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A STUDY OF FLOW THEORY TOWARDS THE DIFFERENT DEGREE OF TROPICAL PEAT DECOMPOSITION

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TAJUK PROJEK: **A STUDY OF FLOW THEORY TOWARDS THE DIFFERENT DEGREE OF TROPICAL PEAT DECOMPOSITION**

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ABSTRACT

Existing literature suggests that Darcy's Law is not valid in different degree of decomposition of peat soil. The present study attempts to validate the applicability of Darcy's Law by comparing the velocity predicted by Darcy's Law and the velocity obtained through experiment for a peat soil column. The suitability of Izbash's Law to predict the flow through peat soil column of different degree of decomposition was tested by determining the Izbash's parameter, n. Izbash's Law ($v = ki^n$) was preferred because of its continuity with the Darcy's Law. Soil columns studies were set-up by applying different value in hydraulic gradient in order to obtain discharge velocity, v, of the sample. From the result, it is expected to find the suitable Izbash's parameter, n, for each depth of peat soil profile of different decomposition stage. The overall result of the study suggests that the Izbash or Power Law provides a much better approximation of water flow through much deeper peat layer.

Keywords : Darcy's Law, peat decomposition, Izbash's Law

ABSTRAK

Maklumat literatur yang sedia ada mencadangkan bahawa Hukum Darcy didapati tidak sah bagi tanah gambut yang mempunyai tahap pereputan yang berbeza. Kajian ini dijalankan bagi mengesahkan kebolehsesuaian Hukum Darcy dengan cara membuat perbandingan halaju air menggunakan anggaran Hukum Darcy dan halaju aliran melalui pengukuran di makmal. Kesesuaian Hukum Izbash untuk menganggar aliran air yang melalui sampel tanah gambut pelbagai kadar pereputan digunakan untuk mendapatkan nilai pekali Izbash, n. Hukum Izbash ($v=k_i^n$) dipilih kerana kesinambungannya dengan Hukum Darcy. Kajian samel tanah dilaksanakan menggunakan pelbagai kecerunan hidraulik untuk mendapatkan halaju kadar alir, v. Daripada keputusan ujian makmal dan analisis, adalah dijangkakan untuk mendapatkan nilai parameter Izbash, n, bagi kedalaman tanah dan kadar pereputan yang berbeza. Hasil kajian keseluruhan mencadangkan bahawa Hukum Izbash mampu memberikan penganggaran yang lebih baik terhadap sistem pengaliran air bagi tanah gambut pada kedalaman yang lebih.

Kata kunci: Hukum Darcy, Pereputan tanah gambut, Hukum Izbash

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION

1.0 General Overview

Peat is commonly defined as an accumulation of partially carbonized vegetable tissue in wet condition by decomposition of various plants and mosses. In older soil classification systems, peat soils are usually defined as soils having more than 65 percent organic matter. Tropical peat are different with temperate regions due to the plants which peat is formed are different and also due to climate differences which has direct effect on peat area characteristics such as hydrology. Peat of tropical regions such as Malaysia when compared to those found in temperate regions are insufficiently studied. Even though peat research stations were opened in Malaysia, the research efforts were mostly on agronomic aspects.

Peat soil poses potential hazards to engineering works such as road construction and development of new township built on it due to severe damage as a result of subsidence. Subsidence is caused by changes in conditions brought about by drainage. An understanding of water flow characteristics through peat soils by studying its hydraulics properties is important in assessing this subsidence problem. Beside that, the results of research concerning the hydraulic characteristics of peat can also be applied to determine how to responsibly extract groundwater for human use. A proper model of flow of water through peat is essential to study the flow of water through peat soil. Classically, the empirical relation known as Darcy's Law is invoked to model the relationship between the specific discharge of water and the hydraulic gradient in peat. However, the literature contains report that peat behaviour, especially that of humified peats, may depart substantially from Darcy's Law. Rycroft, Williams & Ingram (1975) discuss the literature on peat hydraulic conductivity, the methodologies for peat conductivity measurement, and evidence presented by several workers that Darcy's Law does not provide an accurate description of water flow through saturated peats, particularly the deeper, humified peats layer.

Due to the reason given, further studies on peat soils, especially tropical peat are needed to better understand its hydraulics characteristic in the hope that in the near future, engineers and researchers can come out with a proper water flow model through peat thus providing solution for the engineering problems on peat soil.

1.1 Objectives of Project

The objectives of this project can be summarized as follows:

i. To show that Darcy's Law is invalid for flow through peat soil column by comparison between the velocities predicted by Darcy's Law and the measured velocities (through experiment).
ii. To determine the suitability of Izbash's Law to predict the flow through peat soil

column by determining the n value (Izbash's parameter) from the result of the experiment.

1.2 Scope of Project

The scope of this project can be divided into two parts. Part one involves field works such as collecting samples and determining hydraulic conductivity on site. Part two involves laboratory works where the collected samples will be tested on its moisture content and ash content and also the validity of Darcy's Law through a peat soil column apparatus. The research area was at Parit Madirono, Benut, Johor.

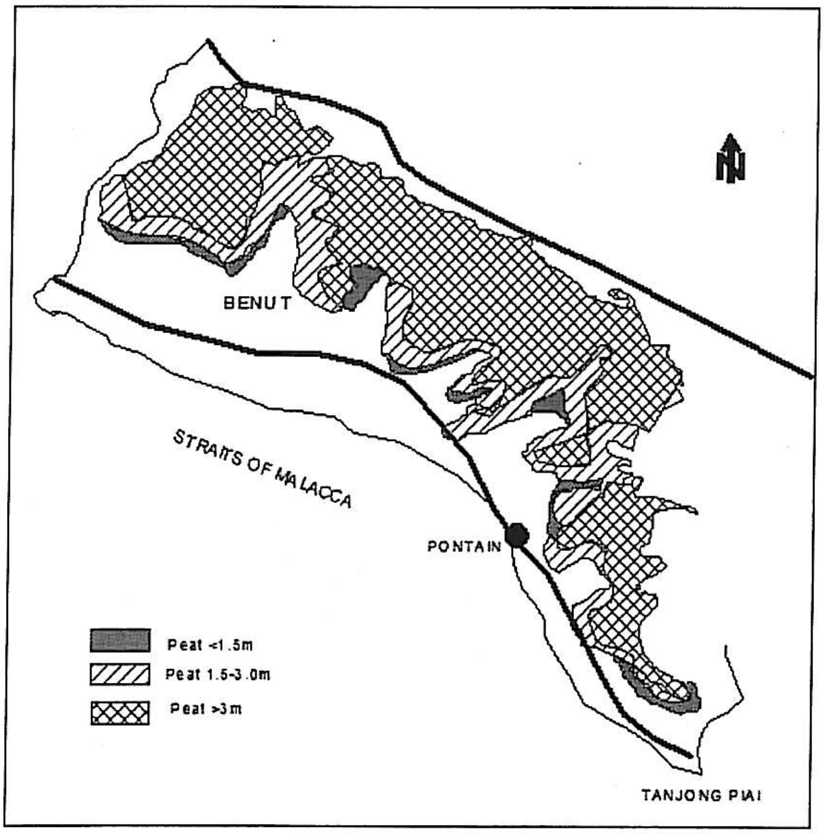


Figure 1.1: Map showing the locality of Benut, Johor.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

The existing body of knowledge concerning peat soil is not so extensive as that concerning mineral soils. Nevertheless, the physical properties of peats have been fairly well documented because they are of interest to a range of scientists and industries. A smaller amount of work has been performed on the hydraulic characteristics of peat. Of the studies available, most deal with hydraulic conductivity and flow in the saturated zone. Most of the studies were performed on temperate peatlands especially in the northern part of the United States, Canada, Europe, and Russia. While peats in northern temperate climates are more extensive and more widely studied, peats also occur in subtropical and tropical climates.

Peat forms when the rate of organic matter deposition exceeds the rate of decomposition, a condition often met in topographic lows with standing water. In temperate climates, precipitation usually exceeds evapotranspiration and microorganisms are less active than in tropical climates, leading to a deeper and more extensive deposits. Tropical and subtropical peat deposits are typically shallow compared to their northern counterparts.

The results of research concerning the hydraulic characteristics of peats can be applied to determine how to responsibly extract groundwater for human use. By maintaining some minimum water table depth, water management authorities can ensure that soil moisture is adequate over the long term to maintain isolated wetlands in their historical ecological state.

2.1 Peat Soils Definition and Classification

Peat is commonly defined as an accumulation of partially decayed plant remains under water or in a poorly drained site where preservation has occurred under anaerobic conditions. The classification of peat poses many problems. This is because there are many classification systems, each geared to the objectives of the disciplines responsible for their development. However, for the purpose of this project, only two classification systems was used which were based on ash and organic content and also the Von Post scale.

a) Classification based on ash and organic content

The mineral content of peat is the percentage of inorganic matter present on a weight basis. The mineral content is sometimes called the ash content because it can be estimated by burning off the organic matter at a high temperature. Because most inorganic matter is much dense than plant remains, the weight percentage may tend to overstate its influence on hydraulic properties in the soil matrix. In order for a material to be considered a peat, it must contain no more than an arbitrarily determined maximum inorganic content. This percentage varies somewhat depending on the reason for studying the peat. 20% is a typical value, although some soil scientists allow up to

35%. A peat containing up to 55% inorganic matter may be viable for commercial purposes.

