Document ID: EDF-ER-266
Revision ID: 1
Effective Date: 05/14/02

Engineering Design File

Subsurface Consolidation Calculations

Idaho National Engineering and Environmental Laboratory

Form 412.14
07/24/2001
Rev. 03

ENGINEERING DESIGN FILE

1. Title: Subsurface Consolidation Calculations				
2. Project File No.: NA				
3. Site Area and Building No.: NA		4. SSC Identification/Equipment Tag No.: NA		

5. Summary:

The purpose of this calculation is to determine the maximum consolidation in the landfill foundation soils resulting from the load of the waste material and cover. The maximum amount of consolidation is used to determine the differential settlement and integrity of the landfill liner system.

6. Review (R) and Approval (A) and Acceptance (Ac) Signatures:
(See instructions for definitions of terms and significance of signatures.)

	R/A	Typed Name/Organization	Signature	Date
Performer		Phillip Crouse/ Montgomery Watson	Phillip E. Crouse	05/14/02
Checker	R	(Same as Independent Peer Reviewer)		05/14/02
Independent Peer Reviewer	A	Marty Doornbos/ BBWI	Marty Doornbos	05/14/02
Approver	A	Thomas Borschel/ BBWI	Thomas F. Borschel	05/14/02
Requestor	Ac	Don Vernon/ BBWI	D. Vernon	05/14/02

7. Distribution: (Name and Mail Stop)	M. Doornbos, MS 3930; D. Vernon, MS 3930; T. Borschel, MS 3930
8. Records Management Uniform File Code (UFC):	
Disposition Authority:	Retention Period:
EDF pertains to NRC licensed facility or INEEL SNF program?: ☐ Yes ☐ No	

9. Registered Professional Engineer's Stamp (if required)

ABSTRACT

This calculation determines the amount of settlement that is expected to occur in the subsurface soils beneath the landfill. Soil properties from site investigations are input into a spreadsheet solution using accepted settlement analysis methods. The calculated settlements will be used to determine the deformation in the liner system and resulting strains to determine the integrity of the landfill liner system.

CONTENTS

Figures

ACRONYMS

CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
DOE-ID	Department of Idaho Operations Office
EPA	Environmental Protection Agency
GCL	geosynthetic clay liner
G_s	specific gravity
HDPE	high-density polyethylene
ICDF	INEEL CERCLA Disposal Facility
INEEL	Idaho National Engineering and Environmental Laboratory
LCRS	leachate collection recovery system
LDRS	leak detection recovery system
PLDRS	primary geosynthetic leak detection recovery system
SBL	soil bentonite liner
SLDRS	secondary leak detection recovery system

Subsurface Consolidation Calculation

1. PURPOSE

The purpose of this calculation is to determine the settlement and compression of the foundation soils at the Idaho National Engineering and Environmental Laboratory (INEEL) CERCLA Disposal Facility (ICDF) landfill. The landfill will contain Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)-generated contaminated bulk soil, debris (i.e., rubble, concrete, wood, boxes, drums, personal protective equipment, and metals), and treated waste that are generated at the INEEL and meet the agency-approved Waste Acceptance Criteria for the ICDF Complex. The purpose of the foundation is to support the liner system to prevent failure due to settlement, compression, or uplift during the active life and post-closure care period of the ICDF landfill.

This calculation provides an estimate of the maximum settlement that is used to determine differential settlement in the landfill liner system. The liner system consists of the components listed below from lower to upper most layer:

- Tertiary geomembrane
- Secondary leak detection recovery system (SLDRS)
- Soil bentonite liner (SBL)
- Secondary geomembrane
- Primary geocomposite leak detection recovery system (PLDRS)
- Primary geosynthetic clay liner (GCL)
- Primary geomembrane
- Geotextile cushion
- Leachate collection recovery system (LCRS) piping
- LCRS gravel
- Operations layer.

It is important to note that the tertiary geomembrane and SLDRS are located only along the center of the landfill floor and beneath the sump.

This analysis takes into account the loading due to the waste material in the landfill and the cover. The strain in the SBL and the synthetic liners caused by the maximum differential settlement is calculated and compared to allowable strains to determine the ability of the liners, leak detection recovery system (LDRS), and LCRS to maintain their integrity.

2. METHOD

The soils underlying the landfill consist of dense alluvial deposits overlying basalt bedrock ranging in thickness from 15 to 25 ft. The alluvium consists of gravels, gravel-sand mixtures, and sand-gravel-cobble mixtures to poorly sorted gravels with sand and silt. An intermittent layer of fine sand, silt, and clay (i.e., "old alluvium") between the bedrock and gravels ranges in thickness from 2 to 7 ft, based on the borings located within the landfill footprint. Groundwater is located approximately 440 ft below the bottom of the landfill (EDF-ER-275). The boring locations and cross section are shown in Figures 2-1 and 2-2, respectively.

The existing sand and gravely foundation soils will provide a structurally stable subgrade for the ICDF landfill liner system. Additionally, the foundation layer is relatively thin, dense, and not influenced by a changing groundwater table. As a worst-case estimate, total settlement was determined on the assumption that the SBL is overlying 15 ft of the "old alluvium" soil. This will provide a conservative settlement estimate, because the "old alluvium" will have the largest amount of consolidation. This also takes into account the small amount of immediate settlement in the gravels and secondary consolidation that could occur. Note that these assumptions are to provide a conservative subsurface consolidation amount and may not be valid for other calculations.

