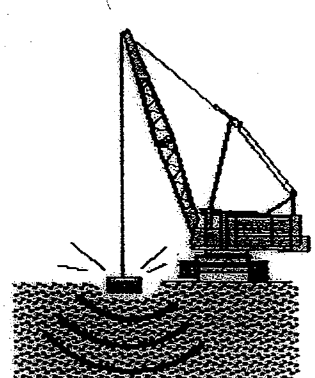


Figure 1

.0 COMPOSITION OF LANDFILL

Most landfills are heterogeneous and they exhibit anisotropic material properties that are difficult to characterize. Typically, a landfill consists of food and garden wastes, paper products, plastics and rubber, textiles, wood, ashes and the soils used as cover material. Table 1 shows the various components of waste fills with their range of unit weights. The unit weight and void ratio vary with the types of waste, composition, depth, method of compaction and the rate of decomposition, among other factors. The rate of decomposition is further complicated by several factors including the effects of time, temperature and environmental conditions. In short, it is a combination of all of the problems of soft clay, uncompacted fill, organic consolidation and decomposition and even collapse of cavities and erosion of soil into cavities. It is as heterogeneous as the modern industrial-urban complex that produces it. Hence, its composition varies from community to community and from nation to nation. Thus, the waste properties can be considered as site-specific.

Two different forms of landfill can be defined. The uncontrolled dump is of random composition, dumped loosely from trucks, accumulated without control or compaction, and sometimes covered with a thin layer of soil when it reached its capacity (see figure 2a). At the other end, it is the well-managed sanitary landfill. The materials are spread in layers and compacted by bulldozers and compactors. In some cases, certain wastes such as tires are segregated from others (see figure 2b). Most of the old landfills are the uncontrolled dumps. Until recently, through privatization scheme the landfill operation follows the engineered landfill scheme. Thus, it is expected that developments over old landfills will require more engineering effort.

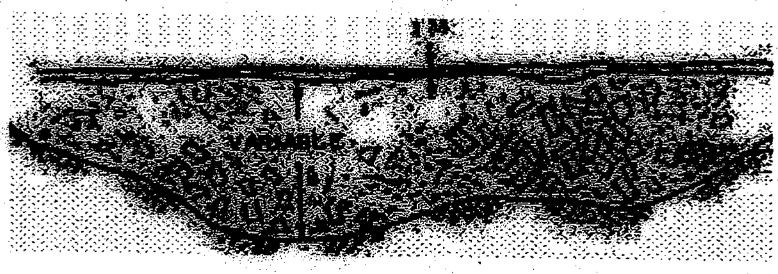


Figure 2(a)
Uncontrolled Landfill (No controlled placement and no compaction)

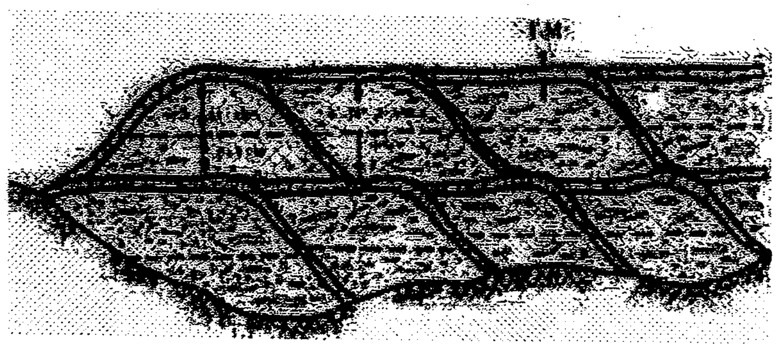


Figure 2(b)
Controlled Sanitary Landfill (Spread and compacted in layers of 2-3m thick; encapsulated with soil in cells of 2-6m thick)

3.0 SETTLEMENT CHARACTERISTICS

Settlement is the major problem with landfills. Sowers (1972) cites a case of a small shopping center built over a landfill. The buildings are on piles driven through the waste fills. The building walls and roof have remained intact. However, floor slabs supported directly on the fill surface have settled as much as 75mm. The floor slabs were connected to the pile-supported exterior grade beams, but was not connected to the interior columns. As a result, the floor drapes downward from the exterior walls toward the interior of the building. Small interior partitions resting directly on the floor have cracked badly and doorframes have been wrecked out of shape.

ble 1 (source: After Tchobanoglous et. al. 1977)