At the Organic Sediments Research Center (OSRC) of the University of South Carolina, definition of peat is based upon ash content. Peat is defined as having 25% or less inorganic material on a dry weight basis (Figure 2.1). The method to determine the ash content is based on the ASTM standards for peat (D 2974). Those organic soils or sediments which are not peat are categorized (in the OSRC System) as being either carbonaceous or mineral sediments, depending on their total ash content (Fig. 2.1). For the benefit of the reader, any further reference to the term "peat" and other organic material is in accordance with the OSRC System in Fig.2.1.

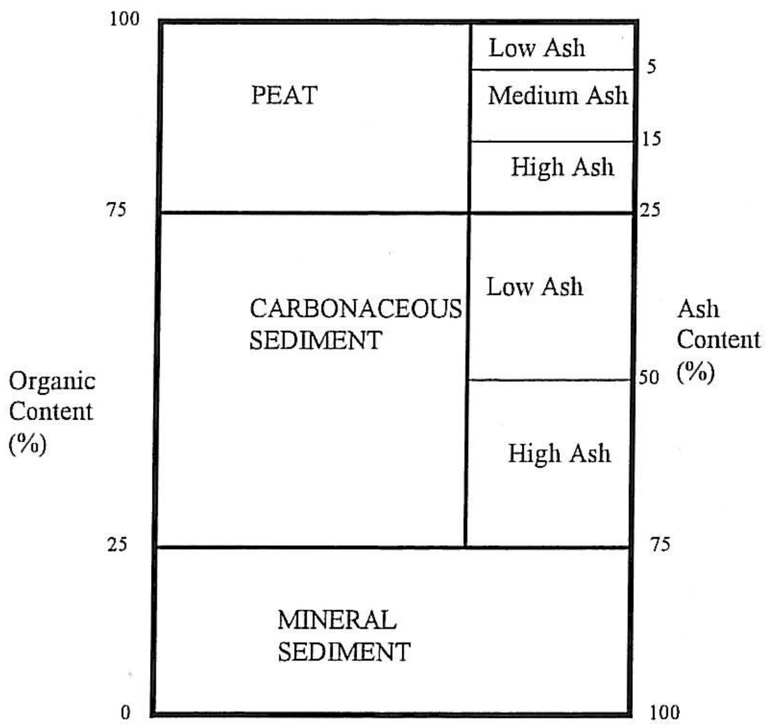


Figure 2.1 : Classification of peats and organic sediments by ash and organic content used by the Organic Sediments Research Center of the University of South Carolina.

a) Von Post scale

Probably the first worker to classify peat on physical properties was Von Post who developed a field method to indicate stages of decomposition. The Von Post scale (Table 2.1) recognizes 10 steps; little decomposed fibrous, light-coloured peat being defined as H_1, whereas the well decomposed, colloidal, dark-coloured material at the other end of the scale in indicated as H_{10}. Root fibres, wood residues and degree of moisture are also indicated. This scheme is still widely used, particularly in northern Europe.

Table 2.1: The Von Post scale of humification

H	Nature of material extruded on squeezing	Nature of plant structure in residue
1	Clear, colorless water, no organic solids squeezed out	Unaltered, fibrous, undecomposed
2	Yellowish water, no organic solids squeezed out	Almost unaltered, fibrous
3	Brown, turbid water, no organic solids squeezed out	Visibly altered but identifiable
4	Dark brown, turbid water, no organic solids squeezed out	Easily identifiable
5	Turbid water and some organic solids squeezed out	Recognizable but vague, difficult to identify
6	Turbid water and 1/3 of sample squeezed out	Indistinct, pasty
7	Very turbid water and ½ sample squeezed out	Faintly recognizable, few remain identifiable, mostly amorphous
8	Tick and pasty, 2/3 of sample squeezed out	Very indistinct
9	No free water, nearly all sample squeezed out	No identifiable remains
10	No free water, all sample squeezed out	Completely amorphous

In this scheme, a sample of peat is squeezed in the hand, allowing liquids and soft solids to ooze out. The appearance of the material squeezed out and the material retained determines the degree of humification on a ten-point scale. Although the method may seem extremely subjective, it has a scientific basis. The maximum pressure applied in squeezing the human hand is sufficient to expel free and most capillary water but not chemically-bound water

2.2 Hydraulic Conductivity Property of Peat

The rate of movement of water or hydraulic conductivity of the soil is highly relevant to drainage problems. The type of peat, degree of composition and bulk density influence hydraulic conductivity and they provide a good basis for its assessment (Boelter, 1974). In a study on samples of peat taken from Thorne Moors National Reserve, Humberhead Peatlands, England by Beckwith et al., (2003), they have found that anisotropy and heterogeneity of hydraulic conductivity (K) exists in a peat soil layer. In anisotrophy soils, the vertical hydraulic conductivity (K_v) of a given volume of soil is not equal to the horizontal hydraulic conductivity (K_h) of the same volume of soil. Heterogeneity is where the hydraulic conductivity in one place differs from that in another. The main findings from the study by Beckwith et al., (2003) are :

i. The degree of anisotrophy was found in most of the peat samples.
ii. The anisotrophy of each depth was such that K_h was generally greater than K_v.
iii. Heterogeneity of K was found throughout the profile of all core samples.
iv. There generally was a significant decrease in K_h with depth. K_v and isotrophy showed a relationship with depth in fewer than half of the peat cores.

In another study by Rizzuti et al. (2004) on core samples for peat taken across

Peat Bay, South Carolina, they have found that in general the highest hydraulic conductivities tended to be found where the peat layers were higher in fiber and lighter in color. On the other hand, the lowest hydraulic conductivities were found where the peat layers were more oxidized/humified and darker in color. They also found that all the core samples from Peat Bay site, the hydraulic conductivities tended to increase with depth for the first 25 cm and then decrease with depth for the rest of the core interval, perhaps as a result of either autocompaction of the peat or changes in original environments of deposition (climate, hydrology, etc.) that effected depositional processes swamp-wide and, consequently, physical composition of the organic sediments.

Laboratory studies on Holland Marsh mucks in Ontario State, USA, give hydraulic conductivity values of 22, 18 and 4 cm/h for depths of 0 – 15, 15 – 30 and 30 – 45 cm respectively. Florida peat soils (12 – 21cm depth) were found to have a hydraulic conductivity ranging from 29 – 67 cm/h depending on soil series. There is little data for peat in tropics, however, fibric materials in tropical peat commonly exhibit high hydraulic conductivity, which gradually diminishes as the peat decompose. Although the applicability of the hydraulic conductivity concept to peats continues to generate controversy, many researchers have attempted to measure the saturated hydraulic conductivity of peats using traditional methods. Figure 2.2 compares the results of a large number of tests by different groups. Values range from 10^{-1} to 10^{-7} cm/s, with most of the values falling between 10^{-3} and 10^{-5} cm/s. Because hydraulic conductivity depends on the pore size distribution of peat, it is related to the degree of decomposition.

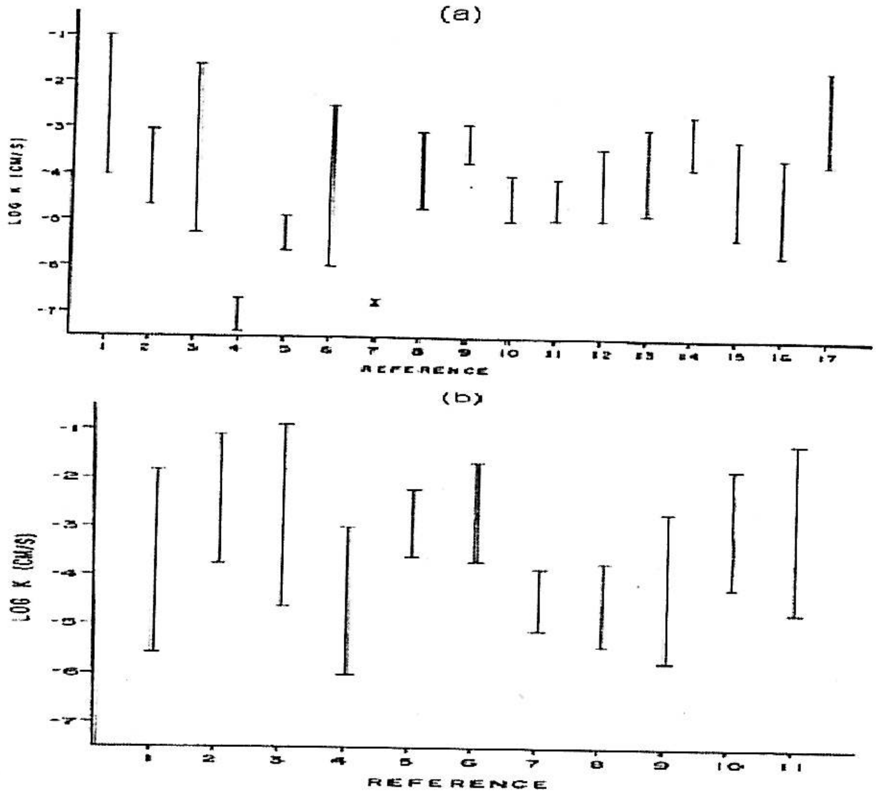


Figure 2.2 : Summary of hydraulic conductivity values from the literature (Chason and Siegel, 1986). (a) Field values: 1, Baden and Egglesman (1961, 1963, 1964); 2, Egglesman and Makela (1964); 3, Boelter (1965); 4, Ingram (1967); 5, Galvin and Hanrahan (1968); 6, Romanov (1968); 7, Sturges (1968); 8, Dowling (1969); 9, Irwin (1970); 10, Yamamoto (1970); 11, Knight et al. (1971); 12, Dai and Sparling (1972); 13,Ingram et al. (1974); 14, Paivenen (1973); 15, Galvin (1976); 16, Dasberg and Neuman (1977); 17, Chason and Siegel (1986); (b) Laboratory values: 1, Malstrom (1925); 2, Sarasto (1961); 3, Boelter (1965); 4, Bazin (1966); 5, Irwin (1970); 6, Korpijaako and Radforth (1972); 7, Bartels and Kunze (1973); 8, Galvin (1976); 9, Dasberg and Neuman (1977); 10, O'brien (1977); 11, Chason and Siegel (1986).

