DEVELOPMENT OF A PERMEAMETER TO MEASURE THE HYDRAULIC CONDUCTIVITY OF CLAY LINERS BASED ON THE INITIAL SATURATION OF THE COMPACTED CLAY

Frank Atuahene, Georgia Southern University

Abstract

Clay liners consist of compacted clay and are used in structures such as landfills, underground storage tanks, dams and levees. The main attribute, desired in a quality clay liner, is a low permeability (hydraulic conductivity) of 10^{-9} m/s. The current instruments used to measure the hydraulic conductivity of clay liners are time-consuming and cumbersome both in the laboratory and the field, thus hindering faster and quality construction of clay liners. This paper will discuss the development of an instrument which measures the hydraulic conductivity of clay liners based on the soil property of the compacted clay, that is, the initial saturation (SI). This property was selected through statistical analysis of a number of experimentally measured hydraulic conductivity and the initial saturation (SI). The data was obtained from a published paper in a refereed journal [2, 3]. The analysis produced the model SI which is an equation which predicts the hydraulic conductivity of the clay liner with the measured initial saturation. The paper backs up the equation using existing theories of soil-water interaction. The proposed instrument will measure permeability faster than current equipment. It will be smaller, portable (possibly pocket-size) and easy to use by even non-technical construction personnel.

Introduction

The solution to the problem of finding a predictor for the permeability (hydraulic conductivity) for clay liners has eluded engineers, geologists, hydrologists, agriculturalists, environmentalists and others for years. The ability to predict or measure the permeability of clay liners during and after construction will result in a better performance of the liners in engineered structures. Most of these structures are landfills, levees, dams, lagoons, retention ponds, which use the liners for their fluid-transport attenuation capabilities. In effect, these liners are expected to serve as plastics to contain fluids, either contaminated or not. In the case of contaminated fluids, the goal is to prevent contamination of precious subterranean resources, such as, potable water in aquifers.

There are many factors affecting the movement of fluids in soils, particularly clays. For this reason, there is not a predictor of hydraulic conductivity at this moment that can be considered reliably accurate. Some of these factors, to mention a few, are water content, dry unit weight, degree of saturation, void ratio, unit weight or density, specific gravity, liquid limit and plastic limit [7,8,9]. With respect to clay liners, the mineralogy of the type of clay used, is an additional factor influencing hydraulic conductivity.

As a result of the numerous factors influencing the hydraulic conductivity of clay liners, early attempts to establish equations or selecting a dominant factor or factors to predict the hydraulic conductivity of clay liners have been futile since the equations produced have been complex and involved with numerous factors. [2, 3]. The simple explanation for this is that, the factors mentioned above are extremely interdependent. The interdependent relations among these factors have been extensively reported in books and other publications [4, 6]. In this case, using statistical means like linear regression on experimental data will result in confounding, making the equations or established models useless. On the other hand, if numerical methods are applied to experimental data, the error terms in each factor will be compounded to yield an overall ballooned error in the established equation. If some of the factors in the established equations happen to have an order of magnitude greater than "1", then the overall error will be exponential [1].

This paper presents an equation, based on the degree of initial saturation (SI) of the clay liner, which was developed by using linear regression analysis on experimental data from a peer- reviewed paper published in the refereed Journal of Geotechnical and Geoenvironmental Engineering [2, 3]. The paper also uses hydraulic and hydrologic theories to prove, mathematically, that the selected attribute, in fact, embodies (or is a function of) almost all of the factors, enumerated above, that affect the hydraulic conductivity of clay liners (see mathematical deduction below).

Theoretical Background

The initial saturation (SI) is expressed mathematically as [1, 2, 3, 4, 6]:

$$\mathrm{SI}=\frac{w}{\frac{\gamma_w}{\gamma_d}-\frac{1}{G_s}} \tag{1}$$

where w = water content
G_S = specific gravity of soil solids
γ_d = the dry unit weight of the soil
and γ_w = the density of water

From (1):

$$\mathrm{SI}=\mathrm{f}(w, \gamma_d, \gamma_w, G_s) \tag{2}$$

The water content, w, is expressed mathematically as [1, 2, 3, 4, 6]:

$$w=\frac{W_w}{W_s}=\frac{\gamma_w V_w}{\gamma_s V_s}=\frac{\rho_w V_w}{\rho_s V_s} \tag{3}$$

where w = water content
W_s = weight of solids
W_w = weight of water
γ_s = the unit weight of the soil solids (particles)
ρ_s = density of the soil solids
ρ_w = the density of water
V_w = volume of water
V_s = volume of soil solids.