The foundation is loaded by the waste, operations layer, and the landfill cover. The stress increase caused by this load is calculated at various depths utilizing published solutions to the Boussinesq Equation. Terzaghi's consolidation theory is then used to determine the settlement in the subgrade soils caused by the increase in effective stress due to the load (Holtz and Kovacs 1981). A general profile showing the stratigraphy of the ICDF landfill and the underlying materials is shown in Figure 2-3.

The loads will be the largest near the middle of the landfill rather than on the sideslopes, resulting in potential differential settlement. Given that the settlement on the sides of the landfill will be very small, the total settlement calculated at the middle of the landfill floor will be the maximum differential settlement. Differential settlement will create strain in the liner system components. This is compared to allowable strains to evaluate the stresses in the liner materials. The impact to the PLDRS and SLDRS piping and drainage was also evaluated. The maximum amount of settlement was also used in determining the final surface slope grades of the final grade. This calculation is provided in the "Landfill Compaction Subsidence Study" (EDF-ER-267).

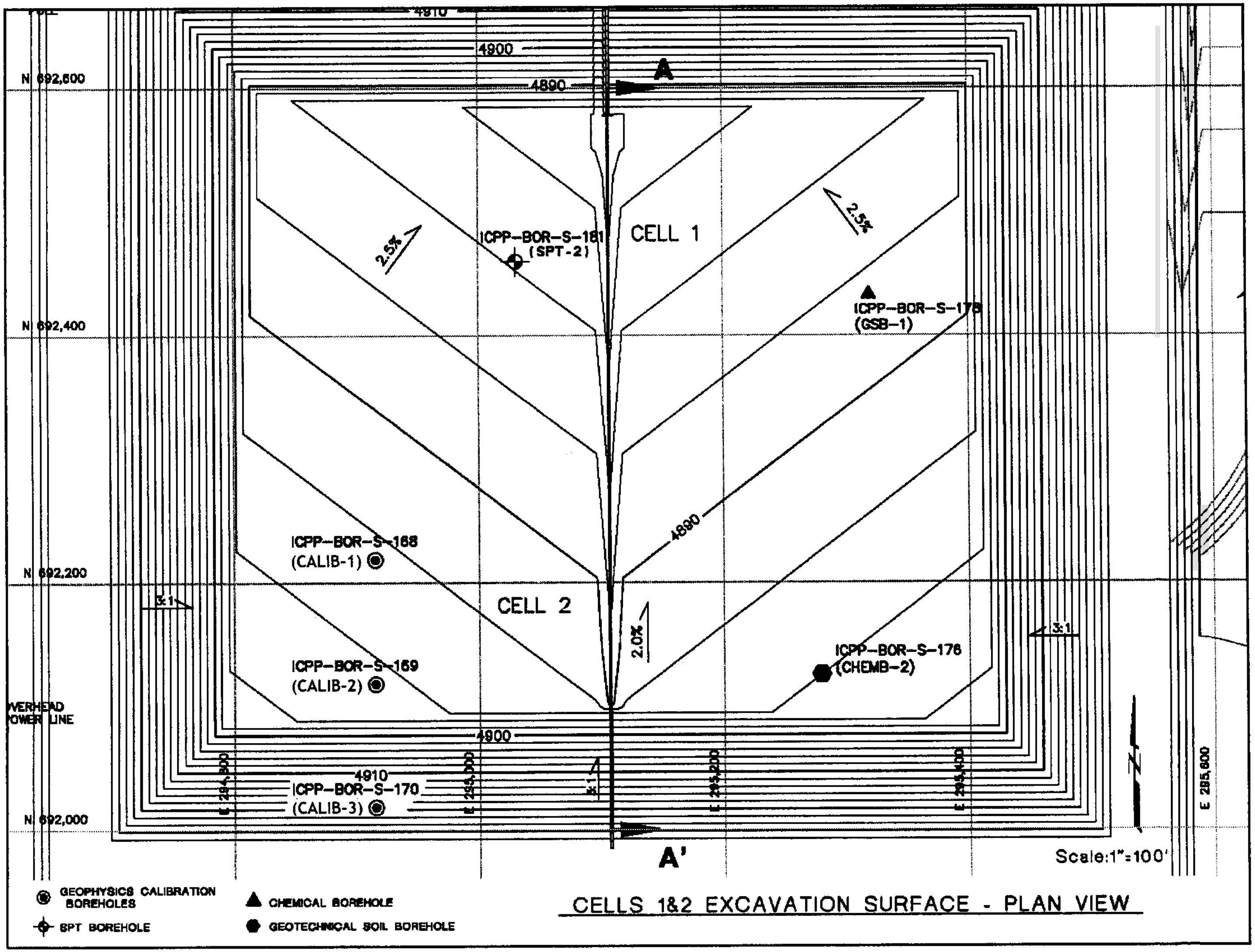


Figure 2-1. Location of borings within the ICDF landfill footprint.

