Golder Associates

CALCULATIONS

Date:	1/28/14	**Made by:**	TMK
Project No.:	130-0193	**Checked by:**	DPM
Subject:	Leachate Flow Modeling	**Reviewed by:**	
Project Short Title:	**CHESAPEAKE ENERGY CENTER ASH LANDFILL - SWP #440**		

1.0 OBJECTIVE

The objective of this analysis is to model the existing conditions of the CEC ash landfill and develop a comparative leachate drainage flow rate to the HELP model (Golder August 2012). A perimeter leachate collection system will be installed during the initial stages of closure construction; therefore as part of the analysis, the anticipated time for existing leachate to drain to zero flow following closure will be evaluated utilizing three, one-dimensional models. Hydraulic head on the existing bottom liner system was not evaluated.

2.0 METHOD

The analysis was performed using an empirical groundwater drainage equation (Darcy's Law), a subsurface drainage lateral spacing analysis (Hooghoudt's Equation) and the one-dimensional unsaturated flow model (HYDRUS 1-D) for the following scenarios:

- Darcy's Law: Continuity Equation describing flow through porous media.
- Hooghoudt Equation: Steady-flow drain spacing formula.
- HYDRUS 1D: Unsaturated/Saturated Flow with 39 feet of fly ash in place.

3.0 MODEL INPUTS AND ASSUMPTIONS

1. The hydraulic conductivity of the ash was 51 feet per year (5.0×10^{-5} cm/s)
2. The closure cap is essentially impermeable, therefore, no water is infiltrating the landfill after the cap is installed.
3. The lift thickness of ash at closure was set at 39 feet, corresponding to approximately the average thickness of in-place ash at the landfill.

<u>Darcy's Law: Seepage velocity (average linear flow velocity)</u>

- Represents the average rate at which water moves between 2 points
- Includes the effective porosity
- Describes flow via the following equation:

$$V_x = \frac{Q}{n_e A} = \frac{-K\,dh}{n_e\,dl}$$

Golder Associates Inc.
2108 W. Laburnum Avenue, Suite 200
Richmond, VA 23227 USA
Tel: (804) 358-7900 Fax: (804) 358-2900 www.golder.com

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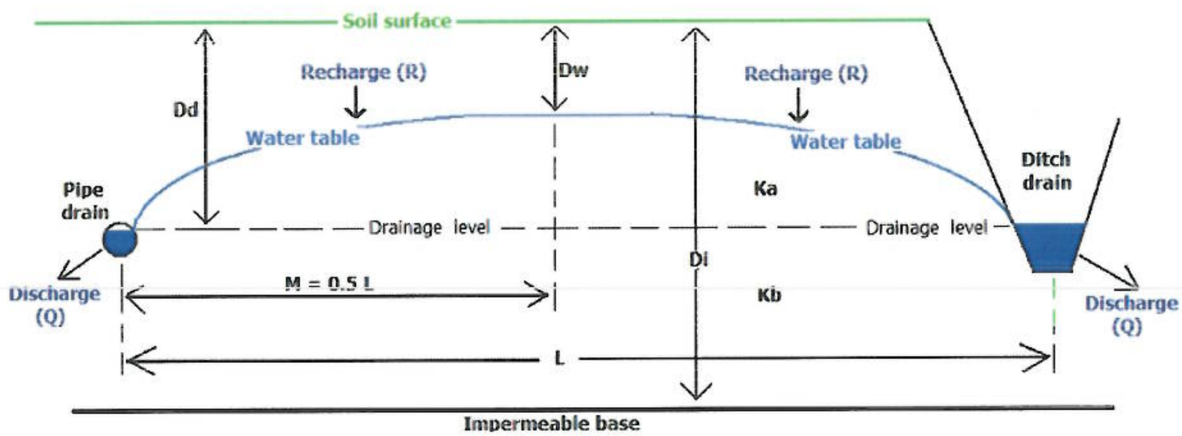
where

- V_x = average linear flow velocity
- n_e = effective porosity: the volume of the void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment.
- Units = dimensionless porosity; this value is a decimal (NOT a %). Ex: 18% porosity = 0.18 n_e
- Note: this equation does not account for diffusion or dispersion