Waste Component	Uncompacted Unit Weight (kN/m^3)	Water Content	Ratio of Compacted to Uncompacted Unit Weight	
			Normal Compaction	Well Compacted
Food waste	1.3 – 4.7	50 – 80	2.9	3.0
Paper / paper board	0.3 – 1.3	4 – 10	4.5	6.2
Plastics	0.3 – 1.3	1 – 4	6.7	10
Textiles	0.3 – 0.9	6 – 15	5.6	6.7
Rubber and leather	0.9 – 2.5	1 – 12	3.3	3.3

Yard waste	0.6 – 2.2	30 – 80	4	5
Wood	1.3 – 3.1	15 – 40	3.3	3.3
Glass	1.6 – 4.7	1 – 4	1.7	2.5
Metals	0.5 – 11.0	2 – 6	4.3	5.3
Ash, brick, dirt	3.1 – 9.4	6 - 12	1.2	1.3

Furthermore, settlement has increased since then, probably due to a change in the moisture environment from leaking sewers in the fill.

There are two possible approaches to the assessment of settlement:

(a) Extrapolation of monitored data obtained specifically for the given fill
   1) By graphical method
   2) By analytical method

(b) Estimation from existing published data on similar type of fills
   1) By graphical method
   2) By analytical method

Method (a) is the most reliable but requires time for monitoring. This method relies on the approximately linear relationship between settlement and logarithm of time elapsed since placement of waste fill. Method (b) relies on published data for other fills of similar type, and gives approximate answers quickly. However, the results are less dependable since the published data are rarely likely to apply exactly to a specific given fill. Preliminary estimates obtained by method (b) should be checked by monitoring. We shall address the different categories of settlement as follow:

3.1 Settlement Under Self-Weight

One of the contributing factors to the overall settlement is caused by the self-weight of the fill. The time-settlement relationship under self-weight is analogous to the secondary compression of soils after a short period of pseudo-primary settlement, typically, 1 to 4 months long. Measurements taken from past records indicate a coefficient of secondary compression ranging from 0.1 to 0.4 (NAVFAC, 1983). Thus, settlement of the waste fills under its self-weight after completion of filling can be estimated by equation (1) below.

$$(\Delta H)_{sw} = H\, C_\alpha \log(t_2 / t_1) \quad \text{.......... (1)}$$

where

$(\Delta H)_{sw}$ = self-weight settlement at time t_2 (m)

H = thickness of waste fill (m)

t_1 = time pseudo-primary settlement to occur after completion of fill (years)

t_2 = time after completion of fill (years)

C_α = coefficient of secondary compression

Table 2 below suggests typical self-weight settlements. According to Leach & Goodger (1991), a good compaction can reduce the self-weight settlement potential by between 50% and 75%.

Typical unit weights for municipal waste are summarized in Table 3.

Table 4 below shows the unit weights obtained from various landfills sites.

3.2 Settlement Under External Loads

The time-settlement behavior of an old waste fills under an applied load is analogous to the behavior of peat. As load is placed large primary (mechanical) settlements occur rapidly with little or no pore pressure build up. This is followed by secondary compression, which occurs over a long period of time.

The relation of the imposed stress to settlement can be expressed as follow:

$$(\Delta H)_p = H\, C_r \log(\{\sigma'_o + \Delta\sigma'\}/\sigma'_o) \quad \text{....... (2)}$$

where

$(\Delta H)_p$ = primary (or mechanical) settlement (m)

H = thickness of waste fill (m)

e_o = initial void ratio

Table 2 (Source: Leach & Goodger (1991) – CIRIA Special Publication 78)

Material	Potential Self-Weight Settlement (expressed as % of depth of fill)
Well compacted, well graded sand and gravel	0.5

Well-compacted, well-graded sand and gravel	0.5
Well-compacted shale and rockfill	0.5
Medium-compacted rockfill	1
Well-compacted clay	0.5
Lightly compacted clay	1.5
Lightly compacted clay placed in deep layers	1 – 2
Nominally compacted opencast backfill	1.2
Uncompacted sand	3.5
Uncompacted (pumped) clay	12
Well-compacted mixed refuse (waste fill)	30
Well-controlled domestic refuse (waste fill) placed in layers and well compacted	10