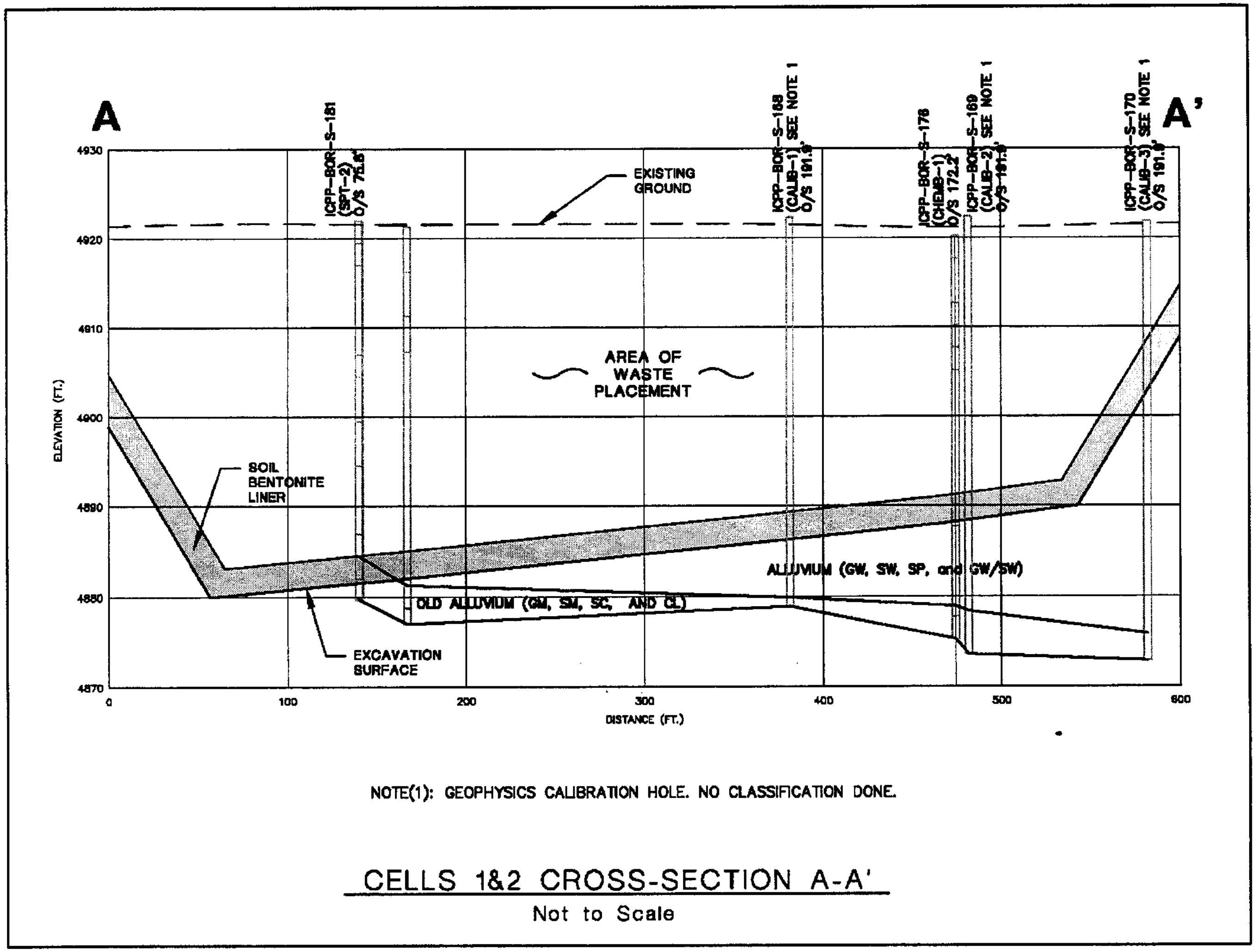


Figure 2-2. Cross Section A-A.