Hooghoudt Equation

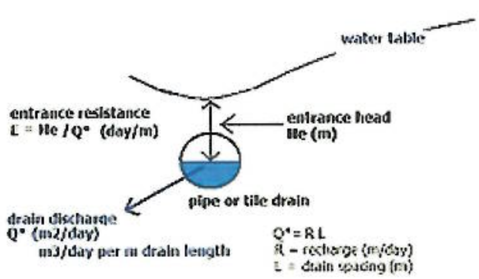
Field drainage can be simulated using the Hooghoudt equation in homogenous soil. The drainage was modeled as single-level system and the bottom flux was calculated according to the boundary conditions adopted in the model. This equation simulates subsurface water movement into drains and ditches. Here we assume saturated flow only.

Hooghoudt's flow equation (steady state)



Geometry subsurface drainage system by pipes or ditches

D = depth K = hydraulic conductivity L = Drain spacing



Hooghoudt's equation can be written as:

$$Q L^2 = 8 Kb\, d\, (Di - Dd)\, (Dd - Dw) + 4 Ka\, (Dd - Dw)^2$$

where:

- Q = steady state drainage discharge rate (m/day)
- Ka = hydraulic conductivity of the soil above drain level (m/day)
- Kb = hydraulic conductivity of the soil below drain level (m/day)
- Di = depth of the impermeable layer below drain level (m)
- Dd = depth of the drains (m)
- Dw = steady state depth of the watertable midway between the drains (m)
- L = spacing between the drains (m)
- d = equivalent depth, a function of L, (Di-Dd)
- r = drain radius (m)

HYDRUS 1D - Model Description

The HYDRUS-1D program numerically solves the Richards equation for variably-saturated water flow and the convection-dispersion equation for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots (which was not used).

The program was used to analyze water movement in the partially/fully saturated porous media (ash). The water flow part of the model incorporated prescribed head and flux boundaries, boundaries controlled by atmospheric conditions, and contained a free drainage boundary condition (to simulate the drainage medium).

4.0 CALCULATIONS AND RESULTS

4.1 Darcy's Law

In order to determine the time to drain the landfill, Darcy's Law was used to estimate the amount of time it would take to remove the water in the ash from the landfill into the perimeter drain. This approach assumes steady flow out of the landfill as well as a uniform gradient. Using this approach, each year would drain the volume of leachate equally (approximately 85,877 cubic feet) and as shown on the attached spreadsheet, it is predicted that it will take approximately 5.2 years to drain the water from the ash. After this time (and based on its assumptions), Darcy's Law predicts that no further flow would be released from the landfill into the perimeter drain.

4.2 Hooghoudt Equation

Using a similar approach to Darcy's Law, the Hooghoudt Equation was also used to determine how long it would take to dewater the landfill. Using this approach, each year would drain the volume of leachate equally (approximately 65,670 cubic feet) and as shown on the attached spreadsheet, the Hooghoudt Equation predicts that it will take approximately 6.8 years to drain the water from the ash, using a drain spacing of 830 feet. With no further inputs of leachate (i.e., leakage from the impermeable cap), this equation predicts that after 6.8 years, no further flow of leachate is being discharged into the perimeter drainage piping.

4.3 HYDRUS 1D

As a final check, the unsaturated/saturated flow model HYDRUS-1D was utilized to determine how long drainage would occur in the ash landfill until all the simulated surface flux (0.5 meters/year with minimal evaporation) of leachate was transmitted through the ash profile into the perimeter drain. The results showed that HYDRUS-1D was able to successfully simulate leachate movement in the ash landfill. Using this approach, the surface flux was added to the ash profile instantaneously (<1 year) and after 4 years the leachate began flowing from the perimeter drain and the initial flux equaled the bottom flux indicating that flow had ceased from the ash landfill and hence the perimeter drain. Unfortunately, this model cannot predict the amount of leachate flow per year through the landfill. Using the model inputs shown on the attached spreadsheet, for a surface flux of 0.5 meters per year, it took approximately 6 years for this surface flux to exit out the drains (located 39 feet below the simulated water flux at the surface).