Table 3

Description	Average Total Unit Weight γ_w (kN/m^3)	Source
Sanitary Landfill		
• Poor compaction	2.8 – 4.7	Tchobanoglous et.al. (1977)
• Moderate to good compaction	4.7 – 7.1	
• Good to excellent compaction	7.1 – 9.4	
• Baled waste	5.5 – 10.5	
• Shredded and compacted	6.4 – 10.5	
• In situ density	5.5 – 6.9	
Active landfill with leachate mound	6.6	
Household Trash Can	1.1	NAVFAC (1983)
Delivery Truck	2.4	
Sanitary Landfill		
(a) Not shredded		
• Poor compaction	3.1	
• Good compaction	6.3	
• Best compaction	9.4	
Shredded	8.6	
Sanitary Landfill		
• In a landfill	6.9 – 7.5	NSWMA (1985)
After degradation and settlement	9.9 – 11.0	

Table 4

Landfill Sites	Waste Density (kN/m^3)
Old Klang Road, Kuala Lumpur	7.0
Kelana Jaya, Kuala Lumpur	6.0
Merrylands, Sydney[1]	9.4
Thornleigh, Sydney[1]	8.4
Lucas Heights, Sydney[1]	11.3
Albany, New York[2]	7 – 16
Fayetteville, Arkansas[3]	4.8
Richmond, California[4]	7.2

Note: 1 – data obtained from Hausmann et.al (1993)
2 – data obtained from Gifford et.al. (1992)
Note: This is a construction and demolition debris landfill
3 – data obtained from Welsh (1983)
4 – data obtained from Sharma et.al. (1989)

σ'_o = effective overburden pressure (kN/m^2)
$\Delta\sigma'$ = effective imposed stress (kN/m^2)
C_r = compression ratio (= $C_c/1+e_0$)
C_c = compression index

NAVFAC (1983) reports that the primary compression ratio (C_r) ranges from 0.1 to 0.4. Sowers (1972) reports that the compression index (C_c) is related to the initial void ratio as shown in figure 3. The relation can be expressed as follow:

For fills low in organic matters $C_c = 0.15e_o$
For fills high in organic matters $C_c = 0.55e_o$

It is interesting to note that the maximum Cc for peat is about one-third greater than the maximum observed for waste fills.

