8-2015

Performing a steady-state seepage analysis using SEEP/W : a primer for engineering students.

Matthew R. Broaddus
University of Louisville

PERFORMING A STEADY-STATE SEEPAGE ANALYSIS USING SEEP/W:

A PRIMER FOR ENGINEERING STUDENTS

By

Matthew R. Broaddus

B.S.C.E., University of Kentucky, 2013

M.S.C.E., University of Louisville, 2015

A Thesis

Submitted to the Faculty of the

J.B. Speed School of Engineering of the University of Louisville

in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Civil Engineering

Department of Civil Engineering

University of Louisville

Louisville, Kentucky

August 2015

PERFORMING A STEADY-STATE SEEPAGE ANALYSIS USING SEEP/W:

A PRIMER FOR ENGINEERING STUDENTS

By

Matthew R. Broaddus

B.S.C.E., University of Kentucky, 2013

M.S.C.E., University of Louisville, 2015

A Thesis Approved on

August 11, 2015

by the following Thesis Committee:

_____

Thesis Director

Dr. Thomas Rockaway

_____

Dr. Qian Zhao

_____

Dr. James Lewis

DEDICATION

This thesis is dedicated to my mother and grandparents, Marilyn, Bill & Shirley, for their

love and support, and to my wife, Alexis, whose love and confidence is a constant source

of inspiration and encouragement.

ACKNOWLEDGEMENTS

I would like to thank my academic advisor, Dr. Thomas Rockaway, for his patience. I would also like to thank the other committee members, Dr. Qian Zhao and Dr. James Lewis, for their assistance. Additionally, I would like to thank my wife, Alexis, for picking me up when I needed it the most. Finally, I would like to thank my mother, and grandparents who have given me invaluable educational opportunities.

ABSTRACT

PERFORMING A STEADY-STATE SEEPAGE ANALYSIS USING SEEP/W:

A PRIMER FOR ENGINEERING STUDENTS

Matthew R. Broaddus

August 11, 2015

This thesis is comprised of five independent modules that were developed to provide a primer to understanding groundwater seepage. These modules serve as the template to conduct steady-state seepage analyses through embankments utilizing SEEP/W, a finite element seepage modeling program. Module 1 and 2 are more theoretical in nature to provide the background knowledge necessary to conduct a steady-state seepage analysis, while Modules 3, 4, and 5 focus more on the application of seepage models and how they can be used to solve various groundwater seepage problems.

Supplementary material, including PowerPoint presentations, handouts, and a manual on how to utilize SEEP/W, are provided with this thesis and should be used alongside the modules to provide additional information necessary to understanding how to conduct steady-state seepage analyses. The corresponding PowerPoint presentation utilizes a multitude of different presentation techniques ranging from text only, to text with audio, to video demonstrations.

In general, groundwater seepage is an extremely complicated topic and it is nearly impossible to immediately become effective at conducting a successful seepage analysis without prior experience and understanding of seepage behavior. This thesis should not be considered an all-in-one guide, but should be viewed as a starting place for learning and growing.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

It is well known in geotechnical engineering that groundwater seepage often plays a significant role in slope stability and deformation of geotechnical structures. In order to grasp how groundwater seepage behaves in a particular soil mass, geotechnical engineers conduct various types of seepage analyses. To conduct a seepage analysis, it often requires a fundamental understanding of seepage theory, engineering principals/concepts, soil mass properties, soil geometry, and subsurface soil conditions.

The following thesis is designed to categorize the components of a seepage analysis into self-contained modules. The modules consist of chapters within this report as well as supplementary PowerPoint presentations and handout material submitted with this thesis. The modules are organized by a specific order which allow for one to build upon the knowledge gained from previous modules. Together the modules provide a base understanding of what groundwater seepage analyses entail.

It is nearly impossible to immediately become effective at conducting a successful seepage analysis without prior experience and understanding of seepage behavior. However, all experienced geotechnical engineers started somewhere in order to learn how to conduct a successful seepage analysis. The following modules outlined in this thesis will attempt to provide a primer to learning conducting a steady-state seepage analysis utilizing SEEP/W from which one can grow to become further competent.

MODULE 1: FUNDAMENTALS OF GROUNDWATER FLOW

Module 1 provides a review of groundwater basics, groundwater theory and the equations that are fundamental to groundwater seepage. To understand what groundwater is, where it comes from, how it behaves, and how it relates to permeability and porosity, review the bulletin by Lyle S. Raymond Jr. of the New York Water Resource Institute Center of Environmental Research at Cornell University provided as a supplementary document along with this thesis. It is important to note that the term "permeability" in the bulletin and geotechnical applications is synonymous with "hydraulic conductivity." However, in other industries (such as the oil and gas industry), permeability is taken to mean the "intrinsic permeability" which is a soil property and independent of the permeating fluid.[1] To show the relation between intrinsic permeability and hydraulic conductivity we need to review Bernoulli's Equation and Darcy's Law.

Bernoulli's Equation

Bernoulli's Equation quantifies energy potential in a fluid system in terms of the fluid column height, most commonly referred to as "head." According to Bernoulli's Equation, the total head is derived from the following equation.

---

[1] "What is Hydraulic Conductivity?" Preene Groundwater Consulting. July 8, 2014. Accessed August 7, 2015. http://www.preene.com/blog/2014/07/what-is-hydraulic-conductivity.

Equation 1: Bernoulli's Equation

$$h = z + \frac{P}{\gamma_w} + \frac{v^2}{2g}$$

Where h is the total head, z is the elevation head, P is pressure, γ_w is the unit weight of water, v is the flow velocity and g is gravitational acceleration.

Using Bernoulli's Equation, the head loss between two points for steady-state flow through a system can be expressed by the following equation.

Equation 2: Steady-State Head Loss Equation

$$\Delta h = h_a - h_b$$

Where Δh is the head loss, or change in head between Point A and Point B, h_a is the total head at Point A, and h_b is the total head at Point B. Using the head loss and Darcy's Law, the hydraulic conductivity of a soil sample can be determined. This is discussed in the next sub-section.

Darcy's Law

Darcy's Law is an equation that relates flow velocity to hydraulic gradient under laminar flow conditions.[2]

Equation 3: Darcy's Law

$$Q = KiA$$

$$Hydraulic\ Conductivity = K = \bar{K}\frac{\gamma_w}{\mu}$$

---

[2] Ibid

$$Hydraulic\ Gradient = i = \frac{\Delta h}{\Delta L}$$

Where, Q is the flow rate (flow volume over time), K is the hydraulic conductivity, $\overline{K}$ is the intrinsic permeability, γ_w is the unit weight of water, μ is the viscosity of water, i is the hydraulic gradient, Δh is the head loss, ΔL is the change in length, and A is the cross-sectional area. Based on the equation above it is demonstrated that hydraulic conductivity is in fact a property of both the soil and the permeating fluid. In most geotechnical applications, water is the permeating fluid. Although the viscosity of water varies with temperature, in geotechnical engineering, the variations are often small enough that changes in hydraulic conductivity can be neglected. [3]

Why is Hydraulic Conductivity Important to Geotechnical Engineers?

As demonstrated in the previous section, hydraulic conductivity is a quantitative measure of a soil's ability to transmit water when subjected to a hydraulic gradient, but what does that mean to geotechnical engineers and why is it important? The answer to this question is not necessarily black and white and it all depends on context and application. A few geotechnical scenarios are discussed below and describe the role of hydraulic conductivity.

Internal Erosion (Piping)

The potential for piping through dam or levee is directly related to hydraulic conductivity. If foundation soils underneath a dam have high hydraulic conductivity and fluid velocity is uncontrolled, internal erosion can develop and transport fines within the embankment.

---

[3] Ibid

Piping and heaving account for over 50 percent of dam and levee failures today.[4] This fact alone represents how important it is to consider hydraulic conductivity during the design of impoundment structures. Determining factors of safety against piping is further discussed in Module 4 and Module 5.

Stability Applications

Understanding hydraulic conductivity is critical in geotechnical stability applications. When a load is applied to a soil mass with low hydraulic conductivity, total stress, undrained conditions can occur where pore-water pressure is unable to dissipate. The total stress, undrained conditions results in reduction of shear strength. If hydraulic conductivity is ignored, global instability and failure can occur.[5]

Applications of Flux (Flow Rates)

Hydraulic conductivity is critical in determining flow quantities within a system. Flow rates are especially useful for sizing pipes, pumps and drains within a system. Soils with high hydraulic conductivity will require larger pipes, pumps and drains than soils with low hydraulic conductivity.[6]

Chemical Transport

Leaks and spills at gas stations, abandoned chemical storage facilities, and landfills can result in toxic chemicals to be released into a soil mass which can contaminate groundwater. During chemical transport, hydraulic conductivity plays an essential role in understanding how fast chemicals are moving through subsurface soil layers. The

---

[4] Fleshman, Mandie Swainston, "Laboratory Modeling of Critical Hydraulic Conditions for the Initiation of Piping" (2012). All Graduate Theses and Dissertations. Paper 1364. http://digitalcommons.usu.edu/etd/1364
[5] "What is Hydraulic Conductivity?" Preene Groundwater Consulting. July 8, 2014. Accessed August 7, 2015. http://www.preene.com/blog/2014/07/what-is-hydraulic-conductivity.
[6] Ibid

hydraulic conductivity of a soil layer often depends on whether the layer is subject to saturated or unsaturated conditions as well as vertical or horizontal movement. By correctly modeling the hydraulic conductivity of subsurface soil layers at a chemical spill site, one can determine the horizontal and vertical location of the chemical plume. If the plume can successfully be located, there is a significantly higher chance that the chemical contamination can intercepted for cleanup.