5.0 REFERENCES

1. Šimunek, J., M. Šejna, and M. Th. van Genuchten, The HYDRUS-1D software package for simulating one-dimensional movement of water, heat, and multiple solutes in variably saturated media. Version 2.0, IGWMC - TPS- 70, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado, 202pp., 1998.

2. Van Schilgaarde, J.. Subsurface Drainage Lateral Spacing Analysis Non-Steady Flow to Drains (1974)

3. "Ash Structural Fill Closure Plan Details" Drawing No. 90-283-E3 prepared by GAI Consultants, Inc., April 1993.

Golder Associates Richmond, Virginia	Subject: Time to Drain Ash in Landfill at the CEC Ash Landfill facility in Chesapeake, Virginia - SWP #440			
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Objective Determine the time to drain ash landfill by the Hooghoudt Equation.

Calculation

$$Q L^2 = 8 Kb\, d\, (Di - Dd)(Dd - Dw) + 4 Ka\, (Dd - Dw)^2$$

Where:

Q = steady state drainage discharge rate (m/day)
Ka = hydraulic conductivity of the soil above drain level (m/day)
Kb = hydraulic conductivity of the soil below drain level (m/day)
Di = depth of the impermeable layer below drain level (m)
Dd = depth of the drains (m)
Dw = steady state depth of the watertable midway between the drains (m)
L = spacing between the drains (m)
d = equivalent depth, a function of L, (Di-Dd)
r = drain radius (m)

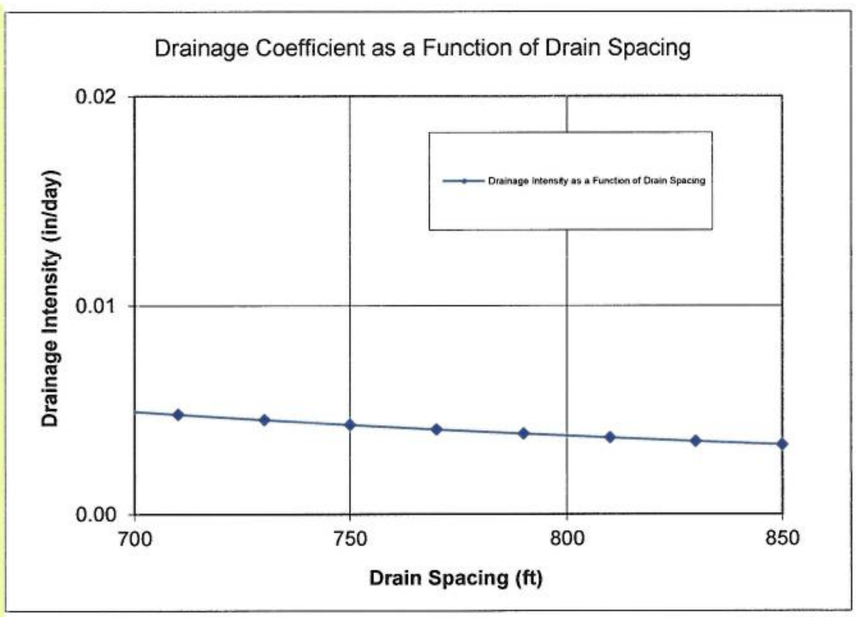
Subsurface Drainage Lateral Spacing Analysis

Hooghoudt Equation - Steady Flow Drain Spacing Formula

Input	
Depth to Drains [d] (ft)	38
Depth to Impervious Layer [D] (ft)	39
Depth to Water Table Midway between Laterals after Drawdown [d_m] (ft)	20
Effective Radius of Drain Lines [r_e] (in)	0.59
Soil Profile Saturated Hydraulic Conductivity above Drain (in/hr)	0.07
Soil Profile Saturated Hydraulic Conductivity below Drain (in/hr)	0.07
Drainable Porosity [f]	0.08
Depth from Impermeable Layer to Drain (ft)	1