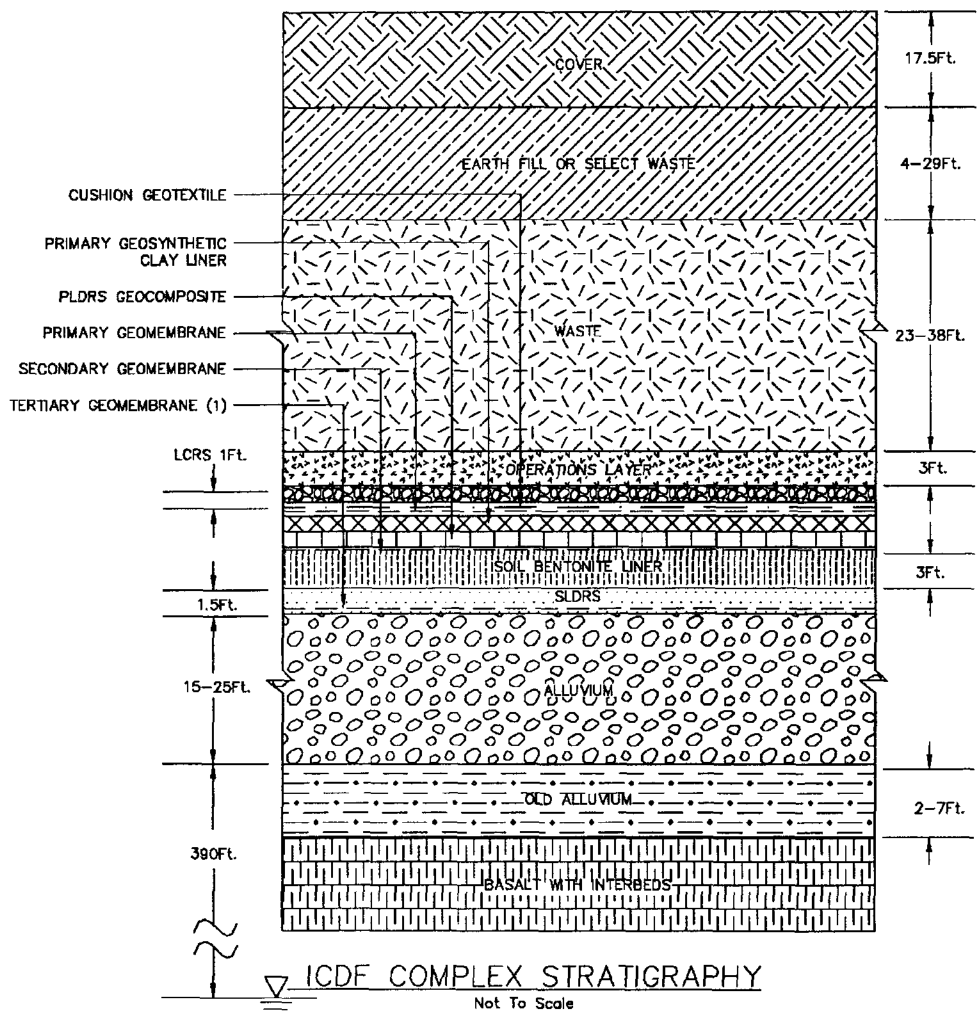


Figure 2-3. General stratigraphy of the ICDF landfill and underlying materials.

3. ASSUMPTIONS

The assumptions listed below were used in determining the subsurface consolidation.

- The foundation soil settlement can be estimated using one-dimensional consolidation theory.
- The immediate settlement is negligible since landfill foundation soils are mainly granular and dense (EPA 1988).
- The secondary compression (creep settlement) is negligible (EPA 1988).
- The stress increases within and below the landfill can be determined with the Boussinesq Equation.
- The Specific Gravity (G_s) for soil is 2.65.
- The maximum amount of settlement occurs at the middle of the landfill having the largest loads.
- The ICDF landfill cover thickness is 17.5 ft and sloped at 7% with 2.5H:1V sideslopes.

The final cover design is provided in the "Liner and Final Long-Term Performance Evaluation and Final Cover Life Cycle Expectation" (EDF-ER-281).

4. SOIL PROPERTIES

The soil properties listed in Table 4-1 were used for the consolidation analysis.

Table 4-1. Soil properties.

Material	Unit Weight γ_{tot} (pcf)	Initial Void Ratio e_0	Compression Index C_c	Recompression Index C_r	Preconsolidation Pressure P_0 (psf)
Cover[a]	133.5	N/A	N/A	N/A	N/A
Waste[b]	133.5	N/A	N/A	N/A	N/A
SBL[c]	121.9	0.61	0.198	N/A	2,800
"old alluvium"[d]	121.9	0.63	0.180	0.031	3,956

a. The cover soil unit weight calculation is provided in Appendix C.

b. Waste total unit weight was based on 95% of the maximum dry density as determined by the Standard Proctor test at the optimum moisture content. The soil excavated from the ICDF landfill was assumed to have the same properties of the waste soil. The operations layer is included with the waste for loading purposes. The calculation is provided in Appendix C.

c. The SBL properties were based on the clay borrow soil properties determined during the clay borrow geotechnical investigation. The preconsolidation pressure was assumed to be small, since the clay will be remolded during construction.

d. "Old alluvium" soil properties are based on the geotechnical test and logs from the ICDF Phase 2 borings.

5. CALCULATIONS

5.1 Stress Increase

Solutions to the Boussinesq Equation that model a ramp load and a rectangular load were used to calculate the stress increase at the center of the landfill liner system. The total load was modeled as shown below in Figure 5-1.