Flow Nets

According to Humboldt State University, "A flow net is a graphical solution to the equation of steady groundwater flow. A flow net consists of two sets of lines which must always be orthogonal (perpendicular to each other): flow lines, which show the direction of groundwater flow, and equipotential lines (lines of constant head), which show the distribution of potential energy."[7] Flow nets can be used to determine the quantity of seepage and upward lift pressure below hydraulic structures.

Equation 4: Flow Rates using Flow Nets

$$Q = \Delta H * K * \frac{n_f}{n_d}$$

Where Q is the flow rate, ΔH is the change in head, K is the hydraulic conductivity, n_f is the number of flow lines and n_d is the number of drops. The figure below demonstrates a constructed flow net and how to solve for flow rate.

---

[7] "Flow Nets for Homogeneous Isotropic Systems." Humboldt State University Geology Department. Accessed June 14, 2015.
http://www2.humboldt.edu/geology/courses/geology556/556_handouts/constructing_flow_nets.pdf.

Figure 1: Solving for Flow Rates using a Flow Net
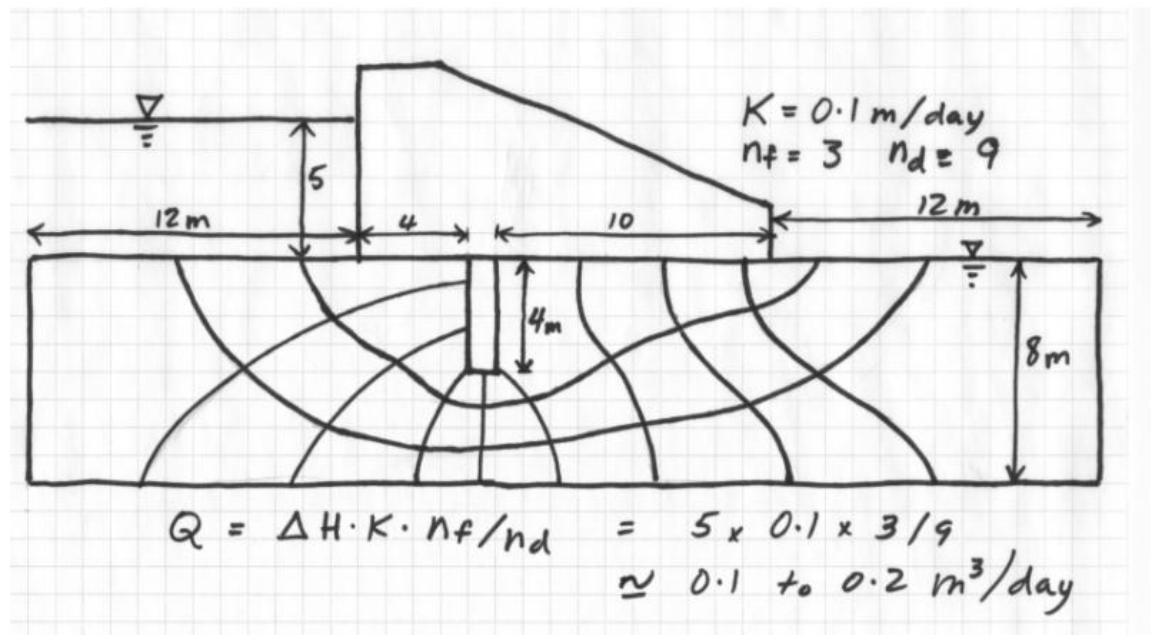
Source: Geo-Slope International Ltd.[8]

To determine the pressure at a specific point, determine the head loss along a flow line, head drop across a square, and the elevation at the point being evaluated. Use the following equation to solve.

Equation 5: Pressure at Specified Point

$$P_n = \gamma(h_n - z_n)$$

Where P is the pressure, γ is the unit weight of water, h_n is the head at point n, and z_n is the elevation at point n. The figure below demonstrates a constructed flow net and how to determine pressure at a specific point, e.

[8] "Seepage Modeling with SEEP/W." SEEP/W Manual. 2012. Accessed August 5, 2015.
http://downloads.geo-slope.com/geostudioresources/8/0/6/books/seep modeling.pdf?v=8.0.7.6129.

Figure 2: Solving for Pressure at a Specific Point using Flow Nets

EXAMPLE: FLOW BENEATH A SHEET PILE COFFER DAM
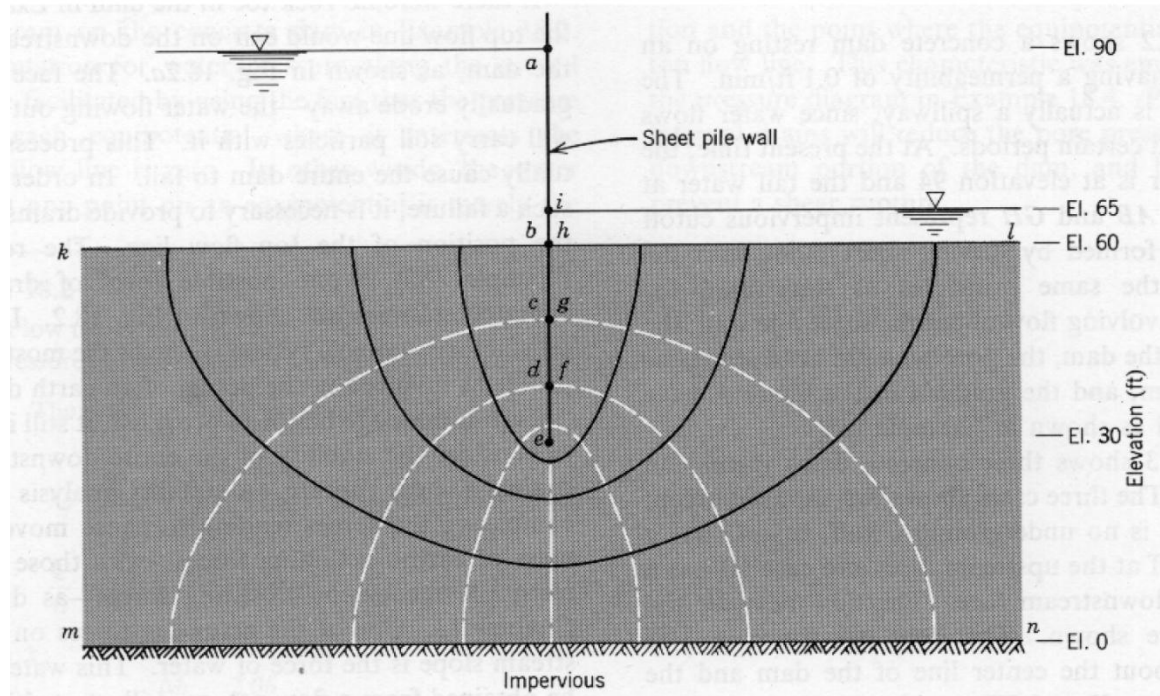
Source: Humboldt State University[9]

The following step-by-step walkthrough is provided to assist with understanding how to solve for pressure at a specific point utilizing a flow net.

1. Determine the total headless across the system:

$$\Delta h = 90ft - 65ft = 25\ ft$$

2. Determine the number of drops: $N_d = 8$

3. Determine the head drop across a square:

---

[9] "Flow Nets for Homogeneous Isotropic Systems." 2015. Accessed August 5, 2015.
http://www2.humboldt.edu/geology/courses/geology556/556_handouts/constructing_flow_nets.pdf.

$$h_d = \frac{\Delta h}{N_d} = \frac{25ft}{8} = 3.125 \; ft \rightarrow h_e = 77.5 \; ft$$

4. Determine the elevation at point e: $z_e = 30$ ft

5. Solve for pressure using Equation 5:

$$P_e = \left(\frac{62.4 \; lb}{ft}\right)(77.5 \; ft - 30 \; ft) = 2964 \; lb/ft^2$$

Note: Example provided by Humboldt State University.[10]

---

[10] Ibid

MODULE 2: DETERMINING HYDRAULIC CONDUCTIVITY

As discussed in Module 1, hydraulic conductivity plays an important role in a variety of applications and scenarios. Module 2 provides information on how to approximate or determine the hydraulic conductivity of various soil types using field methods, empirical methods, and laboratory testing.

Field Method

One reliable and easy way to determine the hydraulic conductivity in the field is to use the Auger-hole Method. The Auger-hole Method obtains the average hydraulic conductivity of soil layers extending from the water table.[11] This is done by boring a hole into the soil to a finite depth below the water table; groundwater seeps into the hole and reaches equilibrium.[12] The water in the hole is then removed and water begins to seep back into the hole.[13] "The rate at which the water rises in the hole is measured and then converted by a suitable formula to the hydraulic conductivity for the soil."[14] Since the auger-hole method is rarely used for determining hydraulic conductivity compared to empirical and laboratory methods, the methodology is excluded in the scope of this thesis.

---

[11] Beers, W. F. J. Van. The Auger Hole Method: A Field Measurement of the Hydraulic Conductivity of Soil below the Water Table. 6th ed. Wageningen, the Netherlands: International Institute for Land Reclamation and Improvement, 1983.
[12] Ibid
[13] Ibid
[14] Ibid

10

Empirical Method

Hazen's Approximation is an empirical relation between hydraulic conductivity with grain size and is shown below in the following equation.