Figure 2.3 shows the relationship of hydraulic conductivity to the von Post humification scale as measured by six different authors. The relationship shows a decrease in conductivity with increasing humification. Moss peats have the lowest hydraulic conductivity at all humifications, while sedge and reed peats have the greatest. The conductivities of the different peat types converge as they reach a high degree of humification.

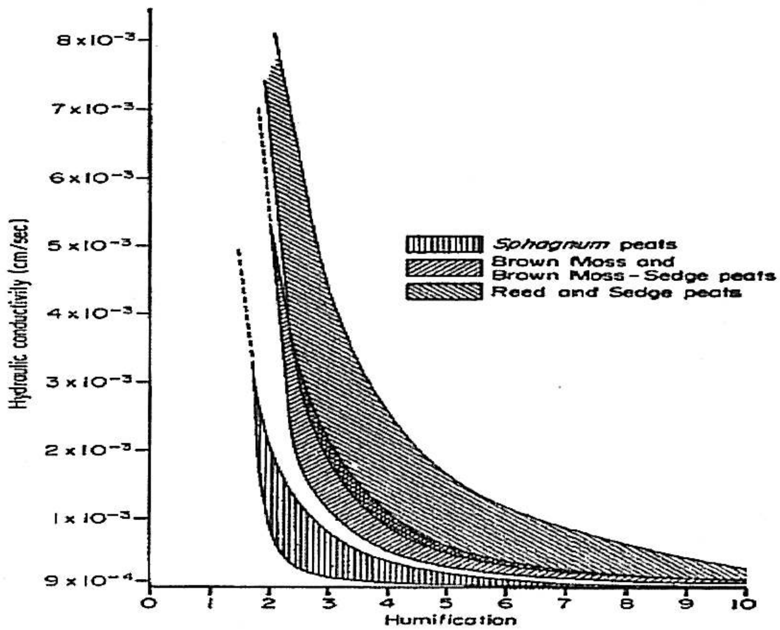


Figure 2.3. Decrease in saturated hydraulic conductivity with increasing humification on the von Post Scale (Rycroft et al., 1975).

Boelter (1969) performed linear regressions to relate hydraulic conductivity to fiber content and bulk density in a Minnesota bog peat. Figure 2.4 shows that hydraulic conductivity increases approximately logarithmically (r^2=0.54) with increasing fiber content and with decreasing bulk density. Hydraulic conductivity ranges from about 10^{-2} cm/s for undecomposed peat to less than 10^{-5} cm/s for very well decomposed samples.

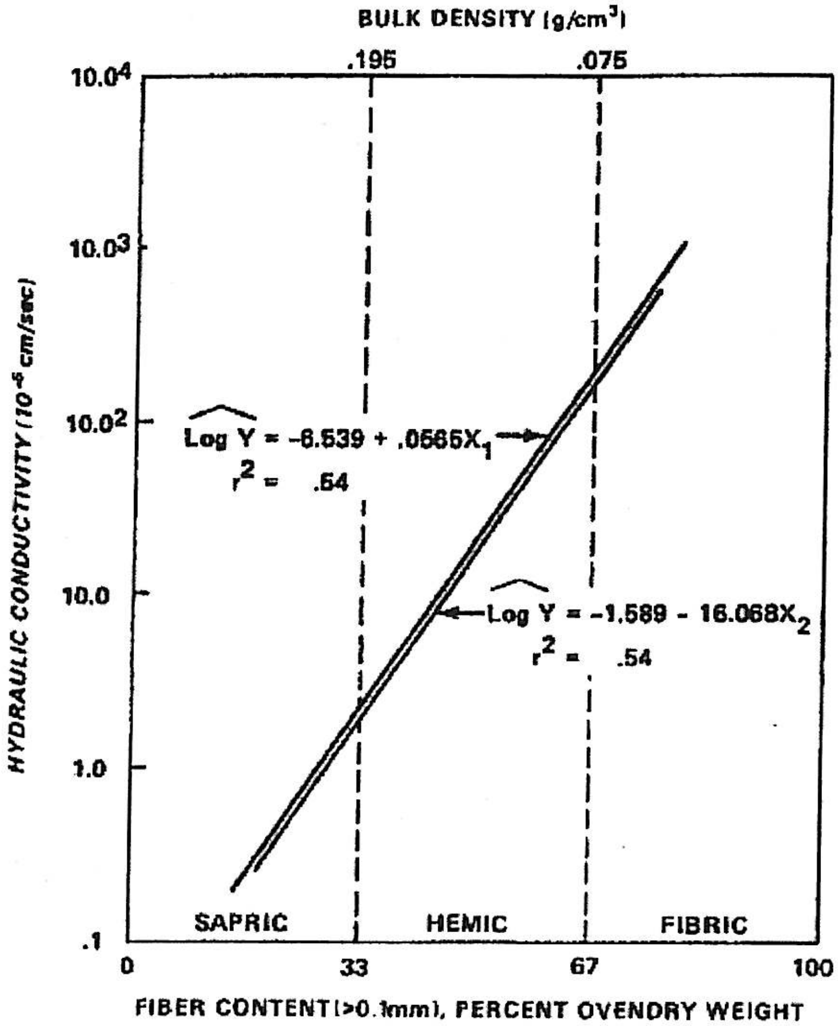


Figure 2.4 : Relationship of hydraulic conductivity to fiber content and bulk density (Boelter, 1969).

2.3 Darcy's Law

In 1856, Henry Darcy, a French hydraulic engineer investigated the flow of water through horizontal beds of sand to be used for water filtration by running an experiment on a vertical pipe filled with sand under conditions simulated by Figure 2.5 below.

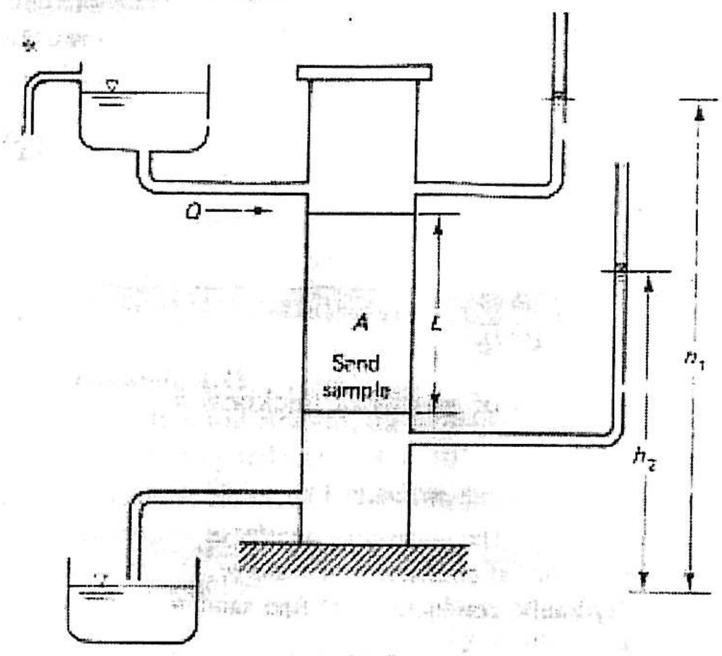


Figure 2.5 : Simulation of Darcy's experiment.

He concluded that the flow rate Q through porous media is proportional to the cross-sectional area A, inversely proportional to the length L of the sand-filter flow path and proportion to head drop ($h_1 - h_2$). This statement is known universally as Darcy's Law. This provided the famous Darcy equation :

$$Q = \frac{KA(h_1 - h_2)}{L} \tag{2.1}$$

where K is the hydraulic conductivity, which represented the constant of proportionality. The ratio $(h_1 - h_2)/L$ is known as the hydraulic gradient. Defining specific discharge, q, or discharge velocity, v, as discharge per unit cross-sectional area, the equation becomes,

$$q = v = \frac{-K\Delta h}{L} \tag{2.2}$$

where q = specific discharge

v = Darcy velocity or discharge velocity

Δh = drop of head in length L (negative sign indicates flow in the direction of decreasing head)

In applying Darcy's Law it is important to know the range of validity within which it is applicable. Because velocity in laminar flow, such as water flowing in a capillary tube, is proportional to the first power of the hydraulic gradient (Poiseuille's law), it seems reasonable to believe that Darcy's Law applies to laminar flow in porous media. For flow in pipes and other large sections, the Reynolds number, which expresses the dimensionless ration of inertial viscous forces, serves as a criterion to distinguish between laminar and turbulent flow. Hence, by analogy, the Reynolds number has been employed to establish the limit of flows described by Darcy's Law, corresponding to the value where the linear relationship is no longer valid. Reynolds number is expressed as

$$R = \frac{Dv}{\nu} \qquad (2.3)$$

where to adapt this criterion to flow in porous media, the Darcy velocity is employed for v, an effective grain size (d_{10}) is substituted for D and υ is kinematic viscocity of pore fluid (water in this case). Experiments show that Darcy's Law is valid for R < 1 (laminar) and does not depart seriously up to R >10 (turbulent). This, then, represent an upper limit to the validity of Darcy's Law. A porous media such as peat can exhibit a Darcian or non-Darcian behaviour depending on the macroscopic velocity.