The dry unit weight of the soil, γ_d, is expressed mathematically as [1, 2, 3, 4, 6]:

$$\gamma_d=\frac{W_s}{V}=\frac{\rho_s g V_s}{V_s+V_w+V_a} \tag{4}$$

where γ_d = the dry unit weight of the soil
V = the total volume of the soil (including air and water)
V_a = the volume of air in the soil
V_w = the volume of water in the soil
V_s = the volume of soil solids in the soil and
g = acceleration due to gravity.

From (2),

$$\mathrm{SI}=\mathrm{f}\,(W_s, W_w, \gamma_w, V_s, V_a, V_w, g, G_s\, \gamma_s) \tag{5}$$

But [1, 2, 3, 4, 6]:

$$\mathrm{S}=\frac{V_w}{V_v}=\frac{V_w}{eV_s} \tag{6}$$

And from Equation 6,

$$V_w = SeV_s \tag{7}$$

where V_v = the volume of voids
e = the void ratio of the soil
S = the degree of saturation

Therefore (5) can be expressed as:

$$\mathrm{SI}=\mathrm{f}(W_s, W_w, \gamma_w, V_S, V_a, S, e, g, G_s, \gamma_s) \tag{8}$$

Since,

$$\mathrm{K}=\mathrm{f}(\mathrm{SI}) \tag{9}$$

$$\mathrm{K}=\mathrm{f}(W_s, W_w, \gamma_w, V_S, V_a, S, e, g, G_s, \gamma_s) \tag{10}$$

where K is the hydraulic conductivity (permeability).

The Equation

The soil-property-based equation upon which the instrument is to be built is [1,2]:

$$\ln\mathrm{K}=-14.89-0.10\mathrm{SI} \tag{11}$$

$$\mathrm{K}=e^{(-14.89-0.10\mathrm{SI})} \tag{12}$$

where SI (same as Si) is the initial saturation of the clay liner. From (9) and (10), it is clear that (11) and (12) incorporate all the soil properties that affect the hydraulic conductivity of clay liners. Having one variable in the equation solves the problem of a compounded error term resulting from individual error terms in the numerous factors if they were to be used explicitly in the equation. Since this equation was determined, statistically [1, 2], with a single variable, the problems of confounding, due to the interdependent relations among the numerous factors, were also minimized or eliminated. It must be noted that, this equation can be used with a simple calculator without the development of the instrument by field personnel. This equation has been validated by using independent experimental data. The hydraulic conductivities produced using cumbersome laboratory methods were very closely predicted by using the SI equation.

Structure of the Instrument

Figure 1 is a schematic drawing of the instrument (permeameter) showing the 3 main components:

a) An initial saturation (SI) measuring unit
b) A computation unit where the formula will be applied; and
c) Data display area.

The data to be displayed will be the initial saturation detected and the computed permeability. The computed permeability will trigger an electronic color-coded display to indicate its acceptability with respect to US Federal regulatory limit of 10^{-9} m/s. In Figure 1, the color red means the reading is not acceptable while green means otherwise.