Equation 6: Hazen Equation (Hazen's Approximation)

$$k \approx C(D_{10})^2$$

Where C is a constant (for simplicity purposes use C=1) and D_{10} is the diameter (effective size), in mm, of the 10th percentile grain size of the sample. The following table provides the hydraulic conductivity for various soil types using Hazen's Approximation.

Table 1: Hazen's Approximation

Material	k (cm/sec)	Effective Size, D_{10} (mm)
Uniform coarse sand	0.4	0.6
Uniform medium sand	0.1	0.3
Clean, well-graded sand and gravel	0.01	0.1
Uniform, fine sand	4×10^{-3}	0.06
Well-graded, silty sand and gravel	4×10^{-4}	0.02
Silty sand	10^{-4}	0.01
Uniform silt	5×10^{-5}	0.006
Sandy clay	5×10^{-6}	0.002
Silty clay	10^{-6}	0.0015
Clay (30% to 50% clay size)	10^{-7}	0.0008
Colloidal clay (minus 2 μm ≥ 50%)	10^{-9}	40 Å $= 4 \times 10^{-6}$

Source: T. R. West[15]

According to the Center for Hydrologic Science, "the Hazen equation yields hydraulic conductivities values that are much too high (when the coefficient C=1)." Hazen's Approximation is just that, an approximation, and values should be approached with

---

[15] West, Terry. "Elements of Soil Mechanics." In Geology Applied to Engineering, 506. 1st ed. Upper Saddle River, New Jersey: Prentice Hall, 1995.

caution, especially when conducting a seepage analysis where the implications of using incorrect values for hydraulic conductivity are significant.

Laboratory Methods

When conducting a seepage analysis, measurement of hydraulic conductivity is often performed on soil samples collected from the field. There are two common tests for measuring hydraulic conductivity in a laboratory setting: the Constant Head Permeability Test and the Falling Head Permeability Test. The Constant Head Permeability Test is preferred for soils with $k > 10^{-3}$ cm/sec (granular soils), and the Falling Head Test is preferred for soils with $k < 10^{-5}$ cm/sec (fine grained soils). For a detailed procedure on how to conduct Constant Head and Falling Head Permeability Tests, refer to ASTM D5084-03.[16]

Constant Head Permeability Test

The constant head permeability test is based on the following equation.

Equation 7: Constant Head Permeability Equation

$$\frac{Q}{t} = Av$$

Where Q is the flow rate, t is time, A is the cross-sectional area and v is the flow velocity.

Flow velocity is measured using Darcy's Law.

Equation 8: Constant Head Permeability Equation for Flow Velocity

[16] ASTM D5084-03, Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter, ASTM International, West Conshohocken, PA, 2003, www.astm.org

$$v = ki = k\frac{h}{L}$$

Where i = h/l and h is the change in hydraulic head over a specific length L.

Solving for k yields the following.

Equation 8: Constant Head Permeability Equation for Hydraulic Conductivity

$$k = \frac{QL}{Aht}$$

Where k is the hydraulic conductivity, Q is the flow rate, L is the length of the specimen, A is the cross-sectional area, h is the difference in head, and t is time.

Falling Head Permeability Test

Falling-head Method: The falling head permeability test is based on the following equation.

Equation 9: Falling-head Permeability Equation for Hydraulic Conductivity

$$k = \frac{2.3aL}{At}log\left(\frac{h_1}{h_2}\right)$$

Where k is the hydraulic conductivity, a is the cross-sectional area of the supply reservoir, L is the length of the soil specimen, A is the cross-sectional area of the soil specimen, t is time, and h_1 is the hydraulic head at time zero, and h_2 is the hydraulic head at time, t.

Equivalent Hydraulic Conductivity

In locations where subsurface conditions have stratified soil, the horizontal and vertical hydraulic conductivities of different soil layers can be different. In cases where hydraulic

13

conductivity is used to determine flux across a soil media, the equivalent hydraulic conductivity of the entire soil mass can be determined. The equivalent hydraulic conductivity will produce the same discharge as that of determining the hydraulic conductivity of each individual soil layer in a system, then adding them together. When calculating the equivalent hydraulic conductivity of a soil mass, it is necessary to calculate the horizontal and vertical equivalent hydraulic conductivity individually.

Horizontal Equivalent Hydraulic Conductivity

Equation 10: Horizontal Equivalent Hydraulic Conductivity

$$k_{h(eq)} = \frac{1}{Z}(k_{h_1}dz_1 + k_{h_2}dz_2 + \cdots + K_{h_n}dz_n)$$

Where $k_{h(eq)}$ is the equivalent horizontal hydraulic conductivity, Z is the total depth of the soil mass, K_h is the horizontal hydraulic conductivity of an individual soil layer, and dz is the depth of an individual soil layer.

Figure 3: Horizontal Equivalent Hydraulic Conductivity
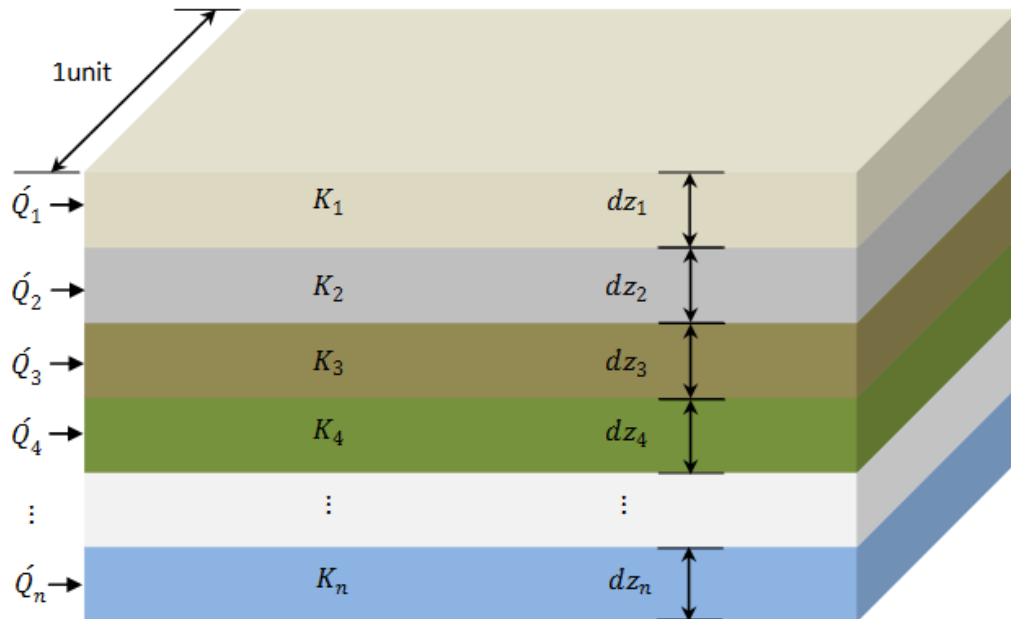
Source: National Program on Technology Enhanced Learning[17]

Vertical Equivalent Hydraulic Conductivity

Equation 11: Vertical Equivalent Hydraulic Conductivity

$$k_{v(eq)} = \frac{X}{\dfrac{dx_1}{k_{v_1}} + \dfrac{dx_2}{k_{v_2}} + \cdots + \dfrac{dx_n}{k_{v_n}}}$$

Where $K_{v(eq)}$ is the equivalent vertical hydraulic conductivity, X is the length of a soil mass, K_v is the vertical hydraulic conductivity of an individual soil layer, and dx is the length of an individual soil layer.

---

[17] "National Program on Technology Enhanced Learning." Module 2: Movement of Groundwater; Lecture 5: Equivalent Hydraulic Conductivity. Accessed August 5, 2015. http://nptel.ac.in/courses/105103026/5

Figure 4: Vertical Equivalent Hydraulic Conductivity

Ratio of Equivalent Hydraulic Conductivity

Equation 12: Ratio of Equivalent Hydraulic Conductivity

$$\frac{k_{h(eq)}}{k_{v(eq)}}$$

The inverse of the equivalent hydraulic conductivity ratio is called the anisotropic ratio and is used in SEEP/W to more accurately model groundwater seepage. Since both the equivalent hydraulic conductivity ratio and anisotropic ratio are often used in groundwater seepage models, it is important to distinguish between the two to ensure that the correct value is being utilized.

---

[18] Ibid

Typical Values for Hydraulic Conductivity

To provide a better understanding of how hydraulic conductivity relates to soil type, typical values for hydraulic conductivity are provided in the following tables.

Table 2: Hydraulic Conductivity Categorization by Degree of Permeability

Degree of Permeability	Hydraulic Conductivity (cm/sec)
High	Greater than 10^{-1}
Medium	10^{-1} to 10^{-3}
Low	10^{-3} to 10^{-5}
Very Low	10^{-5} to 10^{-7}
Practically Impermeable	Less than 10^{-7}

Source: Terzaghi and Peck 1967[19]

---

[19] Terzaghi, Karl, Ralph Peck, and Gholamreza Mesri. Soil Mechanics in Engineering Practice. 3rd ed. New York, New York: John Wiley & Sons, 1996.