Results for Hooghoudt Equation

Drain Spacing (ft)	d_e (ft)	Drainage Coefficient (in/day)
390	0.99	0.016
410	0.99	0.014
430	0.99	0.013
450	0.99	0.012
470	0.99	0.011
490	0.99	0.010
510	0.99	0.009
530	0.99	0.009
550	0.99	0.008
570	0.99	0.007
590	0.99	0.007
610	0.99	0.006
630	0.99	0.006
650	0.99	0.006
670	0.99	0.005
690	0.99	0.005
710	0.99	0.005
730	0.99	0.005
750	0.99	0.004
770	0.99	0.004
790	0.99	0.004
810	0.99	0.004
830	1.00	0.004
850	1.00	0.003



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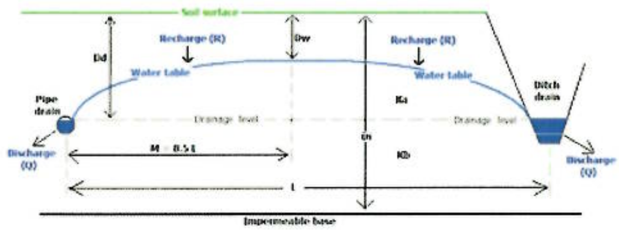
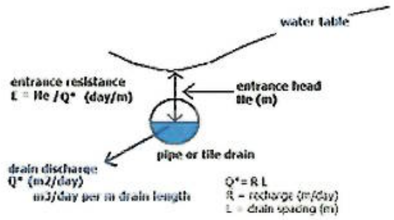


Geometry subsurface drainage system by pipes or ditches
D = depth K = hydraulic conductivity L = Drain spacing



Subsurface Drainage Lateral Spacing Analysis

Non-Steady Flow to Drains (van Schilgaarde, J.. 1974)

Time to Drain from Surface to Required Depth

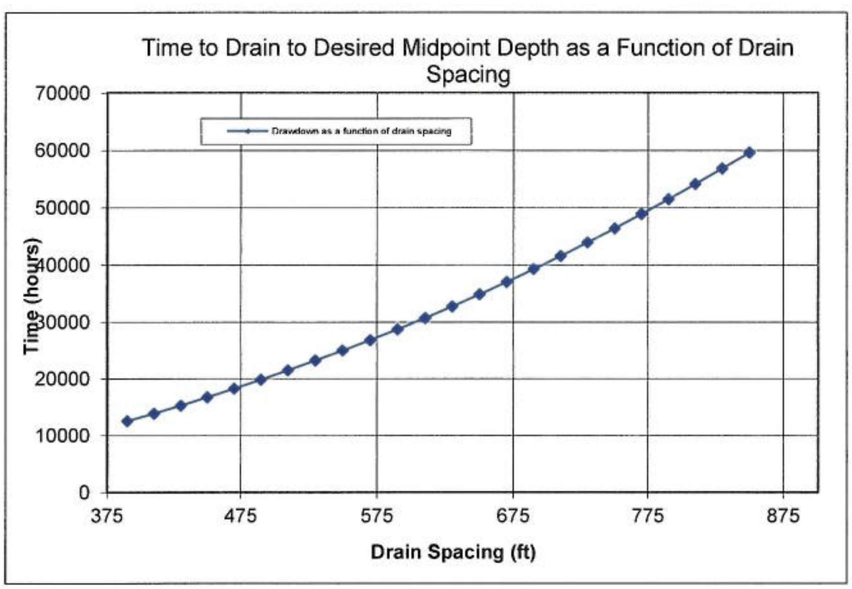
Input

Depth to Initial Water Table (ft)	0
Depth to Water Table Midway between Laterals afte	20

Time to Drain

Hrs	**Yrs**
56778.3	**6.5**
K (cm/sec)	K (in/hr)
5.00E-05	0.07085

Drain Spacing L (ft)	d_e (ft)	Time (hours)	
390	0.99	12541.1	
410	0.99	13859.8	
430	0.99	15244.5	
450	0.99	16695.0	
470	0.99	18211.5	
490	0.99	19793.8	
510	0.99	21442.1	
530	0.99	23156.3	
550	0.99	24936.4	
570	0.99	26782.4	
590	0.99	28694.3	
610	0.99	30672.1	
630	0.99	32715.9	
650	0.99	34825.5	
670	0.99	37001.1	
690	0.99	39242.5	
710	0.99	41549.9	
730	0.99	43923.2	
750	0.99	46362.4	
770	0.99	48867.5	
790	0.99	51438.5	
810	0.99	54075.5	
830	1.00	56778.3	<----------
850	1.00	59547.1	