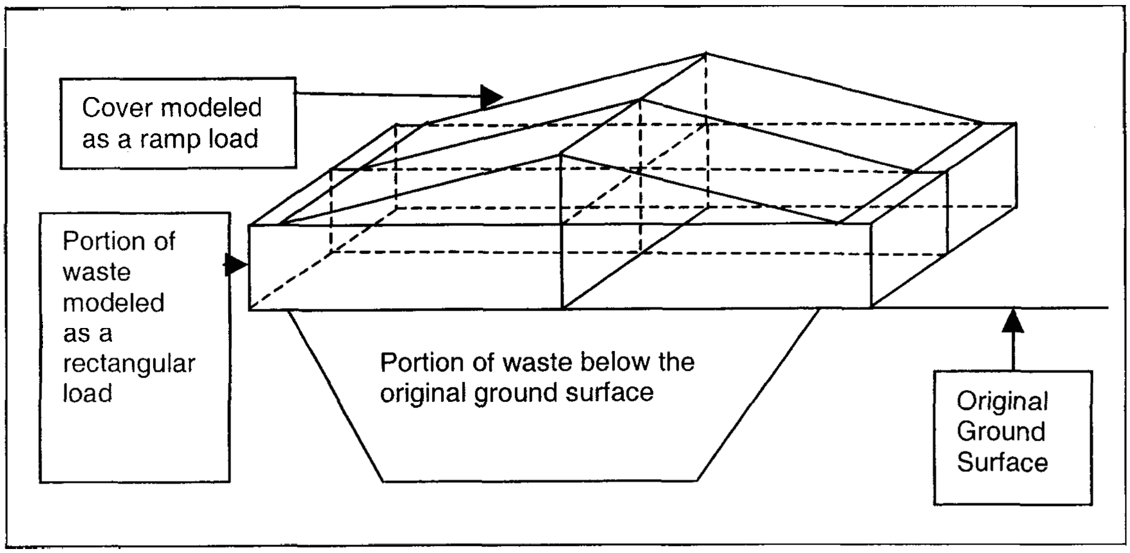


Figure 5-1. ICDF landfill loading.

Settlement in the material below the landfill including the 3-ft-thick SBL was calculated by dividing it into six layers. The total settlement is then determined by summing the settlement from each of the six layers. The general cross section used for the settlement analysis is shown below in Figure 5-2.

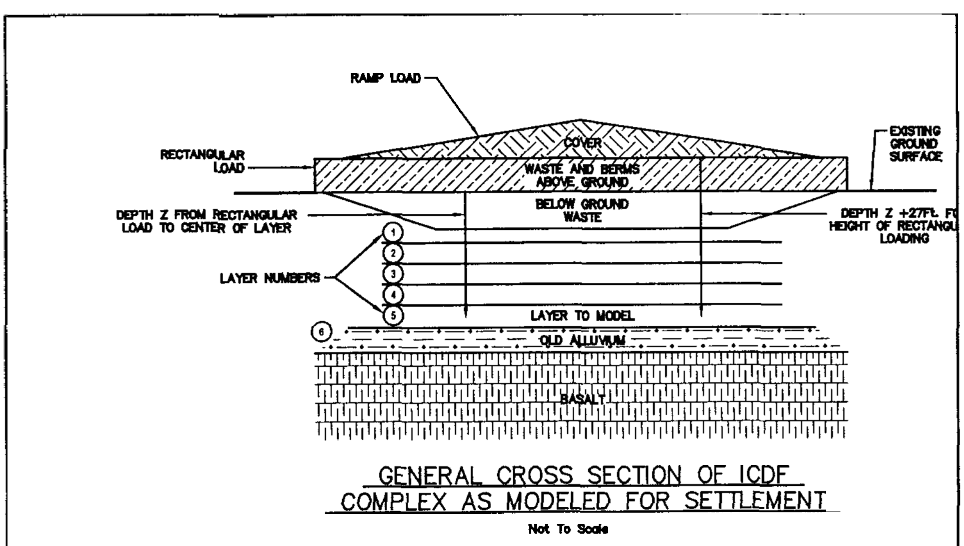


Figure 5-2. General cross section of the ICDF landfill.

The cover load is actually slightly less, since the top surface slope continues to the existing ground surface.

5.1.1 Ramp (Cover) Loads

The stress at a depth (z) below the corner of a ramp load is calculated by the equations below and illustrated in Figure 5-3. These equations were republished and confirmed in Bowles (1996), and originally published by Vitoney and Valsangkar (1986).

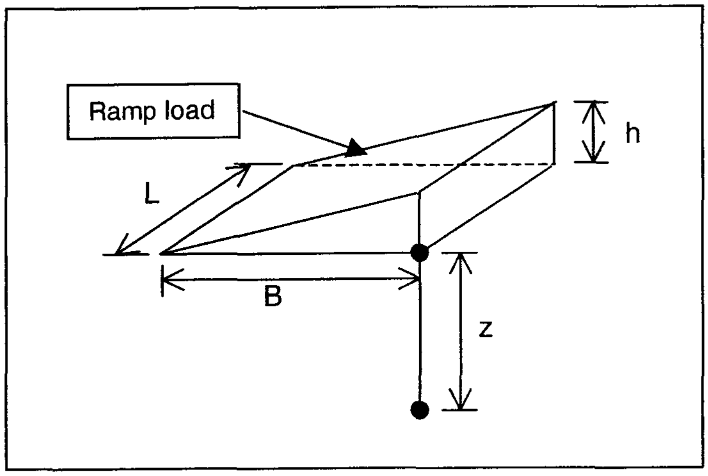


Figure 5-3. Ramp loading.

The combined Cells 1 and 2 landfill dimensions are 707 ft long in the north-south direction and 800 ft in the east-west direction, measured at the inside of the berm at the top of the operations layer (EDF-ER-265). The perimeter berm width is 45 ft so the total cap dimensions are 797 ft by 890 ft. One-half the length and width of the landfill is 398.5 ft ("L" dimension) and 445 ft ("B" dimension), respectively. Assuming a 7% slope, the "h" dimension is 31.2 ft. These dimensions are listed below:

L = 398.5 ft

B = 445 ft

h = 31.2 ft

z = depth to center of layer used for settlement calculation

$\Delta q_{@z\ ramp}$ = The change in total stress at depth z due to the ramp load

Where

$$\Delta q_{@z\ ramp} = \frac{h\gamma_0 L}{2\pi B}\left[\frac{z R_D}{R_L^2} - \frac{z}{R_L} + \frac{B}{L}\sin^{-1}\left(\frac{B L}{(B^2 L^2 + R_D^2 z^2)^{1/2}}\right)\right] = \Delta p \qquad (1)$$

$R_L^2 = L^2 + z^2$

$R_D^2 = B^2 + L^2 + z^2$

An example calculation of the stress increase in the SBL located at a point 58 ft below the ramp load is provided in Appendix D.