Table 3: Hydraulic Conductivity Categorization by Soil Type

Coefficient of Permeability k in cm per sec (log scale)											
10^2	10^1	1.0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}

Drainage	Good						Poor		Practically Impervious		
Soil types	Clean gravel		Clean sands, clean sand and gravel mixtures			Very fine sands, organic and inorganic silts, mixtures of sand silt and clay, glacial till, stratified clay deposits, etc.				"Impervious" soils, e.g., homogeneous clays below zone of weathering		
					"Impervious" soils modified by effects of vegetation and weathering							
Direct determination of k	Direct testing of soil in its original position—pumping tests. Reliable if properly conducted. Considerable experience required											
	Constant-head permeameter. Little experience required											
Indirect determination of k			Falling-head permeameter. Reliable. Little experience required			Falling-head permeameter. Unreliable. Much experience required			Falling-head permeameter. Fairly reliable. Considerable experience necessary		
	Computation from grain-size distribution. Applicable only to clean cohesionless sands and gravels								Computation based on results of consolidation tests. Reliable. Considerable experience required		

Source: Terzaghi and Peck 1967[20]

---

[20] Ibid

Table 4: USBR Hydraulic Conductivity Categorization by Natural Soil Type

Permeability k_H of Unconsolidated Natural Soils
(k_H inversely related to % finer grains)

Soil	k_H Range (ft/yr or 10^{-6} cm/s)
Gravel, open-work	>2,000,000
Gravel (GP)	200,000 to 2,000,000
Gravel (GW)	10,000 to 1,000,000
Sand, coarse (SP)	10,000 to 500,000
Sand, medium (SP)	1,000 to 100,000
Sand, fine (SP)	500 to 50,000
Sand (SW)	100 to 50,000
Sand, silty (SM)	100 to 10,000
Sand, clayey (SC)	1 to 1,000
Silt (ML)	1 to 1,000
Clay (CL)	~0 to 3

References: [15], [18], [22-29], [33-36]

Permeability k_H of Unfractured Rock
(k_H increases with pore size)

Rock	k_H Range (ft/yr or 10^{-6} cm/s)
Sandstone, medium	100 to 200,000
Sandstone, silty	~0 to 5,000
Limestone	~0 to 15,000
Granite, weathered	200 to 10,000
Schist	~0 to 2,000
Tuff	~0 to 1,000
Gabbro, weathered	50 to 500
Basalt	~0 to 50
Dolomite	~0 to 5
Gneiss	~0 to 2

References: [15], [25], [27-28], [34], [36]

Anisotropy of Natural Soil and Rock

Formation	k_H/k_V	Remarks
Stratified deposits	10 to 1,000	k_H/k_V depends on grain size of substrata
Massive soil or rock	1 to 3	Depends on particle shape and orientation
Fractured rock	0.1 to 10	Depends on aperture arrangement
Eolian soil (loess and dune)	0.02 to 2	Depends on consolidation

References: [3], [15], [17], [19-21], [24], [30-31], [35-42]

Source: USBR 2011[21]

---

[21] U.S. Bureau of Reclamation (2011). "Chapter 8: Seepage." Design Standards No. 13; Embankment Dams, October.

Table 5: USBR Hydraulic Conductivity Categorization by Embankment Soil Type

Permeability (k_V) of Embankment Core Materials (k_V inversely related to % fines)

Unified Soil Classification	k_V Range (ft/yr or $\times 10^{-6}$ cm/s)*
GM-SM	0.0 to 10.0
GM or GC	0.0 to 10.0
SP-SM	0.0 to 10.0
SM	0.0 to 10.0
SM-SC	0.0 to 3.0
SM-ML	0.0 to 10.0
SC	0.0 to 3.0
ML	0.0 to 10.0
ML-CL	0.0 to 1.0
CL	0.0 to 1.0
MH	0.0 to 0.1

References: [31-32], [34], [44-45]
* Based primarily on Reclamation laboratory test data

Permeability (k_V) of Embankment Shell Materials (k_V inversely related to % fines)

Unified Soil Classification	k_V Range (ft/yr or $\times 10^{-6}$ cm/s)
GP	2,000 to 1,000,000
GW	1,000 to 100,000
GP-SP	1,000 to 50,000
GW-SW	500 to 5,000
GM	10 to 500
SP (medium to coarse)	10,000 to 20,000
SP (fine to medium)	5,000 to 10,000
SP (very fine to fine)	500 to 5,000
SW	300 to 5,000
SP-SM	10 to 1,000
SM	10 to 500

References: [18], [26], [33], [36], [44-45]

Permeability (k_V) of Washed Embankment Drain Materials (k_V increases with grain size)

Material	k_V Range (ft/yr or $\times 10^{-6}$ cm/s)
Coarse sand and gravel	150,000 to 500,000
Medium to coarse sand	50,000 to 150,000
Fine to medium sand	10,000 to 50,000

References: [18], [26], [33], [36], [45]

Anisotropy (k_H/k_V) of embankment materials (k_H/k_V increases with placement water content)

Material	k_H/k_V Range
Embankment core Reclamation standard placement	4 to 9
Nonstandard placement	9 to 36
Hydraulic fill	64 to 225
Embankment shell Reclamation standard	4 to 9
Embankment drains Reclamation standard	1 to 4

References: [3], [17], [21], [31], [37]

Source USBR 2011[22]

---

[22] Ibid

MODULE 3: GEOSTUDIO SEEP/W

According to Geo-Slope International (Geo-Slope), "SEEP/W is a finite element CAD software product for analyzing groundwater seepage and excess pore-water pressure dissipation problems within porous materials such as soil and rock. Its comprehensive formulation allows for one to consider analyses ranging from simple, saturated steady-state problems to sophisticated, saturated/unsaturated time-depended program. SEEP/W can be applied to the analyses and design of geotechnical, civil, hydrogeological, and mining engineering products."[23] In other words, SEEP/W is a useful tool that uses numerical modeling to solve complex groundwater seepage problems.

Module 3 is designed to teach students how to setup and model steady-state seepage through a system utilizing SEEP/W. This module will directly reference sections and page numbers in the SEEP/W engineering manual, "Seepage Modeling with SEEP/W," provided as supplementary material.

Analysis Types

There are two fundamental types of seepage analysis: steady state and transient. A steady-state seepage analysis is an analysis type where water pressures and water flow rates do not change with time. Since steady-state analyses ignore the time domain, it greatly

---

[23] Geo-Slope International, "SEEP/W 2012 Groundwater Seepage Analysis". Accessed June 22, 2015.
http://www.geo-slope.com/products/seepw.aspx

simplifies the equations being solved. A transient analysis, on the other hand, has pressure conditions that change with time. In general, a transient analysis can provide more accurate results when soil conditions are modeled, however, they are significantly more complicated than steady-state analyses. Both the initial conditions as well as future boundary conditions must be provided. If the initial or future conditions are not accurately represented, the analysis will provide inaccurate results. Since this thesis is considered a primer for understanding seepage analysis, transient analysis is not included in the scope and the steady-state analysis type will be the sole focus.

When developing a numerical steady-state model using SEEP/W, one must determine geometry, assign materials, assign boundary conditions, then review and fine tune the finite element mesh.[24]

For more information steady-state seepage analyses, review, page 107 and 108 in the SEEP/W Engineering Manual, "Seepage Modeling with SEEP/W,"

<div align="center">Soil Geometry</div>

The first step to determine soil geometry is to create a scale model of the cross-section of the system being evaluated. The second step is to define soil regions to the cross-section. Both steps are described below in detail.

Creating Cross-section

There are two features that will allow the user to create a cross-section in SEEP/W. The first feature utilizes the DRAW function to create lines that make up the geometry. This can be an easy tool for creating cross-sections where the user wants to simplify geometry.

---

[24] "GeoStudio 2012: SEEP/W Tutorial." YouTube. December 16, 2014. Accessed June 22, 2015. https://www.youtube.com/watch?v=5lYnf1bYDRs

The second feature uses the KEYIN function to manually enter points along a cross-section. This feature can be more time consuming, but is useful if the user wants to define actual contours derived from topographic mapping. Step-by-step instructions to create a cross-section utilizing the KEYIN function are provided below:

1. Utilize the KEYIN function and click on POINTS.

2. Establish a datum along the cross-section and record its elevation in the Y column; the X column will be zero since it represents the datum.

3. Find the cross-section location on a topographic map and document the elevation and horizontal distance from the datum in the KEYIN POINTS table. In general utilize two-foot intervals for elevation and record its associated horizontal distance from datum. The horizontal distance can be both a positive or negative value based on direction.

4. Utilize boring logs, obtained from a geotechnical investigation, to mark boundary locations between soil layers and document the elevation and horizontal distance from the established datum in the KEYIN POINTS table.

5. Once the points are entered the points should now display in SEEP/W.

6. Additional points may be required to carry out boundary conditions of subsurface layers to the extent of the domain. In other words, borings may not be located directly on the boundary of the domain, therefore, the user must carry the soil layer elevation all the way to the boundary.

Creating Regions

Regions are created by connecting points and are used to define areas of different material properties and conditions. Step-by-step instructions on how to create a region are provided below:

1. Utilize the DRAW function and click on REGION. This will allow the user to create a polygon that connect points defined in the previous section. The user can "snap" to nearby points or create a new point if one is not defined nearby by simply left-clicking with the mouse. Regions can also be created by utilizing the KEYIN function and clicking on REGION. This feature will allow the user to manually enter specific points to define a region.

2. To close the polygon, click on the first point defined in the region, or right-click with the mouse. Each polygon created should define a specific material layer within the cross-section. The physical dimensions of each soil layer should be derived from subsurface boring information and available record drawings of the site.