2.4 Non-Darcian Property Of Peat

Classically, the empirical relation known as Darcy's Law is use to model the relationship between the specific discharge of water and the hydraulic gradient in peat (e.g. Dasberg & Neumann 1977; Hemond & Fifield 1982). The existing literature suggests that such flow violates Darcy's Law in humified peat, and casts doubt on the applicability of existing models for flow through porous media when applied to peatlands.

Darcy's Law states that the rate of flow through a porous material is linearly related to the piezometric head gradient. The constant of proportionality, K, is called hydraulic conductivity. Darcy's Law may be written for an isotropic porous medium as,

$$q = v = \frac{-K\Delta h}{L}$$

where q = specific discharge

v = Darcy velocity or discharge velocity

Δh = drop of head in length L (negative sign indicates flow in the direction of decreasing head)

Although K varies from material to material and with fluid viscosity, it is by definition constant as head gradient varies. Darcy's Law has been found to hold for a wide range of conditions. In any soil, the flow rate of water increases along with the magnitude of the hydraulic gradient applied to it. In mineral soils, this relationship has been shown to be essentially linear, an assumption of Darcy's Law. While the relationship may not be linear for organic soils, it may be approximately linear within a certain range of gradients or for a particular peat type.

A number of studies suggest that Darcy's Law is applicable only to the upper layer and only to slightly decomposed peat (e.g., Hemond & Goldman, 1985; Rycroft et al., 1975). They identify two possible causes of a departure from Darcy's Law in the deeper layers. First, although the structure of the medium is constant, the flow rate may vary nonlinearly with hydraulic gradient or with the absolute magnitude of head applied. Second, the structure itself may vary with hydraulic gradient or with absolute head, leading to a nonlinear variation in hydraulic properties. The former cause of departure from Darcian behaviour is expected and observed as the Reynolds number becomes large in coarse materials at high discharges. The second cause of departure from Darcian behaviour must be associated with changes in pore geometry. If such changes are primarily controlled by vertical effective stress, discharge may still be essentially proportional to head gradient as long as the absolute piezometric head does not exhibit large changes. Hemond and Goldman (1985) recommend that Darcy's Law be applied only in cases of small hydraulic gradients and fairly constant effective stress. They suggest that the Richards equation, a generalized form of Darcy's Law in which hydraulic conductivity varies as a function of hydraulic gradient, may be applicable to saturated peats with a high degree of humification.

2.5 Available Non-Darcian Equations

Widely available experimental data, which are piling up for the last few decades, to justify the validity and applicability of Darcy's Law have helped to evolved a general consensus that there is an upper as well as a lower limit beyond which Darcy's linear law does not hold good. Combining the works of various investigators over different velocity or Reynolds number (based on macroscopic velocity) zones, the shape of velocity response for any type of soil over a wide range of velocities can be represented in Figure 2.6. Different zones of flow that are expected are demarcated in Figure 2.6. The total flow regimes are divided into five zones.

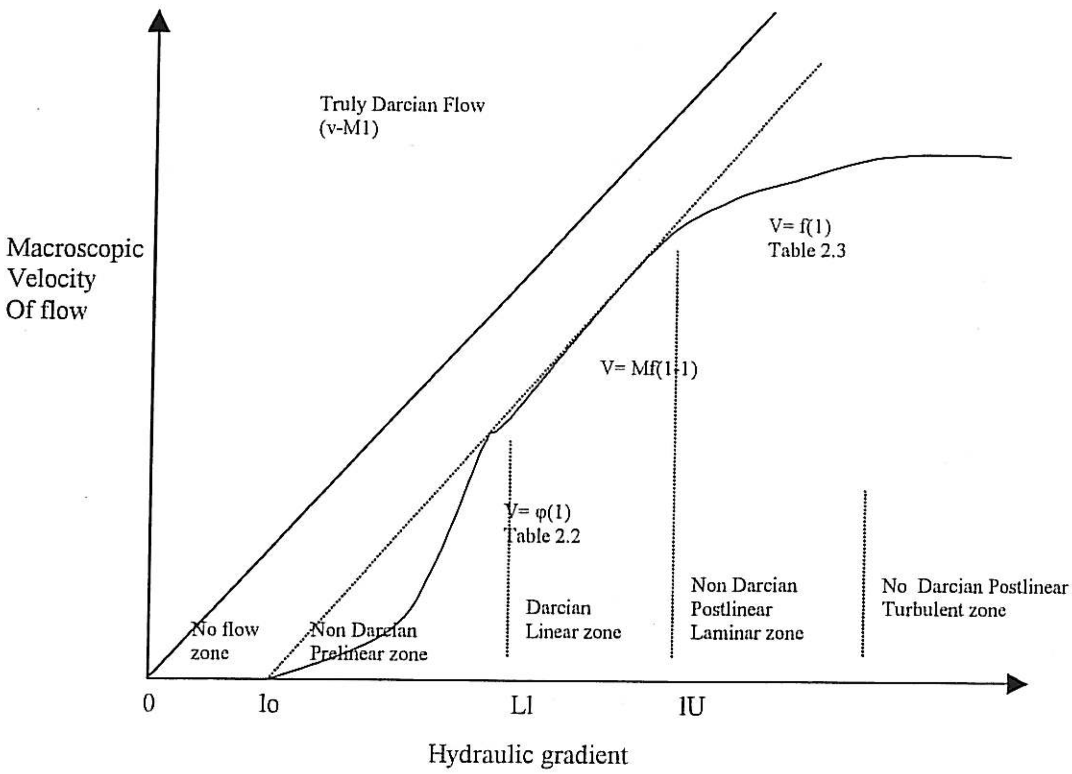


Figure 2.6: Probable velocity – gradient relationship over large range of velocity.

The five zones are :-

i. No flow zone: This zone is likely to exists only in case of dense porous media of high colloid content. In this zone, surface forces are strong enough to counteract a certain portion of applied gradient and is denoted by i_0.

ii. Non-Darcy prelinear laminar zone: Any surface active porous media is likely to show this zone. The surface forces arising out of the solid-fluid interaction due to strong negative charges on particle surfaces and dipolar nature of water molecules causes the velocity gradient response to be nonlinear and thus non-Darcian (Swartzendruber, 1962). Various authors have suggested various forms of equations to describe the flow process in this zone and they are summarized in Table 2.2.

Table 2.2: Available non-Darcy equations at low Reynolds number.

Equation	Original proposer	Comments
$v = Mi^n, n > 1$	Izbash, Hansbo	Empirical
$v = \alpha(u/\alpha)^{f-1} K^f i^f, f > 1$	Slepicka	Semiempirical
$v = Ai + C/i^f - B$	Valarovich and Tchuraev	Empirical
$v = Ki(1/3)(i_0/i)^4 - (4/3)(i_n/i) + 1)]$	Nerpin and Tchudnovskij	Theoretical
$v = M[i-1)1 - e^{-1/I})]$	Swartzendruber	Empirical
$v = M[i - j(1 - e^{-ci})]$	Swartzendruber	Empirical
$v = M[(1/B)\log(A + e^{\alpha i}) - I_0$	Kutilek	Empirical
$Note: A, B, C, f, I, I_0, M, n, \alpha = constant$		

iii. Darcian laminar regime. Almost all the natural soils exhibit this zone to a certain extent though the width of this zone may vary widely depending on the type of soil. In this zone the effect of surface forces is not felt, and the influence of inertial forces are negligibly small compared to viscous forces.

iv. Non-Darcy post-linear laminar zone: This is the zone where flow is still laminar but a gradual increase in inertial force makes the flow deviate from Darcian linearity. Various available equations for this high velocity zone proposed by various authors are summarized in Table 2.3.

v. Non-Darcy post-linear turbulent zone: Here, the onset of turbulence is first noted and the substantial part of applied gradient becomes dissipated in overcoming the inertial forces and consequently the rate of velocity gain is very much less compared to earlier regimes.

Note that for all soils, all the flow zones previously mentioned may not exist.

Table 2.3: Published nonlinear flow equations at high Reynolds numbers.

Equation	Original proposer	Explanation of terms	comments
$i = av + bv^2$	Forchhiemer	a,b, constantswith unitsof $(T/L)^2$	Empirical but theoretical basis was found later by Irmay (1958) and Ahmed (1967)
$i = av + bv^2 + cv^3$	Forchhiemer	a,b,c constants	Empirical
$i = av + bv^{1.5} + cv^2$	Rose	a,b,c constants	Empirical
$i = av + bv^2 + c(\partial v / \partial t)$	Poluborinova-Kochina	a,b,c constants	Empirical
$i = av + bv^m$	Muscat and Harr	a,b,m constants	Empirical
$v = Mi^n, n < 1$	Isbazh	N constant with unit L/T, n non-darcy exponent	Empirical value of n lies between 1-1.5
$i = av^m, m > 1$	Missbach	a=constant, m non-Darcy exponential	Empirical
$v = (Bi)^{1/2}$	Escande	B= constant	Empirical B varies between 80 (cm/s)2-290 (cm/s)2 for particle of 2.54cm dia
$v = 32.9m^{1/2}i^{0.54}$	Wilkinson	m, hydraulic radius	Semi-empirical based on test results with particles 1.905-7.62cm
$v = \alpha(\mu /\sigma)^f (ki)^f$	Slepicka	α, f, k constant, μ viscosity, σ surface tension	Semiempirical derived from dimensional analysis

For example, for clays, the existence of the last two zones is highly improbable whereas for sands and other coarse inert materials, the first two zones may not exist or may not noticeable within the ordinary experimental accuracy. Moreover, neither any unified theory nor any consistent experimental data are available for critical gradients or velocities demarcating different zones of flow mentioned. Preceding analysis points to the fact that while using Darcy's linearity for various field problems, one should be careful in interpreting and using the results in pre and post-linear regime. If the published experimental velocity-gradient response for the last few decades for clays and sands under low gradients is any indication of the actual state of affair, then the majority of flow problems in clayey, loamy, and organic soils (such as peat), as well as flow through fine grained sandy deposits under low gradients, would be largely met by prelinear regime (e.g. Dudgeon 1966; Kutilek 1969; Swartzendruber 1962).