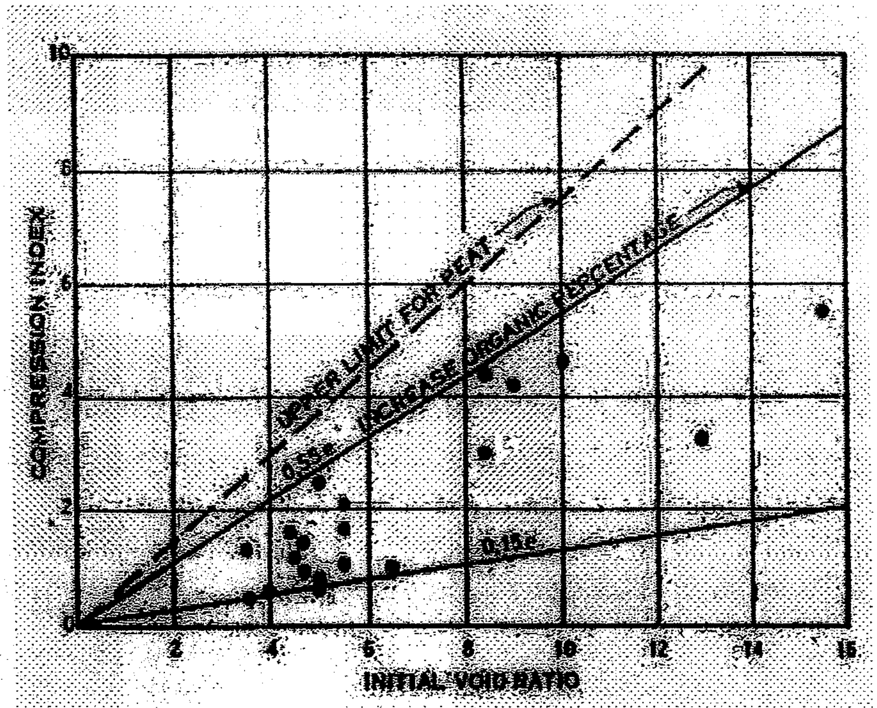


Figure 3

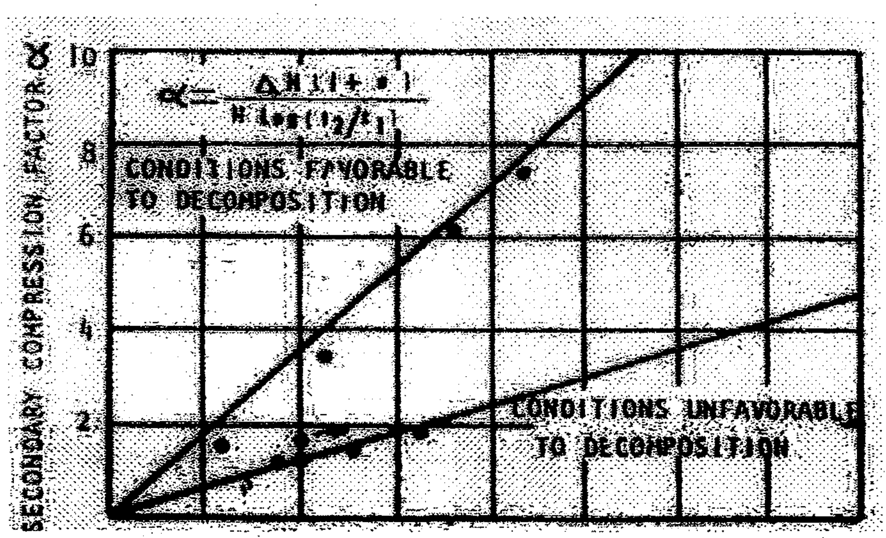
Environmental conditions as well as the composition of the waste fills determine the amount of long-term settlement. This long-term settlement is a combination of mechanical secondary compression, physico-chemical action, and bio-chemical decay. When there is no drastic change in the environment the settlement-log time relationship is more or less linear, similar to secondary compression of soils. The settlement can be expressed by the same equation (1) above. NAVFAC(1983) reported the coefficient of secondary compression (C_α) ranged from 0.02 to 0.07. These values are for fills, which have undergone decomposition for about 10-15 years. Higher compressibility is usually associated with high organic content. It is also true for advanced degree of decomposition.

Sowers (1972) introduces a factor "α" for the long-term settlement. He suggested "α" as a function of the initial void ratio (e_o). This "α" value is high if the organic content subject to decay is large and the environment is favorable (i.e. warm and moist, with fluctuating water table that pumps fresh air into the fill). This value is low for more inert materials and under non-favorable environments. Nonetheless, for any given void ratio there is a large range of values for "α" (see figure 4). The relation can be expressed as follow:

For favorable condition to decay $\alpha = 0.03e_o$

For unfavorable condition to decay $\alpha = 0.09e_o$

This "α" value can be translated to the classical C_α by dividing "α" by $\{1+e_0\}$ i.e. $C_\alpha = \alpha/\{1+e_0\}$.



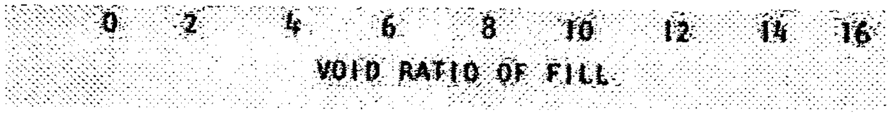


Figure 4

Other calculation methods include the use of a rheological model as presented in the Gibson and Lo theory or the power creep law. The power creep law provides a better representation of the field measured settlement data than the rheological model. However, the rheological model has parameters that can be assigned physical meaning and reflect the effects of certain refuse placement conditions. The details are not presented in this paper.

4.0 DIFFERENTIAL SETTLEMENT & DESIGN MEASURES

There are too many uncertainties for accurate prediction of differential settlement on waste fills. In this case, recourse should be made to the generally accepted rule in engineering practice that, in uniform ground, differential movement will not exceed 75% of the total overall settlements. Thus, once the potential overall settlement has been estimated the likely order of differential movement can be assessed.
Defensive design for buildings demand either the transfer of loading to sound ground through piling or the acceptance of some residual settlement, even after ground improvement, with the load supported directly on the fill. Foundations bearing on fill should be designed to permit settlement without subjecting the superstructure to damaging differential movements or unacceptable tilt.

According to Padfield and Sharrock (1983), most framed buildings can tolerate a differential settlement of about 20mm between columns. This sets the limits for flexible floating supports with individual footings. If this acceptable settlement is likely to be exceeded, a raft foundation for low-rise structures or piling for higher-rise structure shall be considered. The piles are then designed against all adverse features of a refuse waste fills site.