3. Define the remaining material layers in the model by creating additional regions. In general, there should be a region for each material type (e.g. clay, sand, granular backfill, impervious concrete/grout). Additional regions should be defined and modeled if material properties change dramatically within a soil type (e.g. lean vs. fat clay, alluvial clay vs. compacted clay).

It is important to note that regions cannot overlap one another and must maintain continuity (no gaps). If regions overlap or do not form a complete polygon (gaps are present), the analysis will be unsolvable until corrected.

For more information on soil geometry, review page 16 and Chapter 3 in the SEEP/W Engineering Manual, "Seepage Modeling with SEEP/W."

Assign Materials

The next step in developing a numerical model in SEEP/W is to assign materials to the regions defined in the previous subsection. Step-by-step instructions to assign materials are provided below.

1. Utilize the KEYIN function and click on MATERIALS. Add a new material, provide it a name (e.g. Alluvial Clay, Compacted Clay, Alluvial Sand, Riprap) and assign it a color.

2. Use the material model dropdown menu to select one of the options:

   a. Saturated Only – Use if a steady state analysis is conducted on a domain that will remain saturated for the entire duration of the simulation.[25]

   b. Saturated/Unsaturated – Use if unsaturated zones are expected to occur.[26]

   c. Interface – Use for materials with a hydraulic conductivity value of zero (e.g. impermeable cutoff wall below a dam).[27] Note that this function is not available in the student version of SEEP/W.

3. If the Saturated Only option is chosen, provide the saturated hydraulic conductivity, anisotropy, saturated water content volume, and the coefficient of volume compressibility (Mv) for each material.

---

[25] Ibid

[26] Ibid

[27] "Detailed Example: Cutoff Trench." Geo-Slope International: Direct Contact Volume 6, Issue 1.January 2010. Accessed June 28, 2015.
http://www.geo-slope.com/contact/directcontact_jan10.aspx

If the Saturated/Unsaturated option is chosen, you will have an option to provide a function for the volumetric water content and hydraulic conductivity. For steady-state analyses, it is not required to provide a volumetric water content function since there is no change in storage within the domain.[28] However, a volumetric water content function is used to for internal estimation algorithms for the hydraulic conductivity function.[29] Therefore, it will be necessary to develop a volumetric water content function for the sole purpose of developing a hydraulic conductivity function.

4. To create a volumetric water content function, follow the steps below:

    a. Click on the ellipsis button next to the Vol. Water Content Fn. and assign the function material type to its corresponding name (e.g. Alluvial Clay, Alluvial Sand).

    b. From the TYPES dropdown menu, choose the VOL WC DATA POINT FUNCTION option and click on ESTIMATE.

    c. Use the SAMPLE FUNCTIONS option from the estimation method dropdown menu and provide a Saturated WC and select the sample material from the dropdown menu. The suction range values can be changed based on preference, but generally a minimum suction of 0.01, a maximum suction of 1,000 and the number of points to be 20 will suffice for an analysis.

---

[28] "GeoStudio 2012: SEEP/W Tutorial." YouTube. December 16, 2014. Accessed June 22, 2015. https://www.youtube.com/watch?v=5lYnf1bYDRs
[29] Ibid

d. Repeat steps A through C for each material type in the steady-state analysis.

e. The data points can be edited by clicking the EDIT DATA POINTS option. Points can be moved, added, and/or deleted.

f. Once a desired function is created for each material type, choose the corresponding function for each material type from the VOL WATER CONTENT FN dropdown menu.

5. To create a hydraulic conductivity function, follow the steps below:

a. Click on the ellipsis button next to the Hyd. Conductivity Fn and provide it with one of the names created in Step 4.

b. From the TYPES dropdown menu, choose the HYDR DATA POINT FUINCTION option and click on ESTIMATE.

c. Two estimation methods can be chosen for the hydraulic conductivity function: Fredlund & Xing or Van Genuchten Method. For the Fredlund & Xing Method, choose the associated Vol. Water Content Function developed in Step 4 from the dropdown menu, provide a saturated hydraulic conductivity value. Again the suction range values can be changed based on preference, but generally a minimum suction of 0.01, maximum suction of 1,000 and number of points to be 20 will suffice for an analysis. For the Van Genuchten Method, follow the same steps as the Fredlund & Xing Method and add a Residual Water Content value.

d. Repeat Steps A through C for each material type in the steady state analysis.

6. Now that the parameters are set for each material type, you can now assign a material for each region developed in the "Soil Geometry" section by following the steps below:

   a. Utilize the DRAW function and click on MATERIALS. Pick a material type from the ASSIGN dropdown menu and click on the associated region.

   b. Repeat step A for each material type.

   Each region should now display a color that corresponds to its defined material type. The analysis now recognizes different material properties for each region based on the parameters entered in the previous steps.

For more information on assigning materials and material properties, review Chapter 4 in the SEEP/W Engineering Manual, "Seepage Modeling with SEEP/W,"

Assign Boundary Conditions

The next step in performing a seepage analysis in SEEP/W is to assign boundary conditions. Setting up the boundary conditions in the model is an essential component as the solution is dependent upon the type of boundary conditions defined in the model. As stated in the SEEP/W manual provided as a supplementary document along with this thesis, "Boundary conditions can only be one of two fundamental options – you can specify H (head) or Q (total flux)." For simplicity purposes a few, fundamental types of boundary conditions are described below.

1. Potential Seepage Face – A boundary condition where both the head and total flux are unknown along a slope. This allows the solver to locate the position where a seepage face may develop.[30]

2. Head – A boundary condition used where there is free water present within the domain such as a reservoir behind a dam, or a river on the flood side of a dike.

3. Zero Pressure – A boundary condition used to model a drains and areas where pore-water pressure dissipates near instantly.

To setup the boundary conditions for a model, follow the steps below.

1. Utilize the KEYIN function and choose BOUNDARY CONDITIONS to open the define boundary conditions window.

2. Click on one of the default options or click on ADD to add a new hydraulic boundary condition.

   a. To setup a potential seepage face boundary condition, choose the TOTAL FLUX (Q) option from the TYPE dropdown menu and check the box POTENTIAL SEEPAGE FACE REVIEW option.

   b. To setup a head boundary condition, choose the HEAD (H) option from the dropdown menu. Choose the CONSTANT HEAD option and define the specific pool elevation you are utilizing for the analysis (e.g. normal pool elevation, 100 year flood, 500 year flood).

3. To define the boundary condition on the model, utilize the DRAW function and selection BOUNDARY CONDITION. Select one of the boundary conditions

---

[30] Ibid

defined in Step 2 and click on the face where the boundary condition exists. Repeat this step to define all boundary conditions across the model.

A simple example of where two boundary conditions would be located can be demonstrated along a cross-section of a dam. The reservoir side would have a boundary condition between the pool and the soil media and the entire downstream side of the dam would be the potential seepage face.

For more information on assigning boundary conditions, review Chapter 5 in the SEEP/W Engineering Manual, "Seepage Modeling with SEEP/W."

<center>Fine Tuning the Finite Element Mesh</center>

As stated earlier, SEEP/W uses finite element numerical modeling to solve groundwater problems. In order to solve these problems, SEEP/W divides the entire domain of the model into smaller, simpler parts known as discretization. This discretization is shown by viewing the finite element mesh. To view the finite element mesh, use the DRAW function and select MESH PROPERTIES. The default global element size is 5 feet. For some seepage problems, it may be necessary to create a finer discretization for the global mesh or at specific locations within the cross-section where there is likely changes in the phreatic surface (such as toe drain). To do this, highlight the line representing the location where you want a finer discretization. From the EDGE LENGTH dropdown menu, choose the LENGTH OF option and define the desired discretization value.

For more information on fine tuning the finite element mesh, review Chapter 3 in the SEEP/W Engineering Manual, "Seepage Modeling with SEEP/W."

MODULE 4: ANALYZING RESULTS

Developing and running seepage model in SEEP/W only represents half of the total analysis. The next step once the model is solved is to analyze the results and make conclusions. Before you can analyze the results, the user must ask, "Why is the seepage analysis being performed." Seepage analyses are often conducted for three major applications: calculating flow rates, gathering hydraulic gradient data for determining factors of safety against piping and to be used as a parent analysis for a slope stability analysis. Module 4 is discusses these applications and how SEEP/W can be used to analyze results.

Calculating Flow Rates

Knowing the flow rate through a dam can be very useful when it comes to designing sizes for pipes, pumps and drains within a system. A pipe, pump or drain too large can be costly and unnecessary to implement. On the other hand, a pipe, pump or drain that is too small will result in insufficient capacity and may cause significant problems (e.g. overflow, backup, increased pore-water pressure). SEEP/W can easily calculate flow rates through a section by drawing a FLUX SECTION across any plane of interest. When the analysis is solved, it will automatically calculate the flow rate through the defined section.

Computing Factors of Safety against Piping

One of the most critical areas of any dam is the downstream toe where blowouts, piping and excessive seepage can occur. Seepage analyses are often conducted to evaluate such areas for the potential for piping. There is no clear guidelines when it comes to picking a location to evaluate along the toe. However, a good place to start would be within a few feet of the phreatic surface and across soil layers near the ground surface, since many failure modes initiate in this region.

SEEP/W does not automatically compute factors of safety against piping, but it does provide seepage gradients at nodes within the finite element mesh; which provides the information required for computing factors of safety against piping. It is best not to calculate factors of safety from individual nodal points, but from the average hydraulic gradient over the entire surface being evaluated. Factors of safety for vertical and horizontal seepage exits must be computed independently and are described below.