As seen from Table 2 and Table 3, no general equation is available which gives the actual shape over the entire gradient range. Equation in Table 2 cover only the prelinear regime and equations in Table 3 cover only the post-linear regime, and a single equation covering prelinear, linear and post-linear regime is very much lacking. In this mitigating circumstances, the best alternative is to use Izbash's flow equation of the type

$$v = Mi^{n} \tag{2.4}$$

which is one of the two most widely used non-Darcy flow equations, the other being Forchhiemer's which reads

$$i = av + bv^{2} \tag{2.5}$$

Izbash's equation is preferred over Forchhiemer's because the former can be made to represent all three zones, e.g., prelinear ($n>1$, $i<1$), linear ($n = 1$), and post-linear ($n < 1$, $i>1$) zones, whereas the latter can be made to represent only the linear ($b = 0$) and the post-linear regime. Thus it becomes apparent that a very useful purpose would be served by having solutions of various physical problems incorporating Izbash's flow equation and observing the effects on various parameters as the non-Darcy exponent, n, changes its value from more than unity to unity and then less unity.

2.6 Application Of Izbash's Equation In Coarse Porous Media

A study on the suitability of Izbash's equation in predicting flow in different coarse materials have been done by Bordier & Zimmer (2000). In their studies, gravel materials and geosynthetic products have been used. In coarse porous media, Darcy's Law is not valid because of turbulence. Owing to turbulence, head loss increases more than proportionally with macroscopic velocity.

To investigate this issue, Bordier & Zimmer (2000), studies have been done on the flow of different types of granular and geosynthetic drainage materials experimentally and the fitness of Izbash's equation was compared. The Izbash's equation is in the form of :

$$v = Mi^n \qquad (2.6)$$

known as the Izbash's Law or power law (Izbash, 1931). This law is only empirical and is likely to be preferred to for modeling purposes as pointed out by Basak (1977) because it is in continuity with Darcy's Law which corresponds to the case n =1. M would be the hydraulic conductivity, λ and represents the effective permeability of the material at unit hydraulic gradient. The results of the studies done by Bordier & Zimmer (2000) are summarizes in Table 2.4 below with the fitted coefficients of Izbash's Law. Figure 2.8 shows the graph of macroscopic velocity against hydraulic gradient of the five tested materials for the measurements in experiment and also fitted by the Izbash's Law. From the results of their study, it can be shown that excellent adjustments were obtained for all materials by using the Izbash's Law.

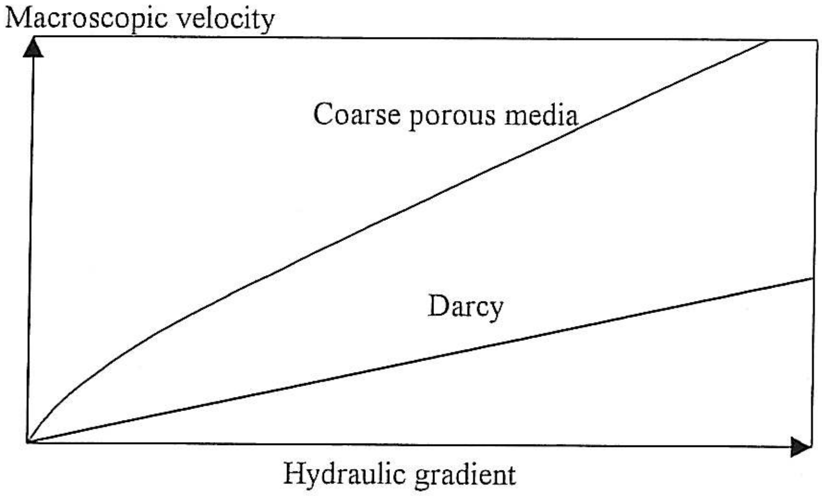


Fig 2.7: Relationship between hydraulic gradient and macroscopic velocity in fine porous media complying with Darcy's Law (straight line) and coarse porous media (dotted line).

Table 2.4: Fitted coefficients of Izbash's Law for the five tested materials

Material	Gravel 1	Gravel 2	Geonet	DCC geo-composite	3-layered geo-composite
Porosity	*0.49*	*0.46*	*0.90*	*0.95*	*0.85*
Izbash law					
n	*1.89*	*1.76*	*1.78*	*1.80*	*1.34*
λ	*0.145*	*0.176*	*0.394*	*0.380*	*0.142*
Regresion coefficient, r^2	*0.996*	*0.999*	*1.000*	*0.995*	*0.997*

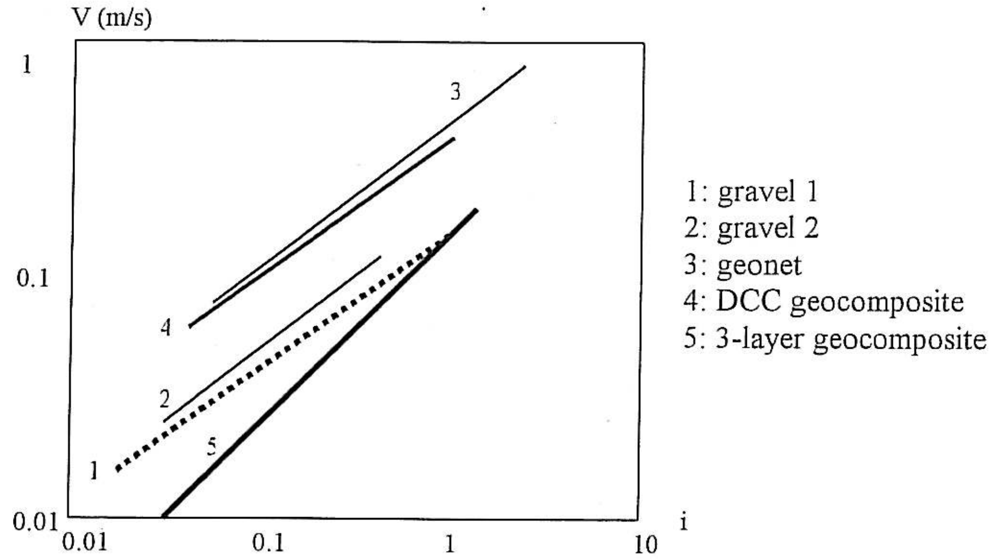


Fig 2.8: Macroscopic velocity (v) vs hydraulic gradient (i) for the five tested materials

From the studies of Bordier & Zimmer (2000), it seems that Izbash's Law is quite suitable to predict the flow through coarse porous media. It can also be observed that the n value (Izbash's parameter) is strictly lower than 2 because if n value reaches 2, the flow becomes fully turbulent. Thus, in this project, the suitability of Izbash's Law will be determined to predict the flow through peat soil column by determining the n value (Izbash's parameter) from the result of the experiment.

CHAPTER 3

METHODOLOGY

3.0 Introduction

The experimental works of this project was divided into two parts. Part one involved field works such as collecting samples and determining the hydraulic conductivity value on site. Part two involved laboratory works where the collected samples were tested on its moisture content and ash content and also the validity of Darcy's Law through a peat soil column apparatus. The peat samples were taken from a research area at Parit Madirono, Benut, Johor. Most of the laboratory works were done in the Hydraulic Laboratory of the Faculty of Civil Engineering, Universiti Teknologi Malaysia.

3.1 Preparation of Peat Samples

Sampling was done at Parit Madirono in Benut, Johor. Samples from 3 different depths were taken. Before the samples were taken, a peat auger was used to get the sample of peat from different depths so as to determine the thickness of different decomposition of peat for the area. Different decomposition can be determined by comparing the changes of colour of the peat samples from different depth or through a Von Post scale scheme by using the samples from peat auger. Figure 3.1 shows a sample of peat taken by using peat auger where the different in colour with depth shows different degree of decomposition. Figure 3.2 shows the Von Post scale determination by squeezing a sample of peat in the hand, allowing liquids and soft solids to ooze out.

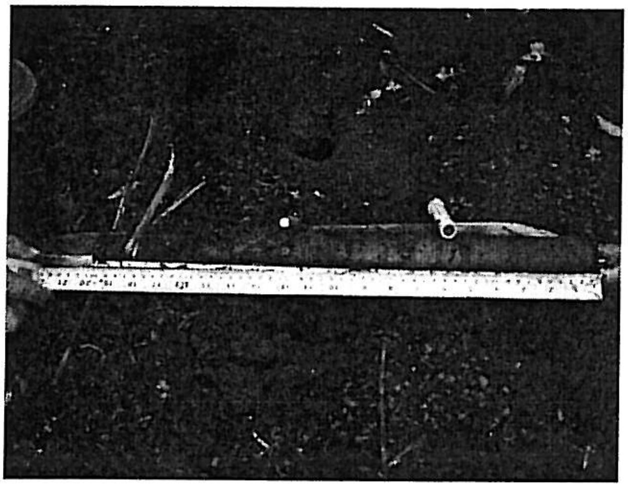


Figure 3.1. Peat sample as taken by peat auger with markings showing the difference colour or degree of decomposition.