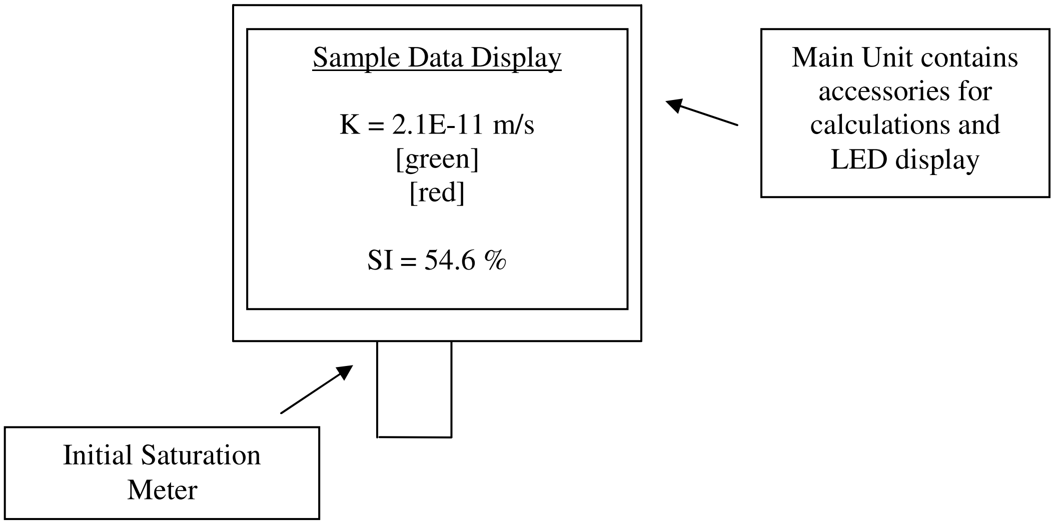

Figure 1: Schematic Drawing of Permeameter

Figure 2 shows the steps performed by the proposed permeameter prototype instrument.

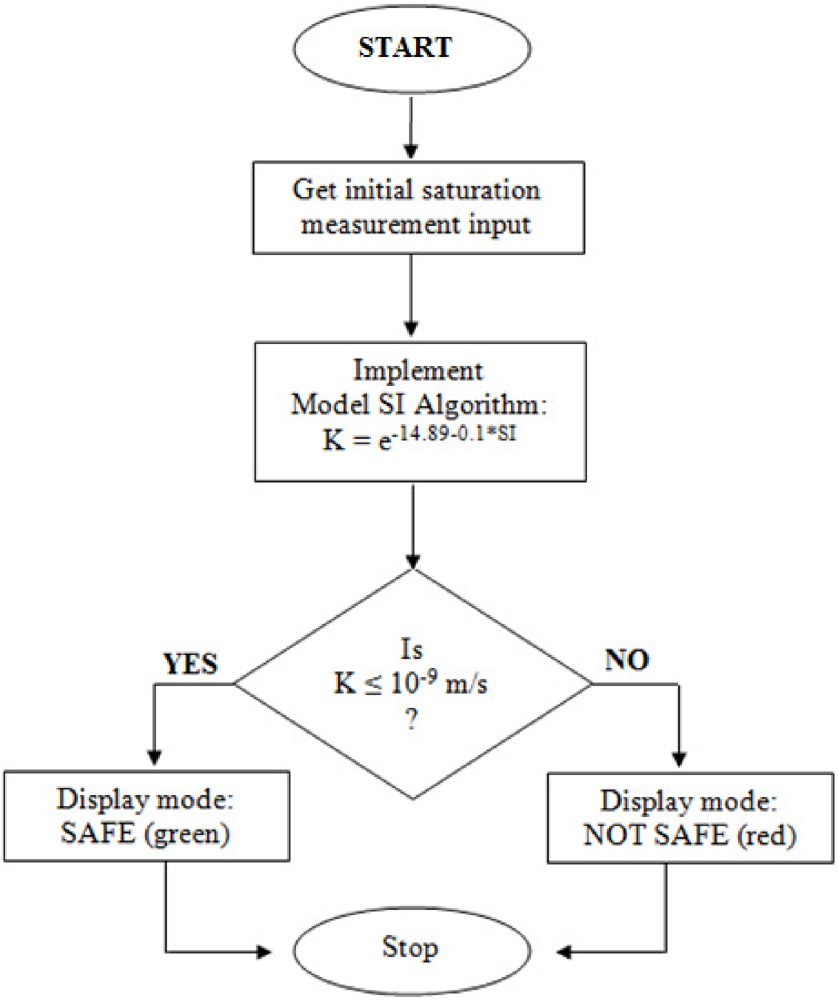

Figure 1-Flowchart of Prototype

Advantages of the Instrument

There is a wide application of the knowledge of permeability (hydraulic conductivity) in the construction and performance of structures using clay liners; examples include, dams, foundations, runways, roads, highways, lagoons and fluid containment structures. However, the measurement, to date has been cumbersome (because they are made of several separate parts to be assembled before use) and time consuming, using existing instruments like Boutwell Permeameter and Constant Borehole Permeameter [4, 5, 6,]. There are similar instruments, namely, the Air Entry Permeameter, the Ponded Infiltrometer, and the Tension Infiltrometer that use infiltrometer methods. The instruments and/or methods mentioned above are useful in the field only and mostly on saturated soils. [1, 5]. They also make the following assumptions about the soil:

- It is homogeneous and uniformly soaked;
- Porewater pressure = 0 at the base and center of the soil;
- The effects of soil suction are negligible; and,
- There is no volume change [5].