Vertical Seepage Exit

In areas where water seeps vertically upward to a relatively level surface, the factor of safety against piping at the seepage exit can be evaluated using the equation below.

Equation 13: Factor of Safety against Vertical Piping

$$FS_{exit} = \frac{\downarrow \ gravitational \ pressure}{\uparrow seepage \ pressure}$$

For a soil prism measuring D by D/2 and having a unit thickness the seepage pressure and gravitational pressure is equal to the following.

Equation 14: Seepage Pressure

$$\uparrow seepage\ pressure = \frac{i\,\gamma_w(0.5D \cdot D)}{0.5\,D} = i\,\gamma_w\,D$$

Equation 15: Gravitational Pressure

$$\downarrow gravitational\ pressure = \frac{(\gamma_t - \gamma_w)(0.5D \cdot D)}{0.5\,D} = \gamma_{sub}D$$

Where i is the hydraulic gradient, γ_w is the unit weight of water, D is the depth and γ_{sub} is the submerged unit weight of the soil (the saturated unit weight minus the unit weight of water). Combining Equations 14 and 15 yields the following.

Equation 13: Factor of Safety against Vertical Piping

$$FS_{exit} = \frac{\gamma_{sub}}{i\,\gamma_w}$$

Based on the equation above it is evident that a higher value for hydraulic gradient will result in a lower factor of safety. A computed factor of safety of 1.5 can be acceptable for certain cases, however, that depends on how well the soil and seepage conditions are understood.[31] If you do not have a good understanding of soil and seepage conditions, factors of safety in the range of 2.5 to 5 is more appropriate to account for uncertainty.[32]

Horizontal Seepage Exit

In areas where water seeps horizontally along a seepage face, the horizontal factor of safety against piping can be evaluated using the equations for critical gradient and seepage gradient shown below.

[31] U.S. Army Corps of Engineers (1986). "Seepage Analysis and Control for Dams." EM 1110-2-1901, September 30.
[32] Ibid

Equation 14: Critical Gradient

$$i_{crit} = \left(\frac{\gamma_{sub}}{\gamma_w}\right)\left(\frac{\tan(\phi')\cos(\beta) - \sin(\beta)}{\cos(\beta - \alpha) + \tan(\phi')\sin(\beta - \alpha)}\right)$$

Where γ_{sub} is the submerged unit weight of the soil, γ_w is the unit weight of water, ϕ' is the drained friction angle, α is the seepage angle and β is the slope angle. The slope angle (β) and seepage angle (α) are defined in Figure 4.

Figure 5: Slope Angle (β) and Seepage Angle (α)
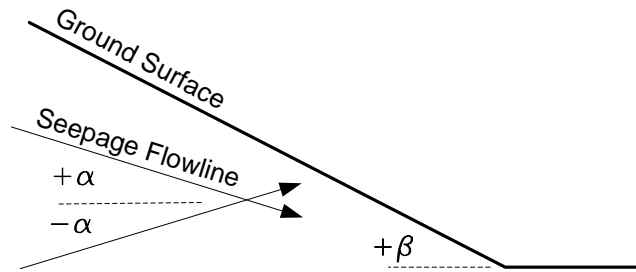
Source: G. Kovács 1981[33]

Equation 15: Seepage Gradient

$$i = \frac{\sin(\beta)}{\cos(\beta - \alpha)}$$

Where α is the seepage angle and β is the slope angle.

Combining Equations 14 and 15 yield the following equation.

[33] Kov.c s, György. 1981. Seepage hydraulics. Amsterdam: Elsevier Scientific Pub. Co. http://www.sciencedirect.com/science/book/9780444997555.

Equation 16: Factor of Safety against Horizontal Piping

$$FS_{exit} = \frac{i_{crit}}{i}$$

It is important to note that the factor of safety against horizontal piping is computed using the vector magnitude of the seepage gradient at the exit (not the horizontal component).

Stability Analysis

Stability analyses lie outside the scope of this thesis, however, one of the most common applications for developing a seepage model in SEEP/W is to utilize it as a parent analysis for a slope stability model in SLOPE/W. Since it is among the most common applications, this subsection will briefly discuss how to utilize SEEP/W as a parent analysis for a SLOPE/W analysis.

The major benefit to developing a seepage model for the purpose of utilizing it as a parent analysis for a slope stability model is that it allows for a more accurate representation of groundwater seepage conditions. As discussed in Module 1, hydraulic conductivity plays an essential role in slope stability problems. Therefore, modeling the groundwater condition in SEEP/W can provide more precise results for a slope stability model.

To add a SLOPE/W model to an existing SEEP/W model, simply go to the KEYIN ANALYSIS menu and add a SLOPE/W model to the analysis tree underneath the SEEP/W model. If you choose to use SEEP/W as a parent analysis, it is important to remember that slope stability results are dependent upon the results of the seepage model,

therefore, it will be necessary to develop pa seepage model prior to developing a slope stability model.

In SLOPE/W models, the major component that must be considered when analyzing the results is the lowest factor of safety computed for slope stability. Typically a factor of safety of 1.5 is an acceptable value for stability application.

MODULE 5: SEEP/W EXAMPLES

Module 5 provides a few examples of how to conduct a steady-state seepage analysis in SEEP/W for the purpose of demonstrating the usefulness of SEEP/W to solve various seepage problems.

Example 1 shows how to determine flow rates through a dam utilizing SEEP/W. A step-by-step walkthrough of how to conduct the analysis is provided as a PowerPoint presentation attached with this thesis. Audio is provided in the PowerPoint presentation to assist with understanding the steps completed.

Examples 2 demonstrates how to determine the factor of safety against vertical piping along the downstream toe of a dam utilizing hydraulic gradient values obtained from a SEEP/W model. Example 3 compares piezometric conditions and pore-water pressure distribution of two different systems: one system that does not utilize any drain systems within the dam, and one system that utilizes a chimney filter drain and toe drain within the dam.

The examples demonstrated in Module 5, review the overall goals of the seepage analysis, provide a scenario and soil parameters for setting up the model, discuss how results are obtained, and then finally offer conclusions based on the obtained results.

Example 1: Flow Rate through a Dam

Goal: Develop a steady-state seepage model in SEEP/W to determine the amount of flow through a dam's centerline. Additionally, determine the amount of flow through the alluvial foundation to a depth of 10 feet below the original ground line directly below the toe of the dam.

1. Scenario: A 50 foot high earthen clay dam is constructed on alluvial clay with 2H:1V side slopes and a 25 foot wide crest. The dam retains water in a reservoir with a pool elevation of 40 feet. Use the following soil parameters for the model.

Alluvial Clay Soil Parameters:

Anisotropy (Ky/Kx Ratio) = 0.1

Saturated Water Content = 0.4 ft^3/ft^3

Saturated Horizontal Hydraulic Conductivity = $1x10^{-6}$ ft/sec

Clay Embankment Soil Parameters:

Anisotropy (Ky/Kx Ratio) = 0.2

Saturated Water Content = 0.48 ft^3/ft^3

Saturated Horizontal Hydraulic Conductivity = $1x10^{-8}$ ft/sec

Analysis: Refer to the Example 1 PowerPoint presentation submitted with this thesis for a step-by-step walkthrough of the SEEP/W setup and analysis.

Conclusion: Using SEEP/W, it was determined that the total flow rate through the dam's center is $7.392x10^{-8}$ ft^3/sec and the total flow rate through the alluvium directly below the

toe of the dam to a depth of 10 feet was 2.2912×10^{-6} ft^3/sec (see Figure 6). These flow rates could be used to assist with sizing a graded filter drain within dam and/or a graded toe drain.

Figure 6: Example 1 Flux Results
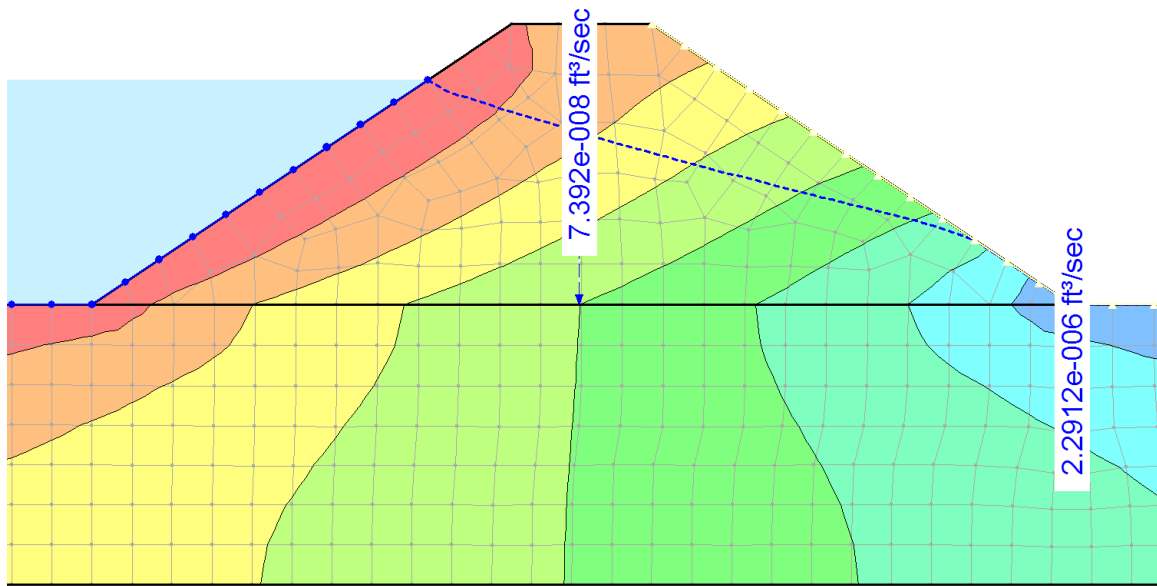
Example 2: Factor of Safety against Vertical Piping

Goal: Develop a steady-state seepage model in SEEP/W and determine the average vertical hydraulic gradient along the downstream horizontal surface of the dam. Utilize nodes that lie within the first 30 feet of the downstream end of the dam, up to a depth of 10 feet for computing the average vertical hydraulic gradient. Once the average vertical hydraulic gradient is determined, calculate the factor of safety against vertical piping along the downstream toe of the dam.