5.1.2 Rectangular Loads

The stress increase at a depth (z) below the corner of a flexible rectangular surface load, as shown in Figure 5-4, is governed by the equations below. The equations were presented in Al-Khafagi and Andersland (1992). An example of the calculation is provided in Appendix D.

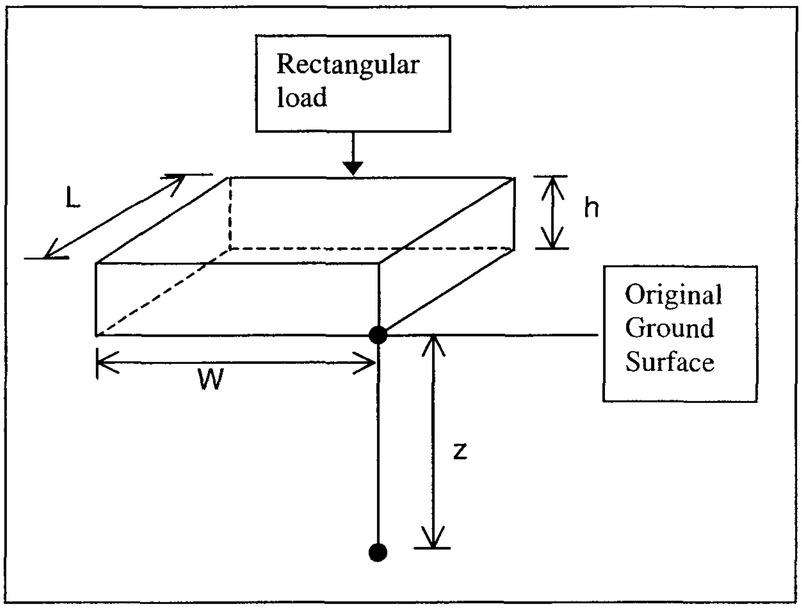


Figure 5-4. Rectangular loading.

L = 478 ft

W = 431 ft

h = 27 ft

z = depth to center of layer used for settlement calculation

$\Delta q_{@z\ rectangle}$ = The change in total stress at depth z due to the rectangular load

Where

$$\Delta q_{@z\ rectangle} = \gamma \text{ total h I} = \Delta p \qquad (2)$$

$$I = \frac{1}{2\pi}\left[\frac{m\,n}{\sqrt{m^2+n^2+1}}\,\frac{m^2+n^2+2}{m^2+n^2+m^2n^2+1} + \sin^{-1}\left(\frac{m\,n}{\sqrt{m^2+n^2+m^2n^2+1}}\right)\right]$$

m = W/z

n = L/z

The total stress increase in the SBL and underlying alluvium is calculated by splitting the loading from the waste above the original ground surface into four equal rectangular surface loads and four equal ramp loads (as shown in Figure 5-1). The resulting stress increase from the above original grade loading is calculated by the following equation:

$$\Delta q_{@z\ \text{total above}} = 4\Delta q_{@z\ \text{rectangle}} + 4\Delta q_{@z\ \text{ramp}} = \Delta p_{\text{total above}} \tag{3}$$

5.1.3 Stress Increase Due to Waste Load

The waste placed in the excavation will produce a load greater than the load of the native soil removed during excavation of the ICDF landfill. This stress increase caused by the waste material and the cap was determined by the following equation:

$$\Delta q_{@z\ \text{total below}} = \sum_{i=1}^{n} h_i (\gamma_{\text{waste below ground}})_i = \Delta p_{\text{total below}} \tag{4}$$

5.1.4 Total Stress Increase

The total stress increase due to the ramp and rectangular loads above the existing ground surface and waste below the ground surface is shown in the following equation:

$$\Delta q_{@z\ \text{total}} = \Delta q_{@z\ \text{total above}} + \Delta q_{@z\ \text{total below}} = \Delta p_{\text{total}} \tag{5}$$

The equations from Section 5.1 were input into a spreadsheet to calculate the settlement of each layer and the combined, total settlement. The spreadsheet is provided in Appendix D.

5.2 Determination of C_c and C_r

Two methods were utilized to estimate the compression index C_c of the native ("old alluvium") soil and SBL. The first method consisted of determining the compression index by evaluating the consolidation test results on representative samples collected from borings located near the footprint of the landfill (DOE-ID 2000). The results of the consolidation tests are provided in Appendix A. A comparison of the soil samples tested and what is below the landfill is also provided in Appendix A since some of the sample tests were from borings located outside the landfill footprint.

The second method consisted of using published empirical relationships of C_c to Atterberg limits and natural water contents since small sample disturbances can have large impacts on consolidation curves generated in the laboratory. Additionally, a one-dimensional laboratory consolidation test was performed on a remolded sample of SBL (that is, clay borrow with 5% bentonite by dry weight) material collected during the ICDF Test Pad construction in August 2001. The laboratory test results and C_c value determined from the soil bentonite liner sample is provided in Appendix E.