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Objective Determine the time to drain ash Landfill

Calculation

$$V_x = \frac{Q}{n_e A} = -\frac{K\,dh}{n_e\,dl}$$

Darcy's Law

Where:

Vx = Average Linear Velocity (L/	7.58
K = hydraulic conductivity (L/T)	51
dh/dl = hydraulic gradient (L/L)	0.052
h = head (L)	
n_e = effective porosity	0.35

K (ft/yr)	v (ft/yr)	t (yr)	dh/dl	n_e	D (ft)
51	7.5771429	**5.147059**	0.052	0.35	39

	Kz (ft/yr)	Kz (in/hr)
5.00E-05	52.56	0.00050
5.00E-05	315.36	0.00300
	51	

Hornberger et al., 1998. Elements of Physical Hydrology,
The Johns Hopkins Press, Baltimore, 302 p.

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Objective Determine the time to drain ash Landfill

Calculation

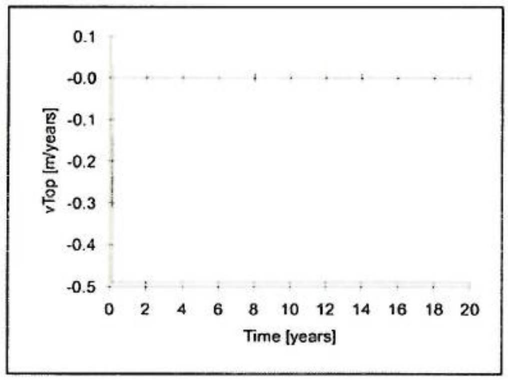
HYDRUS 1D
Van Genuchten Single Porosity Model
No Hysteresis

Where:

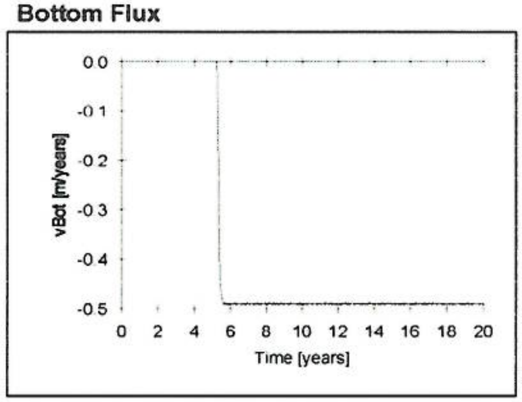
Qr = 0.089
Qs = 0.43
Ks = 15.77 Meters / year

Upper Boundary Conditions
Atmospheric
Lower Boundary Condition
Free Drainage
Leachate Flux
0.5 m / year
Leachate Evaporation
0.01 m / year

Actual Surface Flux



Bottom Flux



Results

******* Program HYDRUS
****
Drainage in an Ash Landfill
Date: 27. 1. Time: 16:37:26
Units: L = m , T = years, M = -

Time [T] 0.1000

Sub-region num. 1

Length [L]	0.13000E+02	0.13000E+02
W-volume [L]	0.26931E+01	0.26931E+01
In-flow [L/T]	0.00000E+00	0.00000E+00
h Mean [L]	-0.10000E+03	-0.10000E+03
Top Flux [L/T]	-0.38864E-05	
Bot Flux [L/T]	-0.38864E-05	