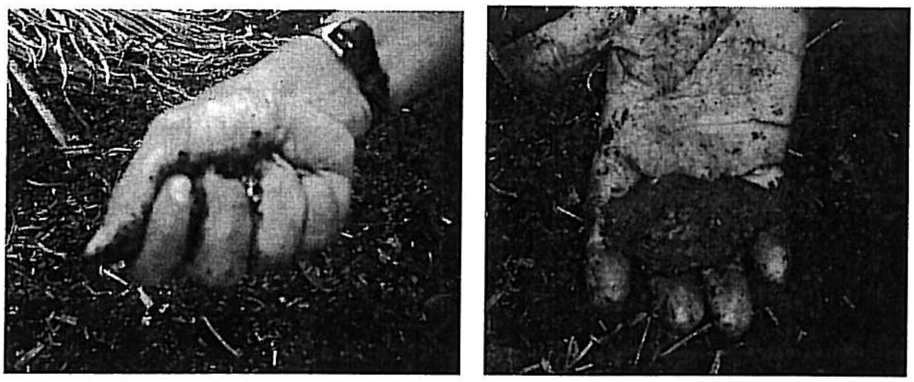


Figure 3.2. Von Post scale determination onsite.

The appearance of the material squeezed out and the material retained determines the degree of humification on a ten-point scale.

From the sampling by peat auger it is decided that the three depths that will produce different decomposition are at 0 cm – 15 cm, 15 cm – 30 cm and 30 cm – 45 cm from ground level. Samples of peat from these three depths were taken and put inside transparent PVC pipes 2" diameter. Figure 3.3 shows the empty transparent PVC pipe 2" diameter before the sample is put in and Figure 3.4 shows the PVC pipes with samples of peat from three different depths. In addition, the sample in the pipes, some soil samples from these three depths were taken for moisture content and ash content experiment in the laboratory. Since the experiment for the peat soil column was done in saturated condition, the PVC pipe together with the soil sample inside was immerse immediately in water after taken out from the site as shown in Figure 3.5.

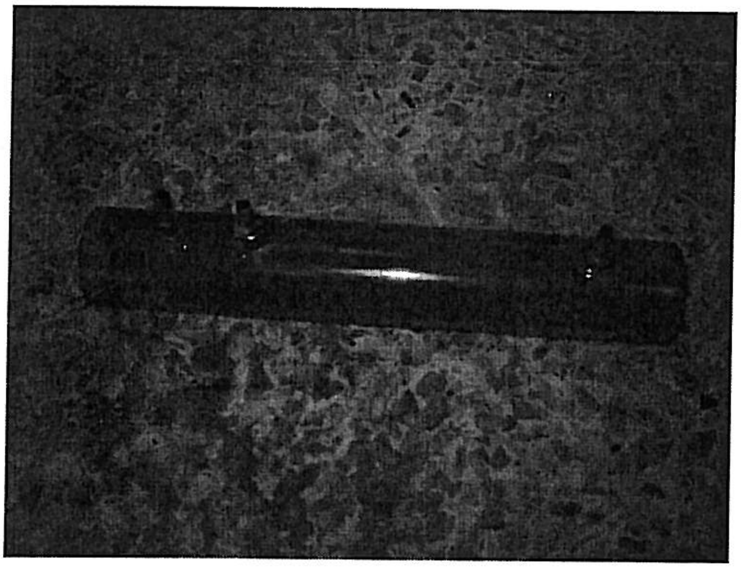


Figure 3.3. The transparent PVC pipe 2" diameter used in column study

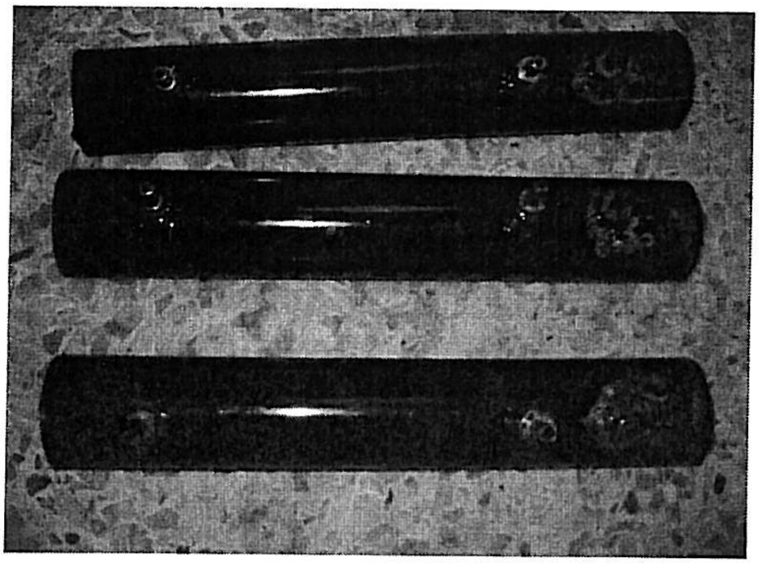


Figure 3.4. The transparent PVC pipes filled with peat samples

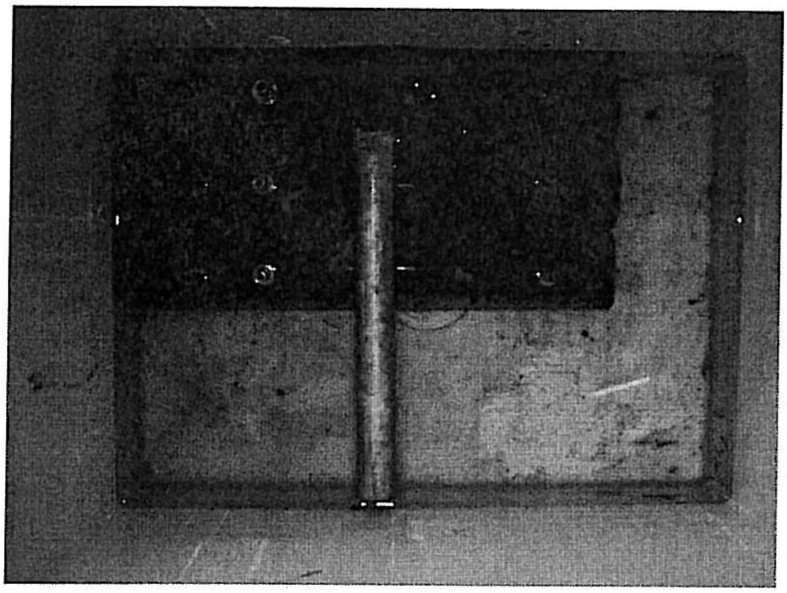


Figure 3.5. PVC pipe together with the soil sample inside immerse immediately in water after taken out from the site.

3.2 Determination of Hydraulic Conductivity on Site

To determine the peat soil hydraulic conductivity on site, an instrument called guelph permeameter was used. The procedure for this experiment is based on a manual from 'Soilmoisture Equipment Corp'. A hole for each depth of 0 cm – 15 cm, 15 cm – 30 cm and 30 cm – 45 cm was make for this experiment. Figure 3.6 shows a diagram of guelph permeameter. Figure 3.7 shows a setup of guelph permeameter onsite.

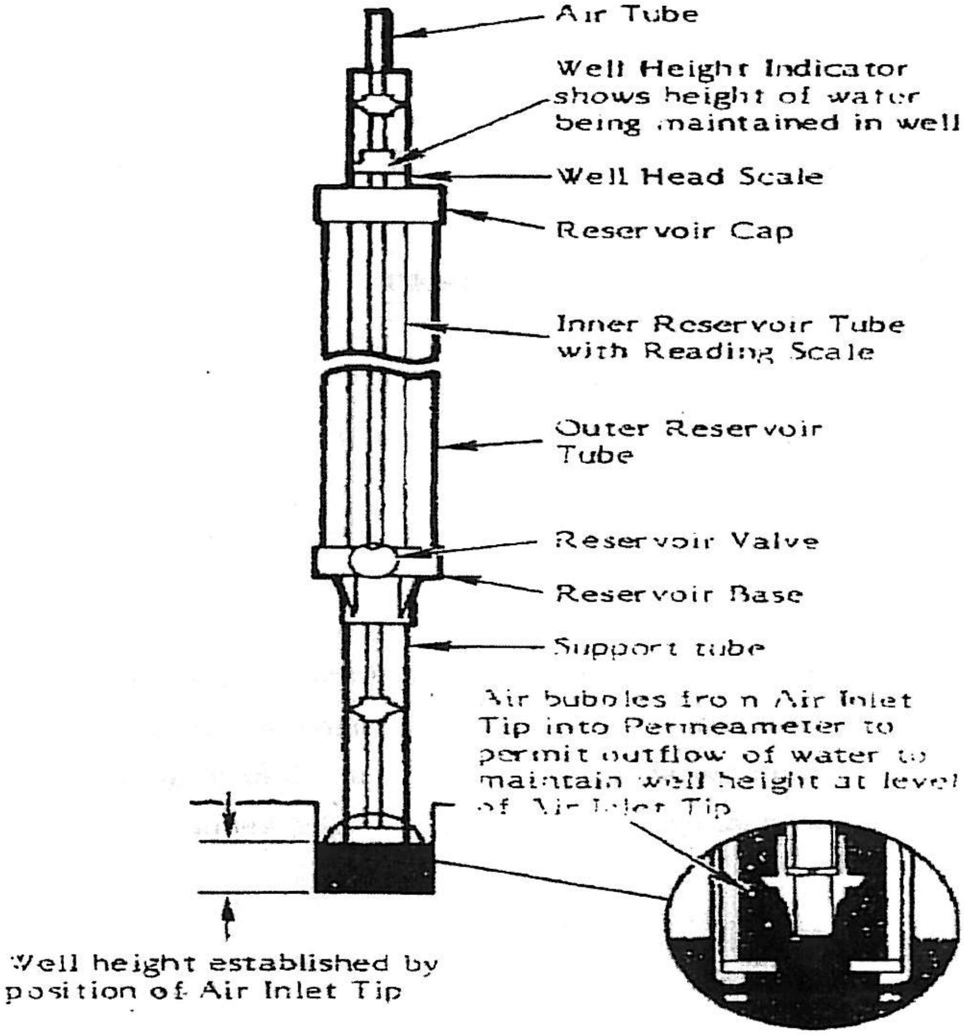


Figure 3.6. Guelph Permeameter.