The assumptions listed above would be hard to come by in natural or compacted soils such as clay liners. Thus, the methods are limited to highly controlled experimental conditions and may not be very useful, in real time, in spite of the tedious work involved.

The proposed permeameter is a panacea for all the shortcomings of the ones listed above because:

a) it will be portable as one unit (may even be pocket-size);

b) will hasten construction because it can measure the permeability faster, so that one does not have to wait hours or days for the results, and during the waiting period, the permeability of the compacted clay may be altered by atmospheric elements when construction resumes;

c) the permeability of the soil can be monitored as often, and at so many places on the liner, as possible during construction, thus ensuring a consistent value throughout the construction period;

d) controlled units could be established in the field to monitor the permeability of the liner when construction of the structure has been completed

e) this instrument will require little or no training for construction personnel, most of whom often have little or no formal education; and,

f) unlike the methods mentioned above, this instrument does not rely on idealistic assumptions of the compacted clay.

Table 1 shows some of the measured hydraulic conductivities (K) and the corresponding predictions (Kp) for Model SI on a sample of the data that was not used for model development. It can be observed that the difference in the order of magnitude between the measured and predicted hydraulic conductivities is 0 or 1. This fact is proven by the differences between the measured and predicted Ks in column 4 of Table 1. Row 11 of the table is an anomaly because the measured K appears to be an outlier in the data used. It was too high to begin with. Row 16 of the table gives a difference of zero which indicates a perfect prediction. It is also a proof that most of the differences are, in fact, close to zero. The fact that this model makes consistent predictions across all levels of compaction is very significant because this makes it possible to use it for field compaction which is considered to be a mixture of all levels of compaction, that is, MP (Modified Proctor), SP (Standard Proctor) and RP (Reduced Proctor). Figure 3 shows a plot of measured K versus predicted Kp, for Model SI. The data used for validation of the model was used in the plot. It is observed that there is a good correlation between measured K and predicted K for the model because the points band uniformly along the 45° line for the whole range of measured K values. The data was plotted on a log-log scale because:

- the equation is a logarithmic function;
- the numbers are too small to be plotted on a Cartesian scale; and,
- there will be only two clots which will yield no meaningful analysis if the data is plotted on a Cartesian scale.

Table 1: Kp (Predictions of K by Model SI) versus measured K

SI % (1)	K (measured) m/s (2)	Kp Model SI (predicted) m/s (3)	Kp – K m/s (4)
40.36	7.00E-09	6.04E-09	9.60E-10
54.84	4.00E-09	1.42E-09	2.58E-09
72.63	2.50E-10	2.40E-10	1.00E-11
89.94	1.20E-10	4.25E-11	7.75E-11
45.05	6.00E-10	3.78E-09	-3.18E-09
59.64	5.50E-10	8.79E-10	-3.29E-10
91.44	1.30E-10	3.66E-11	9.34E-11
67.42	6.00E-11	4.04E-10	-3.44E-10
84.97	1.00E-10	6.99E-11	3.01E-11
91.38	6.00E-11	3.68E-11	2.32E-11
49.64	7.50E-06	2.39E-09	7.50E-06
72.35	1.00E-09	2.47E-10	7.53E-10
89.91	4.10E-11	4.26E-11	-1.60E-12
84.5	7.50E-11	7.32E-11	1.80E-12
52.74	1.10E-09	1.75E-09	-6.50E-10
61.92	7.00E-10	7.00E-10	0.00E+00
91.93	2.50E-11	3.48E-11	-9.80E-12
89.27	7.50E-11	4.54E-11	2.96E-11
78.03	9.00E-12	1.40E-10	-1.31E-10
90.17	3.00E-11	4.15E-11	-1.15E-11
88.21	5.00E-11	5.05E-11	-5.00E-13
86.84	2.00E-11	5.79E-11	-3.79E-11
84.82	7.50E-11	7.09E-11	4.10E-12