The three empirical relationships utilized for the first method were republished in Bowles (1996). The original sources were noted in Bowles and are noted here as well. The equations for the relationships are as follows:

$$C_c = 0.009(LL - 10) \text{ (error +/- 30\%)} \quad \text{Terzaghi \& Peck (1967)} \tag{6}$$

$$C_c = 0.009 w_n + 0.005LL \quad \text{Koppula (1986)} \tag{7}$$

$$C_c = 0.046 + 0.0140 I_P \quad \text{Nakase et al. (1988)} \tag{8}$$

Where

LL = the liquid limit as percent, not decimal

I_P = the index of plasticity as percent, not decimal

w_n = the natural water content of the soil as percent, not decimal.

The C_c estimates calculated from the above relationships were averaged to determine the C_c value. The average of the empirical relationships results in a slightly higher estimate of C_c determined in the laboratory. Therefore, the inclusion of the empirical C_c values for the soil bentonite liner and "old alluvium" were used to estimate settlement.

The recompression index (C_r) was estimated using the following empirical relationship (Nakase et al. 1988) republished in Bowles (1996):

$$C_r = 0.00194(I_P - 4.6) \tag{9}$$

The C_r values estimated from this relationship were averaged and then used to determine the recompression that the alluvium will experience as the landfill is filled with liner materials and waste and returned to its original stress condition. The results of these index calculations are included in Appendices A and B for the SBL and "old alluvium" material, respectively.

5.3 Initial Stress in Soil at Varying Depths

The initial stress in the soil at varying depths was calculated with the following equations:

$$p_{on} = \sum_{i=1}^{n} thickness_i \gamma_i \tag{10}$$

$$p'_{on} = p_{on} - u_n \tag{11}$$

$$u_n = \gamma_{water} z_{\text{depth of water}_n} \tag{12}$$

since ground water is not present,

$$u_n = 0 \text{ so} \tag{13}$$

$$p'_{on} = p_{on} \tag{14}$$

These equations were input into the settlement spreadsheet in Appendix D to calculate the stress conditions in the soil bentonite liner and underlying alluvium foundation soils.

5.4 Consolidation and Re-consolidation Settlement

The consolidation settlement within a soil layer (i) with a thickness (H_i) is calculated utilizing consolidation theory with the following equation:

$$S_i = \frac{H_i}{1+e_{oi}}\left(C_{ci}\log\frac{p'_o+\Delta p'}{p'_o}\right) \tag{15}$$

The total consolidation settlement is calculated as follows:

$$S_{total} = \sum_{i=1}^{n} S_i \tag{16}$$

The re-consolidation settlement is calculated in basically the same manner. However, the compression index is replaced with the recompression index and the equation appears as follows:

$$S_{ri} = \frac{H_i}{1+e_{oi}}\left(C_{ri}\log\frac{p'_o}{p'_{unloaded}}\right) \tag{17}$$

The above equations were input into the spreadsheet in Appendix D to determine the maximum amount of settlement at the middle of the ICDF landfill (Cells 1 and 2 combined). The soil will follow the reconsolidation portion of the consolidation curve until the effective stress prior to excavation is reached. Therefore, the initial effective stress at depth for the soils is used in the preceding equations as p'_o. The soil stress will then transition to the consolidation portion of the curve after the initial effective stress exceeds the effective stress prior to the excavation (e.g., preconsolidation pressure).

6. RESULTS AND CONCLUSIONS

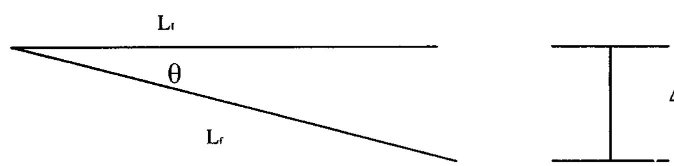
6.1 Maximum Differential Settlement

The maximum total settlement at the center of the landfill is conservatively estimated to be 1.2 ft. Differential settlement may occur due to a difference in thickness of compressible soil (i.e., "old alluvium") underlying the landfill. The maximum difference in the "old alluvium" layer thickness is three ft., based on the cross section shown in Figure 2-2. The thickness of "old alluvium" assumed for calculating total settlement was 15 ft. So, as a worst case, the maximum differential settlement is assumed to be equal to the maximum total settlement of 1.2 ft.

6.2 Stress and Strain in Liner Components

As the bottom of the liner consolidates, it will distort, creating strain in each of the liner components. Assuming all the settlement occurs near the center of the landfill and no settlement occurs on the ends, the maximum differential settlement will be 1.2 ft as described previously. The floor of the landfill in its shortest direction is approximately 528 ft. (EDF-ER-265). The resulting strain is calculated below:

$$\varepsilon = \frac{L_f - L_I}{L_I} \qquad (18)$$



Where

ε = Strain

L_f = Final length

L_I = The length on which the distortion acts

θ = Angle of rotation

Δ = Distortion

Using half of the width of the landfill, the maximum amount of strain is 0.001%. The calculation is presented below:

$$L_I = \frac{528 ft}{2} = 264 ft$$

$$\theta = Sin^{-1}\left(\frac{1.2 ft}{264 ft}\right) = 0.26$$

$$L_f = \frac{264 ft}{\cos(0.26)} = 264.003$$

$$\varepsilon = \frac{264.004ft - 264ft}{264ft} = \frac{0.003ft}{264ft} \times 100 = 0.001\%$$

6.3 Integrity of Liner Barrier Components

The liner system will be comprised of the three types of barrier materials listed below:

- SBL
- GCL
- High-density polyethylene (HDPE) geomembrane.