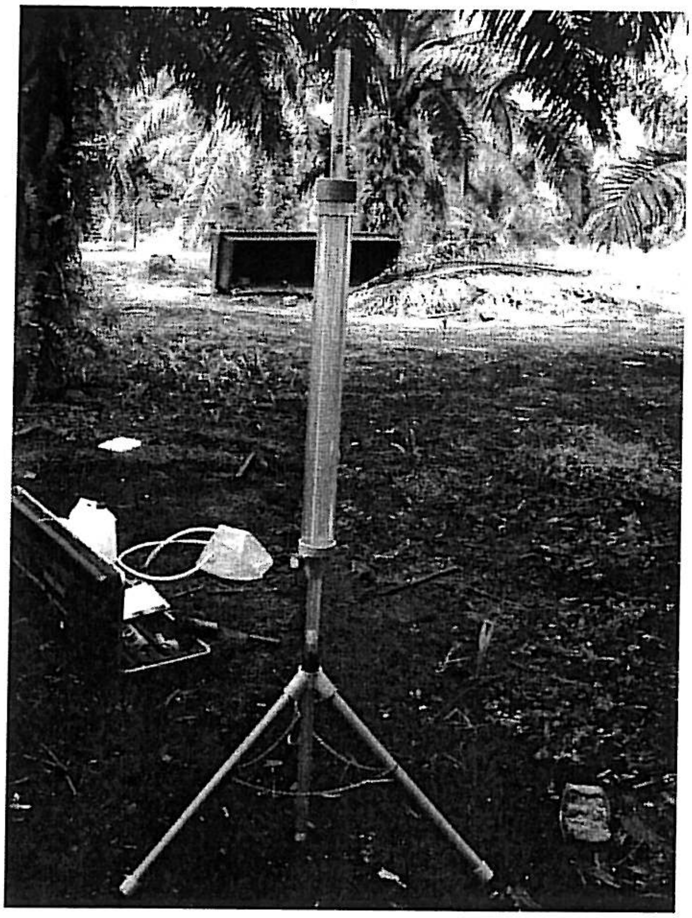


Figure 3.7. Setup of guelph permeameter onsite.

Guelph Permeameter model 2800K1 is a constant head instrument and function based on the Mariotte siphon principle. The procedure for determining the hydraulic conductivity of peat soil is as mentioned below:

i. Drilling was done by hand auger to the required depth.

ii. Install the Guelph Permeameter.

iii. Water was filled into the permeameter reservoir until no air bubble.

iv. Guelph Permeameter was installed into the hole vertically and in the middle of the hole.

v. Type of reservoir was choose, whether combination reservoir for fast flow or inner reservoir for slower flow.

vi. Water is let to flow with head of reservoir at $H_1 = 5$ cm. Reading is recorded at certain interval depending on the rate of water falling from the reservoir.

vii. Reading was recorded until a certain constant rate is achieved for at least 3 readings and the R_1 value is determined.

viii. Steps (i-vii) was repeated with reservoir head at $H_2 = 10$ cm. The R_2 value is determined.

Calculation was done to determine the field saturated hydraulic conductivity, K_{fs} value as follows :-

$$K_{fs} = (0.0041)(X)(R_2) - (0.0054)(X)(R_1) \quad (3.1)$$

where,

H_1 = the first head recorded for the reservoir in unit cm

R_1 = the constant falling rate for the reservoir head with reservoir head at H_1 in unit cm/s

H_2 = the second head recorded for the reservoir in unit cm

R_2 = the constant falling rate for the reservoir head with reservoir head at H_2 in unit cm/s

X = the constant when combination reservoir is used, in unit cm^2

Y = the constant when inner reservoir is used, in unit cm^2

K_{fs}= hydraulic conductivity of saturated soil in unit cm/s

The constant falling head rate of the is calculated as,

$$R = \frac{\text{Difference in reservoir head}}{\text{Time taken}}$$

3.3 Determination of Moisture Content and Ash Content

The peat soil samples were determined for moisture content and ash content based on ASTM D 2974 – 00 but with some modification where necessary. To determine the moisture content, the following procedure was used:

i. The mass of an evaporating dish container was recorded to the nearest 0.01g.

ii. A test specimen of peat soil was place in the container, the thickness of peat inside the container should not exceed 3 cm.

iii. Record the mass of the peat sample and container to the nearest 0.01 g. Figure 3.8 shows peat sample inside evaporating dish container for the three different depths of peat sample.

iv. Drying process was done for at least 16 hours at 105 °C or until there was no change in mass of the sample after further drying periods in excess of 1 hour. Remove the sample from the oven and let it cool. Then, record the mass to the nearest 0.01 g. Figure 3.9 shows the peat sample as dried inside an oven.

Figure 3.8. Peat soil samples inside evaporating dish container.

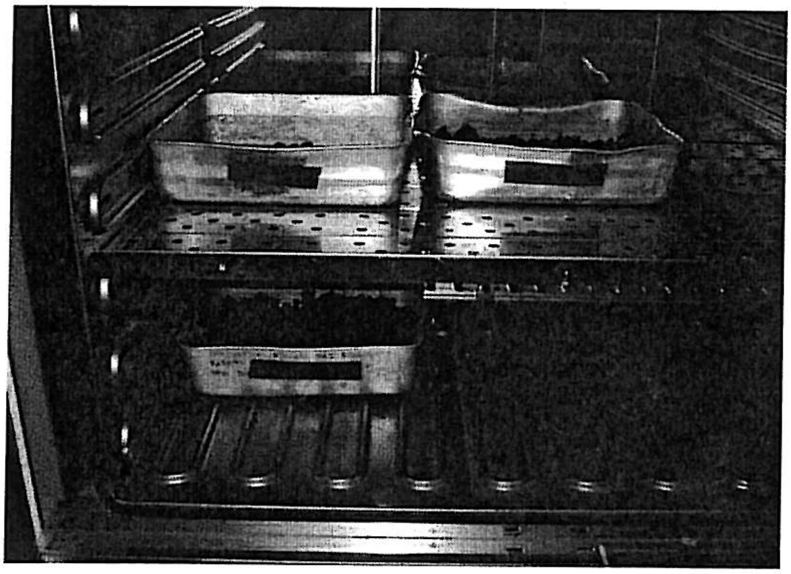


Figure 3.9: Peat soil sample with evaporating dish container inside an oven.

The moisture content is calculated as follows:

$$\text{Moisture Content, \%} = [(A - B) \times 100]/B$$

where : A = as-received test specimen, g, and

B = mass of the oven-dried specimen, g.

To determine the ash content, the following procedure will be used:

i. The mass of a covered high-silica or porcelain dish was determined to the nearest 0.01 g.

ii. A part or all of the oven-dried test specimen from the moisture determination was place in the dish and determine the mass of the dish and specimen. Figure 3.10 shows the determination of the mass for the dish and specimen.

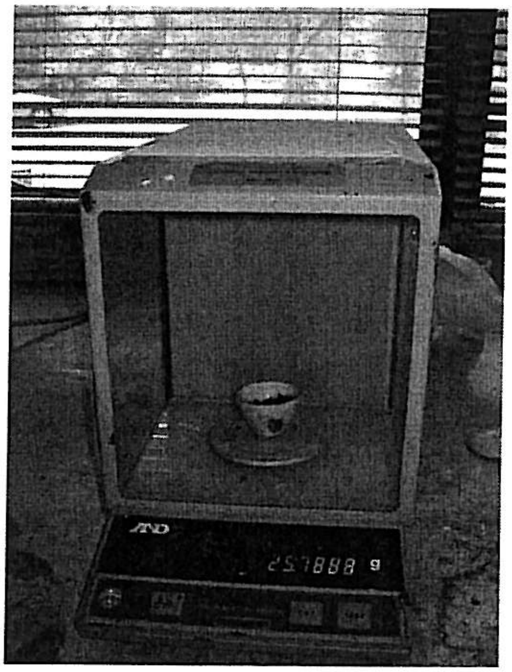


Figure 3.10. Determination of the mass for the porcelin dish and specimen.

iii. Place the dish in a muffle furnace or oven. Gradually bring the temperature to 440 °C (medium temperature ashing) and hold until the specimen was completely ashed (no change of mass occurs after a further period of heating). Figure 3.11 shows the porcelin dishes containing peat sample inside an oven.