Scenario: A 50 foot high earthen clay dam is constructed on alluvial clay with 2H:1V side slopes and a 25 foot wide crest. The dam retains water in a reservoir with a pool elevation of 40 feet. Use the following soil parameters for the seepage model.

Alluvial Clay Soil Parameters:

Anisotropy (Ky/Kx Ratio) = 0.1

Saturated Water Content = 0.4 ft^3/ft^3

Saturated Horizontal Hydraulic Conductivity = $1x10^{-6}$ ft/sec

Clay Embankment Soil Parameters:

Anisotropy (Ky/Kx Ratio) = 0.2

Saturated Water Content = 0.48 ft^3/ft^3

Saturated Horizontal Hydraulic Conductivity = $1x10^{-8}$ ft/sec

According to NAVFAC 7.01, the saturated unit weight of clay typically ranges between 94 and 133 lb/ft^3.[34] Since the saturated unit weight is not explicitly defined above, it will be necessary to calculate the factor of safety for both the maximum and minimum values in this range.

Analysis: The seepage model developed from Example 1 was utilized since soil parameters and geometry did not change. Ten nodes were evaluated along the first 30 feet of the downstream toe along surface and up to 10 feet of depth. The location of these nodes are shown in Figure 5.

---

[34] Naval Facilities Engineering Command (NAVFAC) (1986). Soil Mechanics. Design Manual 7.01, Alexandria, Virginia, September.

Figure 7: Example 2 Node Location for Vertical Hydraulic Gradient Evaluation
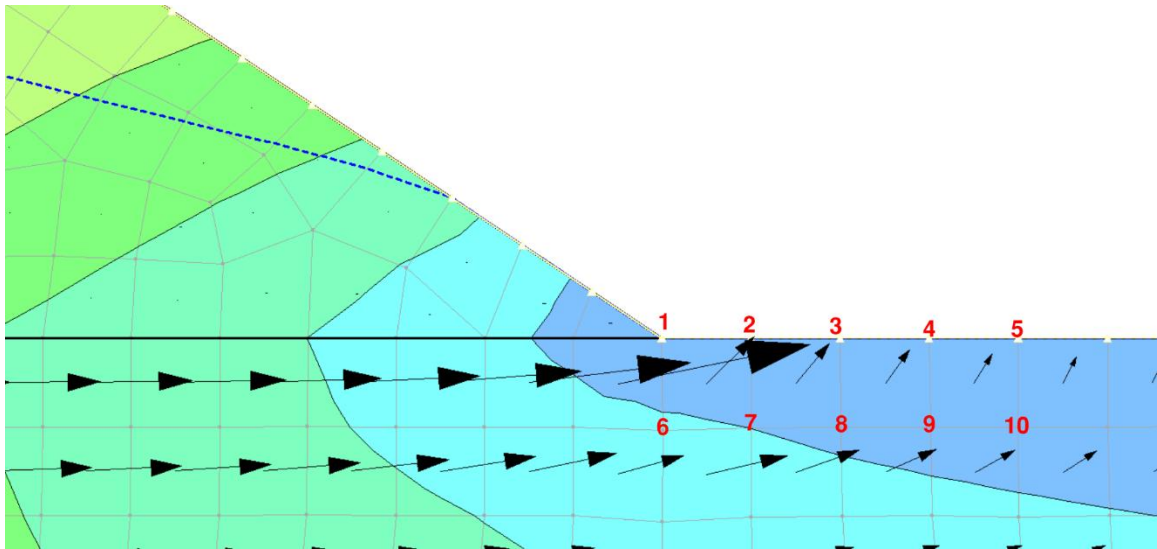
The vertical hydraulic gradients of each of the evaluated nodes are recorded in the following table.

Table 6: Example 2 Average Vertical Hydraulic Gradient

Node	Vertical Hydraulic Gradient
1	0.4787
2	0.6763
3	0.5689
4	0.4924
5	0.4365
6	0.5473
7	0.5090
8	0.4633
9	0.4221
10	0.3859
Average	**0.4980**

Using the average vertical hydraulic gradient of 0.4980, the factor of safety against vertical piping can be determined.

Determining the Factor of Safety against Vertical Piping (γ_{sat} = 133 lb/ft³)

Equation 17: Submerged Unit Weight (γ_{sat} = 133 lb/ft³)

$$\gamma_{sub} = \gamma_{sat} - \gamma_w = 133 - 62.4 = 70.6 \; lb/ft^3$$

Equation 18: Factor of Safety against Vertical Piping (γ_{sat} = 133 lb/ft³)

$$FS_{exit} = \frac{\gamma_{sub}}{i \; \gamma_w} = \frac{70.6 \; lb/ft^3}{0.4980(62.4 \; lb/ft^3)} = 2.2$$

Determining the Factor of Safety against Vertical Piping (γ_{sat} = 94 lb/ft³)

Equation 19: Submerged Unit Weight (γ_{sat} = 133 lb/ft³)

$$\gamma_{sub} = \gamma_{sat} - \gamma_w = 94 - 62.4 = 31.6 \; lb/ft^3$$

Equation 20: Factor of Safety against Vertical Piping (γ_{sat} = 133 lb/ft³)

$$FS_{exit} = \frac{\gamma_{sub}}{i \; \gamma_w} = \frac{31.6 \; lb/ft^3}{0.4980(62.4 \; lb/ft^3)} = 1.0$$

Conclusion: The factor of safety against vertical piping was determined to be 2.2 for a saturated unit weight of 133 lb/ft³ and 1.0 for a saturated unit weight of 94 lb/ft³. This demonstrates that a change in just a single soil parameter can have significant implications on the analysis. Since saturated unit weight was not explicitly defined in the required soil parameters, we do not have a good understanding of soil conditions. As it stands, you must consider there to be a substantial potential for vertical piping along the

toe of the dam. To gain a better understanding, additional laboratory tests are necessary to calculate the saturated unit weight.

Example 3: Model a Chimney Filter and Toe Drain

Goal: Develop a steady-state seepage model in SEEP/W that models the use of a chimney filter drain and toe drain within the dam. Observe how the phreatic surface behaves with the implementation of the drain system and compare the pore-water pressure distribution before and after the chimney filter and toe drain was implemented.

Scenario: There is seepage present along the toe of a dam. Construct a chimney filter and toe drain to intercept the seepage water prior to discharging along the toe. The chimney filter should begin 7.5 feet downstream from the center line and 5 feet below the surface of the crest and extend downstream at a 1:1 slope to the original ground line. The toe drain should begin at the bottom of the chimney filter and extend horizontally toward the toe of the dam. Utilize the following soil parameters for the seepage model.

Alluvial Clay Soil Parameters:

   Anisotropy (Ky/Kx Ratio) = 0.1

   Saturated Water Content = 0.4 ft^3/ft^3

   Saturated Horizontal Hydraulic Conductivity = $1x10^{-6}$ ft/sec

Clay Embankment Soil Parameters:

   Anisotropy (Ky/Kx Ratio) = 0.2

   Saturated Water Content = 0.48 ft^3/ft^3

   Saturated Horizontal Hydraulic Conductivity = $1x10^{-8}$ ft/sec

Analysis: The analysis from example 1 and 2 was utilized as a starting point since the soil parameters did not change. Refer to Module 5 PowerPoint presentation submitted with this thesis for a walkthrough on how the chimney filter and toe drain was modeled in SEEP/W.

Conclusion: By incorporating a chimney filter drain and toe drain within the seepage model, the phreatic surface change drastically. The phreatic surface moved horizontally from the pool elevation and was intercepted by the chimney filter drain where the zero pressure boundary conveyed the majority of seepage water through the drain. The chimney filter drain and toe drain lowered the phreatic surface and caused pore-water pressure along the downstream toe of the dam to become negative which eliminated the seepage face along the toe of the dam. Figures 8 and 9 show the pore-water distribution before and after the chimney filter drain and toe drain was implemented.