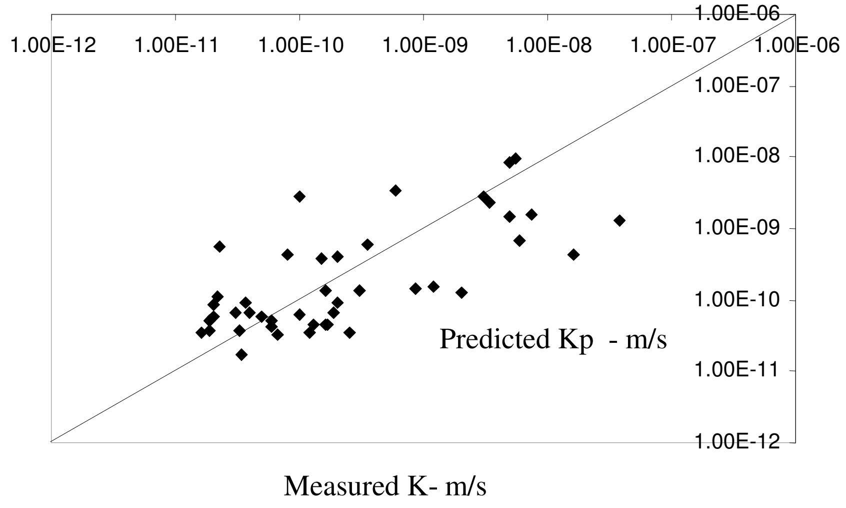

Figure 3: Model SI Predictions

Conclusion

This article chronicles how the application of research results is being used for the invention of a faster and smaller permeameter. The equation to be programmed into the prototype of the permeameter is ln K = -14.89 - 0.10 SI or K = $e^{(-14.89 - 0.10\ SI)}$. K is the coefficient of permeability and SI is the initial saturation of compacted clay. This equation and the proposed instrument apply to the permeability of water in compacted clays only. It may work on aqueous fluids like leachates from landfills but that is yet to be researched after the development of the instrument. The reason for the use of SI, the initial saturation, only as the only variable in the development of the equation is that SI is a function of all the other interdependent factors that influence the permeability (hydraulic conductivity) of compacted clay. A theoretical and mathematical proof of this fact is enshrined in the paper under the heading "Theoretical Background". Sample results of the performance of the equation to be used in the instrument have been provided in Table 1 and Figure 3. A schematic drawing of the instrument and an algorithm for the display of the results has been provided in Figures 1 and 2, respectively.

Size, faster measurement of permeability, ease of use by field personnel and, hopefully, cost will make the SI permeameter superior to existing permeameters. The development of this equipment will benefit organizations or offices such as the Department of Defense, Department of Energy, Environmental Protection Agency (EPA), DOT, the Army Corps of Engineers, Education (at the undergraduate and graduate levels) and Municipalities because they are involved in the study and/or the application of the concepts of permeability (hydraulic conductivity) in most of their projects. Some of these projects are landfills, dams and underground storage tanks (USTs). The consequences of the breach of the mentioned structures are devastating in terms of the loss of property and lives [1]. Therefore, if this equipment is developed, it will have a large market.

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Biography

FRANK ATUAHENE is an Assistant Professor (Construction Management) at Georgia Southern University in Statesboro, Georgia. He holds a BSc (Hon.) in Civil Engineering from the University of Science and Technology, 1979; Masters in Civil Engineering (Structures Major) from the University of Delaware, 1983; Master of Engineering (Industrial Engineering Major) from Penn State University, 1994 and a Ph.D in Civil Engineering (Geotechnical Engineering Major) from Rutgers University in 1998. He has experience in construction project management, higher education instruction, roadway design and environmental consulting in Ghana and the United States. His research interests include instrumentation for hydraulic and hydrologic studies, international construction and statistical modeling of engineering processes. Dr. Atuahene can be reached at fatuahene@georgiasouthern.edu.