SBLs can crack at tensile strains larger than 0.1 to 1% (Daniel 1993). Differential settlement studies performed using geosynthetic clay liners show that they can maintain a hydraulic conductivity below 1 x 10^{-7} cm/sec when subjected to strains between 1 and 10% (LaGatta et al. 1997). Lastly, geomembranes can withstand strains between 20 to 100% (Koerner 1994). Based on these allowable strains, the maximum strain of 0.001% is below the suggested allowable strains of the SBL, GCL, and geomembranes. Since the strains in the landfill liner barrier layers are orders of magnitude less than allowed, stresses caused by settlement will be low, thereby maintaining the integrity of the liner system.

6.4 Integrity of Drainage System Components

To provide adequate drainage, the minimum bottom slope of 1% is required for leak detection recovery systems in landfills (CFR 264.301). The current practice and minimum technology guidance for bottom slopes of landfills is a minimum of 2% (EPA 1989). The ICDF landfill floor is designed at a 2.5% slope, steeper than 2% to allow for differential settlement. A maximum differential settlement of 1.2 ft near the middle of the landfill floor would result in a floor slope of approximately 2%, meeting the regulatory requirement and suggested minimum landfill slope guidance. The calculation is provided in Appendix D.2.

6.5 Conclusion

The differential settlement predicted for the ICDF landfill is within acceptable limits. The predicted 0.0001% strain on the liner component of the landfill is below the allowable 0.1% strain for SBL, the 1.0% strain for GCLs, and the 20% strain for geomembranes. The cell floor is sloped to compensate for settlement in the underlying materials, while maintaining proper leachate drainage. Based on these results, the amount of settlement calculated is acceptable for the ICDF landfill.

7. REFERENCES

40 CFR 264, 1999, "Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities," *Code of Federal Regulations,* Office of the Federal Register, July 1, 1999.

Al-Khafaji, A.W. and O.B. Andersland, 1992, *Geotechnical Engineering and Soil Testing, International Edition*, Saunders College Publishing Harcourt Brace Jovanovich College Publishers, New York.

Bowles, J., 1996, *Foundation Analysis and Design*, Fifth Edition, McGraw-Hill Companies, Inc., New York.

Carter, M. and S.P. Bentley, 1991, *Correlations of Soil Properties*, Pentech Press, London, England.

Daniel, D.E., 1993, *Geotechnical Practice For Waste Disposal*, Chapman and Hall, Boundary Row, London.

DOE-ID, 2000, *Geotechnical Report for the Conceptual Design of the INEEL CERCLA Disposal Facility at Waste Area Group 3, Operable Unit 3-13,* DOE/ID-10812, Rev. 0, Department of Energy Idaho Office Operations, Idaho Falls, Idaho.

EDF-ER-265, 2001, "Air Space Volume Calculation," Rev. 0, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, July 2001.

EDF-ER-267, 2002, "Landfill Compaction Subsidence Study," Rev. 1, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, May 2002.

EDF-ER-275, 2002, "Fate and Transport Modeling Results," Rev. 2, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, May 2002.

EDF-ER-281, 2002, "Liner and Final Cover Long-Term Performance Evaluation and Final Cover Life Cycle Expectation," Rev. 1, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, May 2002.

EPA, 1989, *Requirements for Hazardous Waste Landfill Design, Construction, and Closure*, EPA/624/4-89/022, Seminar Publication, U.S. Environmental Protection Agency, Center for Environmental Research Information, Office of Research and Development, Cincinnati, Ohio.

EPA, 1988, *Guide to Technical Resources for the Design of Land Disposal Facilities*, EPA/625-6-88/018, U.S Environmental Protection Agency, Office of Research and Development, Cincinnati, Ohio.

Holtz, R.D. and W.D. Kovacs, 1981, *An Introduction to Geotechnical Engineering,* Prentice-Hall, New York, N.Y.

Koerner, R.M., 1994, *Designing with Geosynthetics*, Prentice Hall, Englewood Cliffs, New Jersey.

Koppula, S.D., 1986, "Discussion: Consolidation Parameters Derived from Index Tests," *Geotechnique*, Vol. 36, No. 2, June, pp. 291-292.

LaGatta, M.D., B.T. Boardman, B.H. Cooley, and D.E. Daniel, 1997, "Geosynthetic Clay Liners Subjected to Differential Settlement," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 5, p. 402.

Nakase, A. et al. 1988, "Constituted Parameters Estimated by Plasticity Index," *Journal of Geotechnical Engineering Division,* American Society of Civil Engineers, Vol. 114, No. 7, pp. 844-858.

Terzaghi, K. and R.B. Peck, 1967, *Soil Mechanics and Engineering Practice*, 2nd Edition, John Wiley & Sons, NY, pp 7-29.

Vitone and Valsangkar, 1986, "Stresses from Loads over Rectangular Areas," *Journal of the Geotechnical Engineering Division*, American Society of Civil Engineers, Vol. 112, No. 10, pp. 961-964.