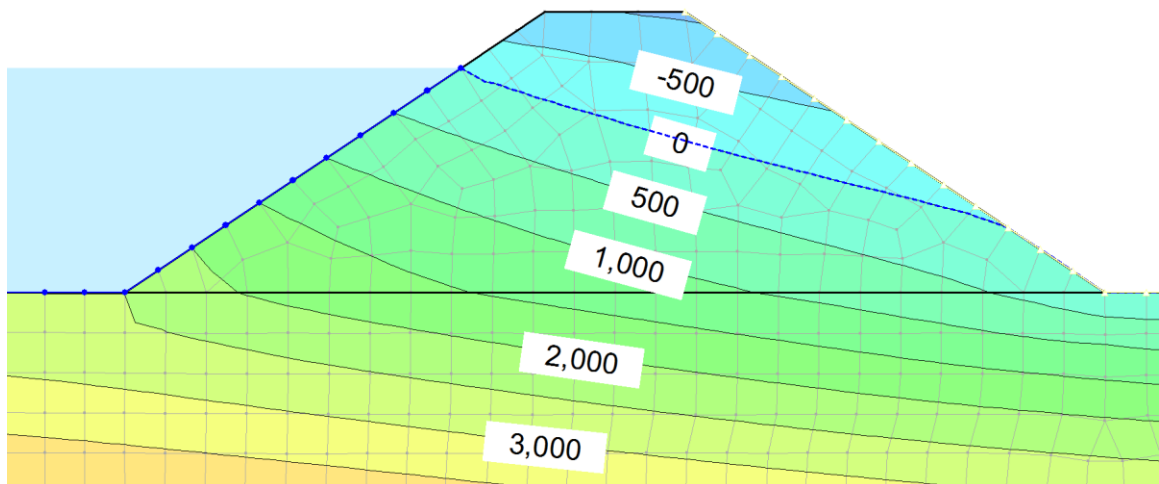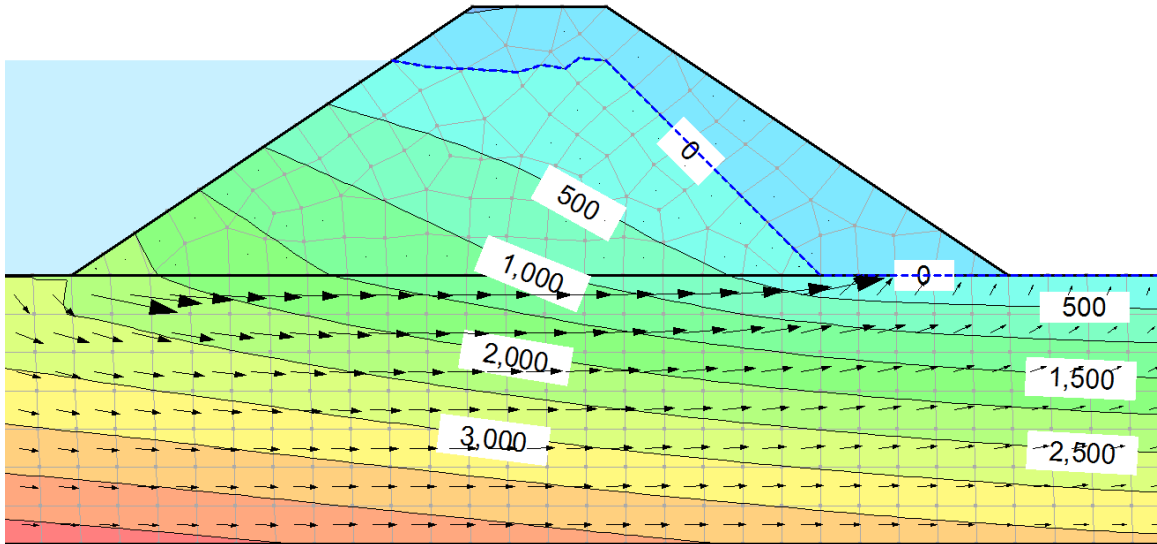Figure 8: Pore-water Pressure Distribution before Drains

Figure 9: Pore-water Pressure Distribution after Drains

CONCLUSION AND DISCUSSION

The modules developed above should provide a primer to understanding groundwater seepage, how to model groundwater seepage in SEEP/W and how to solve and analyze various groundwater seepage problems.

It is important to remember that the modules outlined in this thesis should not be considered an all-in-one guide to how to develop a steady-state seepage model, but rather a starting point for developing the skills to become further competent. The modules only scratch the surface when it comes to understanding groundwater movement and how to develop groundwater seepage models. There is a wealth of additional information not covered in this thesis regarding transient analyses, the relationship of groundwater seepage with slope stability, other SEEP/W analysis tools, and other geometric and material configurations.

Performing groundwater seepage analyses require significant engineering judgement and rely on many assumptions. To alleviate some of the uncertainty it is important to obtain subsurface material data from several sources (e.g. geotechnical boring logs, record drawings, laboratory experiments) in order to gain a better idea of subsurface conditions.

Regardless, even with the best data, the results obtained from a seepage analysis will fail to demonstrate the influence of fissures, discontinuities, and inclusions within a soil media which can significantly impact seepage behavior. Results should never be taken as exact and some considerable thought is necessary to determine the accuracy of any given model.

REFERENCES

ASTM D5084-03, Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter, ASTM International, West Conshohocken, PA, 2003, www.astm.org

Beers, W. F. J. Van. The Auger Hole Method: A Field Measurement of the Hydraulic Conductivity of Soil below the Water Table. 6th ed. Wageningen, the Netherlands: International Institute for Land Reclamation and Improvement, 1983.

"Detailed Example: Cutoff Trench." Geo-Slope International: Direct Contact Volume 6, Issue 1.January 2010. Accessed June 28, 2015. http://www.geo-slope.com/contact/directcontact_jan10.aspx

Fleshman, Mandie Swainston, "Laboratory Modeling of Critical Hydraulic Conditions for the Initiation of Piping" (2012). All Graduate Theses and Dissertations. Paper 1364. http://digitalcommons.usu.edu/etd/1364

"Flow Nets for Homogeneous Isotropic Systems." Humboldt State University Geology Department. Accessed June 14, 2015. http://www2.humboldt.edu/geology/courses/geology556/556_handouts/constructing_flow_nets.pdf.

Geo-Slope International, "SEEP/W 2012 Groundwater Seepage Analysis". Accessed June 22, 2015. http://www.geo-slope.com/products/seepw.aspx

"GeoStudio 2012: SEEP/W Tutorial." YouTube. December 16, 2014. Accessed June 22, 2015. https://www.youtube.com/watch?v=5lYnf1bYDRs

Kovács, György. 1981. Seepage hydraulics. Amsterdam: Elsevier Scientific Pub. Co. http://www.sciencedirect.com/science/book/9780444997555.

"National Program on Technology Enhanced Learning." Module 2: Movement of Groundwater; Lecture 5: Equivalent Hydraulic Conductivity. Accessed August 5, 2015. http://nptel.ac.in/courses/105103026/5

Naval Facilities Engineering Command (NAVFAC) (1986). Soil Mechanics. Design Manual 7.01, Alexandria, Virginia, September.

"Seepage Modeling with SEEP/W." SEEP/W Manual. 2012. Accessed August 5, 2015. http://downloads.geo-slope.com/geostudioresources/8/0/6/books/seepmodeling.pdf?v=8.0.7.6129.

Terzaghi, Karl, Ralph Peck, and Gholamreza Mesri. Soil Mechanics in Engineering Practice. 3rd ed. New York, New York: John Wiley & Sons, 1996.

U.S. Army Corps of Engineers (1986). "Seepage Analysis and Control for Dams." EM 1110-2-1901, September 30.

U.S. Bureau of Reclamation (2011). "Chapter 8: Seepage." Design Standards No. 13; Embankment Dams, October.

West, Terry. "Elements of Soil Mechanics." In Geology Applied to Engineering, 506. 1st ed. Upper Saddle River, New Jersey: Prentice Hall, 1995.

"What is Hydraulic Conductivity?" Preene Groundwater Consulting. July 8, 2014. Accessed August 7, 2015. http://www.preene.com/blog/2014/07/what-is-hydraulic-conductivity.

"What is Groundwater?" by Lyle S. Raymond, Jr., New York State Water Resources Institute Bulletin No. 1, Cornell University, 1988.

APPENDIX A: PERMISSION TO USE "SEEPAGE MODELING WITH SEEP/W"

The following is an e-mail correspondence granting Matthew Broaddus to utilize, "Seepage Modeling with SEEP/W" in its entirety as supplementary material for this thesis.

To: mrbroaddus@yahoo.com

From: pbryden@geo-slope.com

Dear Matt,

Please consider this email as permission to use the SEEP/W engineering book, "Seepage Modeling with SEEP/W" as discussed over the telephone on June 22, 2015. It is my understanding that you will be citing/including this publication in your thesis appendix.

Please contact me if you have any questions or require clarification.

Sincerely,

Paul

J. Paul Bryden, MBA
Vice President, Sales and Marketing
Geo-SLOPE International, LTD
Main: 1+ 403 269 2002

APPENDIX B: PERMISSION TO USE "BULLETIN NO. 1 WHAT IS GROUNDWATER?"

The following is an e-mail correspondence granting Matthew Broaddus to utilize, "Bulletin No. 1: What is Groundwater?" by Lyle S. Raymond in its entirety as supplementary material for this thesis.

To: mrbroaddus@yahoo.com

From: bgr4@cornell.edu

Mr. Broaddus,

Please go ahead and use any WRI documentation you find useful. Either including the material in its entirety or properly referencing it should be fine. If you don't mind, we'd love to know about your final product.

Cheers,

Brian

Brian G. Rahm
Research Associate
New York State Water Resource Institute
Department of Biological & Environmental Engineering
234 Riley-Robb Hall
Cornell University
607-254-7163

CURRICULUM VITA

NAME: Matthew Ryan Broaddus

ADDRESS: 10003 Glen Meadow Road
            Louisville, KY 40241

DOB: Louisville, Kentucky - May 31, 1990

EDUCTION
& TRAINING: B.S. Civil Engineering
                    University of Kentucky
                    2008-2013

                    M.S. Civil Engineering
                    University of Louisville
                    2014-2015