While piling will obviate settlement of the structure, problems may arise from settlement of the fill outside the building area. Service connections and discontinuity of level at the building periphery are particular problems. These problems can be minimized by improving the settlement characteristics of the fill. The treated fill should be sufficiently improved that the loaded areas settle uniformly without imparting significant tilt to the superstructures. Between loaded areas, or between a loaded area and service run, the differential settlement should be reduced to within a tolerable limits and the service lines should be designed according to the likely settlement profiles.

Dynamic consolidation is a good method of compacting refuse and waste fills. Because void ratio or initial density is related to the initial primary settlement as well as secondary compression, compaction (densification) of fills offers an element of control over potential settlement. However, this method will not eliminate biodegradation and, instead, may provoke or accelerate migration and/or emission of gas (Leach and Goodger, 1991).

5.0 DYNAMIC CONSOLIDATION

The basic concepts of dynamic consolidation (also known as dynamic compaction) as it is used today were presented by Menard and Broise (1975). The method consists of dropping heavy weight ("pounder") weighing 15tons to 20tons from a drop heights of 10m to 20m. using a crawler crane of minimum 100-ton. (Figure 5).

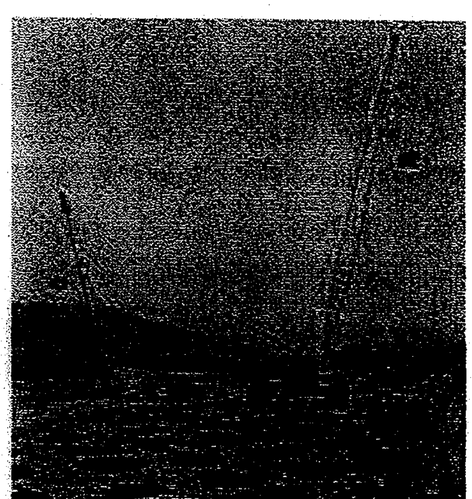


Figure 5

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Sanitary Landfill Settlement Rates

By Bing C. Yen[1] and Brian Scanlon,[2] Members, ASCE

Introduction

An all-embracing definition of a sanitary landfill is difficult to formulate, due to the varying techniques used. The Committee on Sanitary Landfill Practice (6) provided a general description as follows:

> Sanitary landfill is a method of disposing of refuse on land without creating nuisance or hazards to public health or safety, by utilizing the principles of engineering to confine the refuse to the smallest practical area and to reduce it to the smallest practical volume and to cover it with a layer of earth at the conclusion of each day's operation or at such more frequent intervals as may be necessary.

5M c.f.
~ 220'x220'x100'high →

Formal sanitary landfill practice goes back to about 1930 in this country and 1916 in England; informal practice probably goes back to man's beginning. Estimates from the Bureau of Solid Waste Management (BSWM) give a breakdown of solid waste production by source as follows: Municipal (including commercial and institutional)—6.5 lb (2.95 kg) per capita per day; and industrial (excluding mining)—3.9 lb (1.78 kg) per capita per day. Using the BSWM data, a city with a population of 1,000,000 will generate approx 5,000,000 cu yd ($3.8 \times 10^6\ m^3$) of compacted waste per year. The magnitude of this problem has caused great interest in the subject of solid waste disposal and, more recently, in solid waste utilization. The escalation of land values in most parts of the country will increase the demand of converting the sanitary landfill sites to usable land. Well-engineered sanitary landfill sites have become assets to the region in which they are developed and accepted by the citizens (4).

Abundant literature is available for solid waste disposal, including 450 articles

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H_f and t_c is restricted, and the relationship between time elapsed t_1 and s[illegible]ement rate m can be more clearly seen.

Plots of m versus log (t_1) for fills between 40 ft-80 ft deep (12 m-24 m), between 80 ft-100 ft (24 m-31 m), and greater than 100 ft (31 m) are shown in Figs. 2, 3, and 4. The linear relationship between m and t_1 are obtained by least-squares fitting with regression coefficient shown.

These three plots are for only the fill column subgroups with t_c between 70 months and 82 months. Table 1 summarizes results of other subgroups in which the construction period, t_c, ranges from less than 1 yr to nearly 7 yr. The mean values of settlement rate, m, for the fill columns of different depth ranges are shown in Table 1. Values of mean m were computed only in those intervals that contained at least three field survey measurements.