Calculation

HYDRUS 1D
Results

```
 Time      [T]      0.3288
----------------------------------------------------------
 Sub-region num.                1
----------------------------------------------------------
 Length   [L]      0.13000E+02  0.13000E+02
 W-volume [L]      0.28027E+01  0.28027E+01
 In-flow  [L/T]    0.49000E+00  0.49000E+00
 h Mean   [L]     -0.93777E+02 -0.93777E+02
 Top Flux [L/T]   -0.48256E+00
 Bot Flux [L/T]   -0.38864E-05
 WatBalT  [L]      0.44993E-02
 WatBalR  [%]          4.104
----------------------------------------------------------

----------------------------------------------------------
 Time      [T]      0.4137
----------------------------------------------------------
 Sub-region num.                1
----------------------------------------------------------
 Length   [L]      0.13000E+02  0.13000E+02
 W-volume [L]      0.28443E+01  0.28443E+01
 In-flow  [L/T]    0.49000E+00  0.49000E+00
 h Mean   [L]     -0.92001E+02 -0.92001E+02
 Top Flux [L/T]   -0.48647E+00
 Bot Flux [L/T]   -0.38864E-05
 WatBalT  [L]      0.44992E-02
 WatBalR  [%]          2.975
----------------------------------------------------------

----------------------------------------------------------
 Time      [T]      0.4959
----------------------------------------------------------
 Sub-region num.                1
----------------------------------------------------------
 Length   [L]      0.13000E+02  0.13000E+02
 W-volume [L]      0.28846E+01  0.28846E+01
 In-flow  [L/T]    0.49000E+00  0.49000E+00
 h Mean   [L]     -0.90334E+02 -0.90334E+02
 Top Flux [L/T]   -0.48764E+00
 Bot Flux [L/T]   -0.38864E-05
 WatBalT  [L]      0.44991E-02
 WatBalR  [%]          2.349
```

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Calculation

HYDRUS 1D

Results

```
--------------------------------------------------------
 Time      [T]       0.5808
--------------------------------------------------------
 Sub-region num.                  1
--------------------------------------------------------
 Length   [L]      0.13000E+02  0.13000E+02
 W-volume [L]        0.29262E+01  0.29262E+01
 In-flow  [L/T]    0.49000E+00  0.49000E+00
 h Mean   [L]      -0.88664E+02 -0.88664E+02
 Top Flux [L/T]     -0.48868E+00
 Bot Flux [L/T]    -0.38864E-05
 WatBalT  [L]       0.44990E-02
 WatBalR  [%]            1.930
--------------------------------------------------------

--------------------------------------------------------
 Time      [T]       0.6658
--------------------------------------------------------
 Sub-region num.                  1
--------------------------------------------------------
 Length   [L]      0.13000E+02  0.13000E+02
 W-volume [L]        0.29678E+01  0.29678E+01
 In-flow  [L/T]    0.49000E+00  0.49000E+00
 h Mean   [L]      -0.87011E+02 -0.87011E+02
 Top Flux [L/T]     -0.48911E+00
 Bot Flux [L/T]    -0.38864E-05
 WatBalT  [L]       0.44988E-02
 WatBalR  [%]            1.637
--------------------------------------------------------
--------------------------------------------------------
 Time      [T]       0.7479
--------------------------------------------------------
 Sub-region num.                  1
--------------------------------------------------------
 Length   [L]      0.13000E+02  0.13000E+02
 W-volume [L]        0.30081E+01  0.30081E+01
 In-flow  [L/T]    0.49000E+00  0.49000E+00
 h Mean   [L]      -0.85408E+02 -0.85408E+02
 Top Flux [L/T]     -0.48948E+00
 Bot Flux [L/T]    -0.38864E-05
 WatBalT  [L]       0.44988E-02
 WatBalR  [%]            1.428
```

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Calculation

HYDRUS 1D

Results

```
----------------------------------------------------------
 Time      [T]     20.0000
----------------------------------------------------------
 Sub-region num.                    1
----------------------------------------------------------
 Length   [L]     0.13000E+02  0.13000E+02
 W-volume [L]      0.52508E+01  0.52508E+01
 In-flow  [L/T]   -0.15771E-03 -0.15771E-03
 h Mean   [L]     -0.59745E+00 -0.59745E+00
 Top Flux [L/T]    -0.48999E+00
 Bot Flux [L/T]   -0.49013E+00
 WatBalT  [L]      0.44954E-02
 WatBalR  [%]          0.027
----------------------------------------------------------

 Calculation time [sec]  0.340000033378601
```