Effect of Median Fill Age on Settlement Rates as Function of Fill Depth.—The decreasing trend of m with respect to t_1 can be seen in each of the figures and in Table 1. However, even after a period of 6 yr from the completion of a fill (70 months-120 months in terms of median fill age), settlement rates on the order of 0.02 ft/months (0.006 m/month) may still be expected.

It is also interesting to note the range of post-construction settlement for the sites investigated. An estimate of the average total post-construction settlement was computed by integrating the m and log (t_1) functions of Figs. 2-4 between the fill completion date and that extrapolated value of t_1 for which $m = 0$. The results showed that post-construction settlement ranges between 4.5%-6%, of total fill depth, i.e., about 4.5 ft-6 ft (1.4 m-1.8 m) of post construction settlement would be expected for a 100 ft (31 m) of fill without subjecting the fill to any external load other than its own weight and biodegradation.

Effect of Depth on Rate of Settlement.—As can be seen from Figs. 2-4 and Table 1, deeper fill depth generally shows a faster rate of settlement regardless of construction period, t_c, and median fill age, t_1. However, the differences are not linearly proportional to the depth of fill, H_f. Results from the three sites studied indicates that although the rate of settlement increases with depth, this effect levels off for depths greater than 90 ft (27 m). The settlement rates for fill depth of more than 100 ft (31 m) are substantially the same after 5 yr as those with H_f between 80 ft-100 ft (24 m-31 m). This is not surprising when considering that refuse at greater depth probably simulates an anaerobic environment and thus has a slower biochemical decay than those of shallower depth. At shallower depth the environment is probably closer to aerobic and will have a greater rate of decay and thus settlement rates. A greater settlement rate for an aerobic process than an anerobic process has been reported by other investigators. For example, Sowers (8) compared the rate of settlement between aerobic and anaerobic environment at comparable void rates and overburden stresses and showed that an aerobic environment generally has the greater settlement.

Effect of Construction Period on Settlement Rate.—The length of the construction period, t_c, also affects settlement rate. In Table 2, the time required for the completion of settlement (i.e., when $m = 0$) were computed using the least-squares fitted m log (t_1) functions (Figs. 2-4).

It can be seen from Table 2 that the faster rate of the construction (smaller t_c values) will result in a much shorter time for the fill to complete its settl[illegible]nt. [illegible]his effect is more pronounced for the shallower fills. Thus, it [illegible] [illegible]e advantageous to construct the sanitary landfill as fast as [illegible]sible in order to accelerate the settlement.

Length of Post-Construction Settlement Period.—The fill column subgroups with $70 \le t_c \le 82$ months had the largest data populations with the widest coverage in terms of t_1. For some of the fill columns in this group the settlement observations extended over a 9-yr period. Figs. 2, 3, and 4 show the scatter diagrams for these subgroups along with the regression coefficient, r. Extrapolation of these functions suggest that, even without additional surface loads being added, the settlement process may last over 250 months before $m = 0$. There is a long time required for completion of settlement from a geotechnical engineering viewpoint. This appears to be one of the major difficulties for using deep landfill sites as load-bearing fills.

TABLE 2.—Comparison of Settlement and Construction Period

Range of fill depth, H_f, in feet (meters) (1)	Average construction period, t_c, in months (2)	Total time required for construction and settlement, in months (3)	Approximate time required for settlement to complete, in months (4)
40-80	12	113	101
(12-24)	72	324	252
80-100	12	245	233
(24-31)	72	310	238

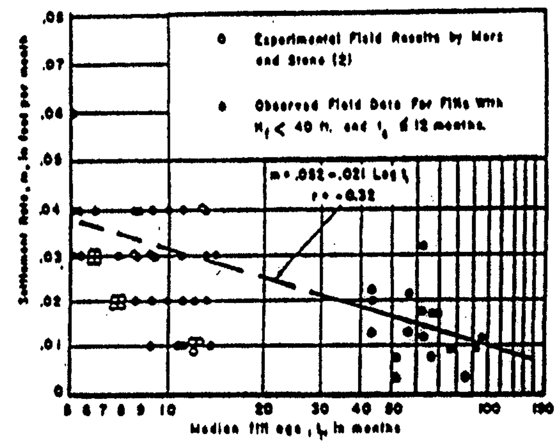

FIG. 5.—Comparison of Field Settlement Rates

COMPARISONS WITH RESULTS OF OTHER INVESTIGATORS

Comparison with Field Model Studies.—Merz and Stone [illegible]nducted field