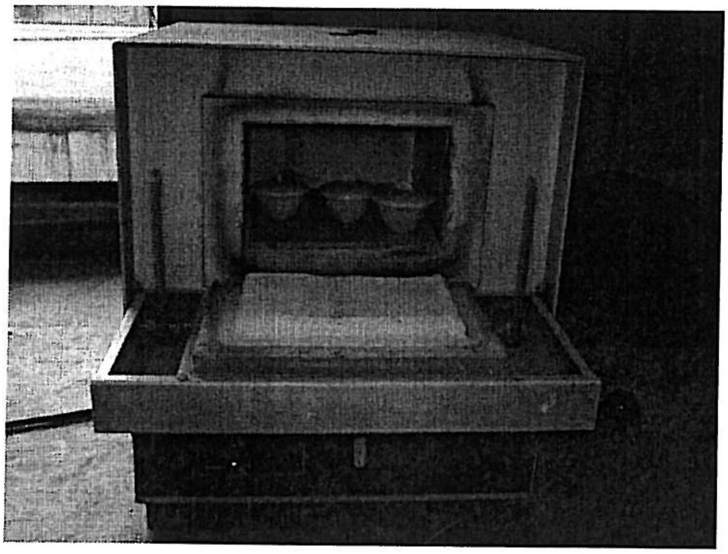


Figure 3.11. Oven with porcelin dishes containing peat sample.

iv. Cover the sample and let it cool, and determine the mass to the nearest 0.01 g.

v. For each depth, three samples will be used. Repeat procedure 1 to 4 for all the samples from the different depths.

vi. Calculate the ash content as follows:

$$\text{Ash Content, \%} = (C \times 100)/B$$

where : C =ash, g, and

B = oven-dried test specimen, g.

vii. Determine the amount of organic matter by difference, as follows:

Organic Matter, % = 100.0 – D

where : D =ash content, %

3.4 Validity of Darcy's Law Test through a Peat Soil Column Apparatus

In order to test the validity of Darcy's Law through peat soil, a peat soil column apparatus as shown in Figure 3.12 was set-up. The peat soil column sample is taken from the site in a transparent PVC pipe from 3 different depths as mentioned earlier.

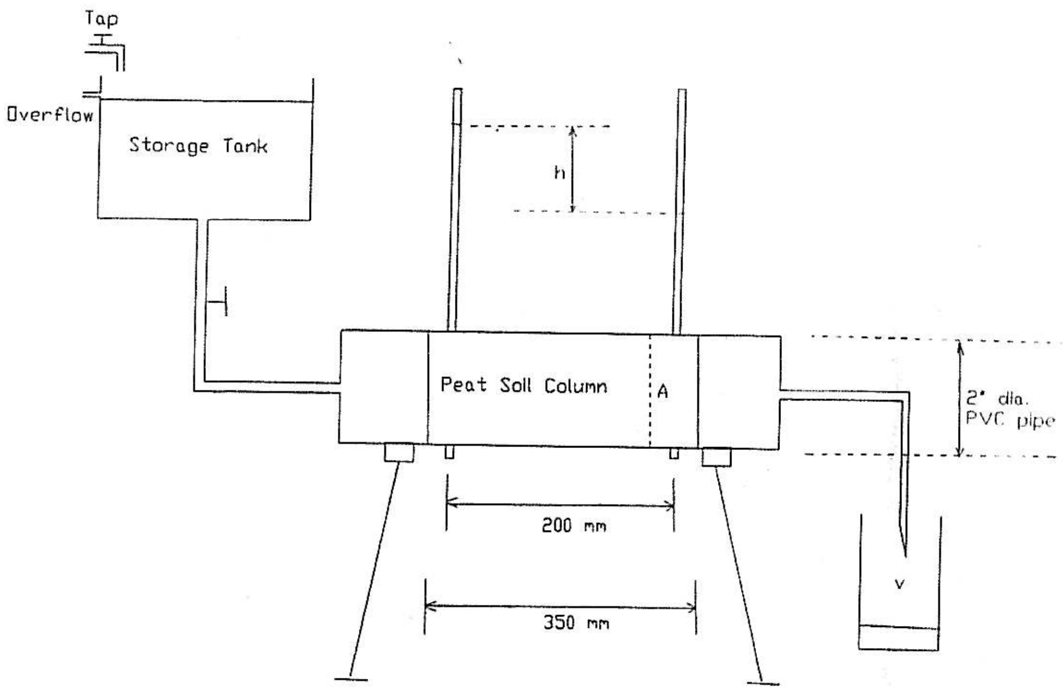


Figure 3.12. Peat soil column apparatus (not to scale).

With the peat soil column, for each soil sample, different values in hydraulic gradient were applied in order to obtain discharge velocity, v of the sample. To obtain the discharge velocity, v, the time taken to fill the measuring cylinder to a certain volume was recorded. The discharge velocity, v can be obtain using the formula below:-

$$\text{Discharge velocity, v (m/s)} = \frac{\text{Volume in measuring cylinder, V}}{\text{Time taken, t}} \div \frac{\text{Area of peat soil}}{\text{column cross section, A}}$$

The experiment was repeated for the other peat soil column of different depths. Figure 3.13 shows the overview of the peat soil column apparatus that has been used in this project while Figure 3.14 shows the close-up side view of the peat soil column apparatus. Figure 3.15 shows how the water flowing through the peat soil column apparatus drips into the measuring cylinder and the time taken to fill certain volume will be recorded in order to determine the discharge velocity while Figure 3.16 shows the difference between the manometer reading for 2 different points inside the peat soil column during the experiment.

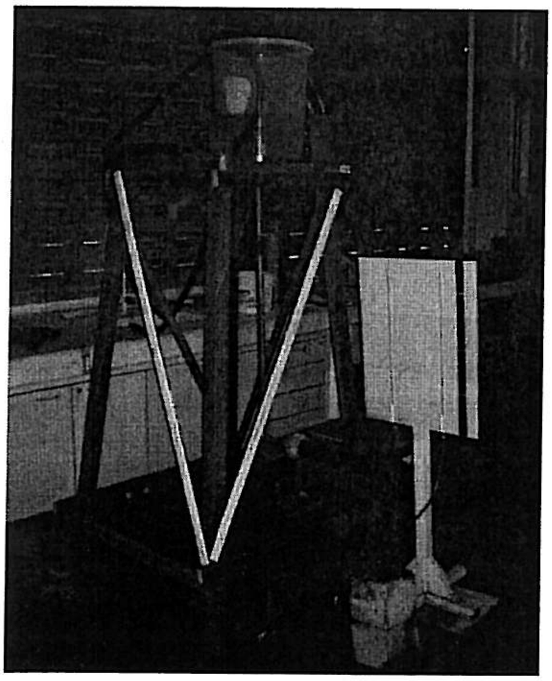


Figure 3.13. The peat soil column apparatus.

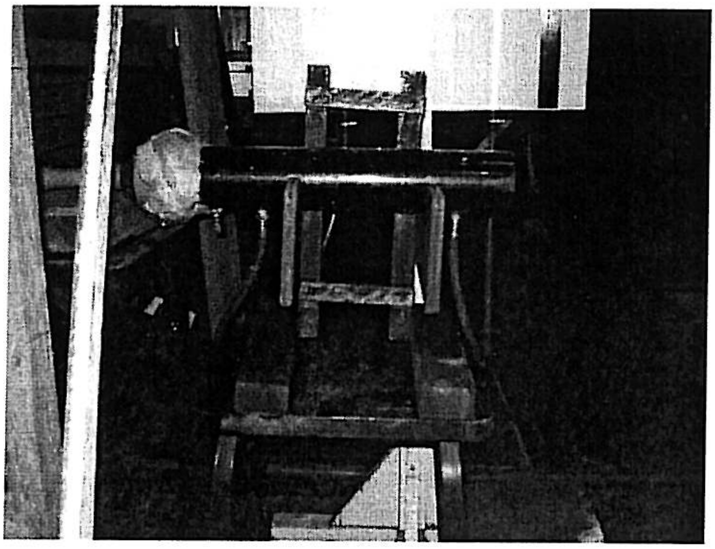


Figure 3.14. Close-up side view of the peat soil column apparatus.

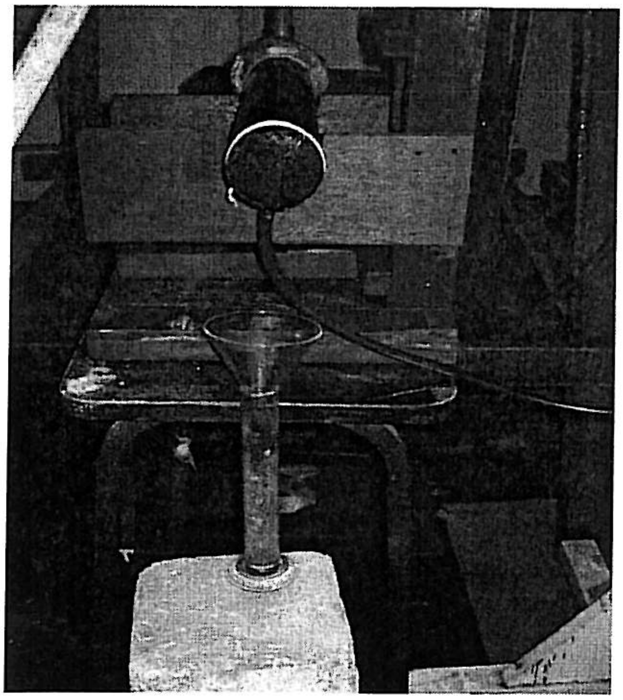


Figure 3.15. Water flowing through the peat soil column dripping into the measuring cylinder.

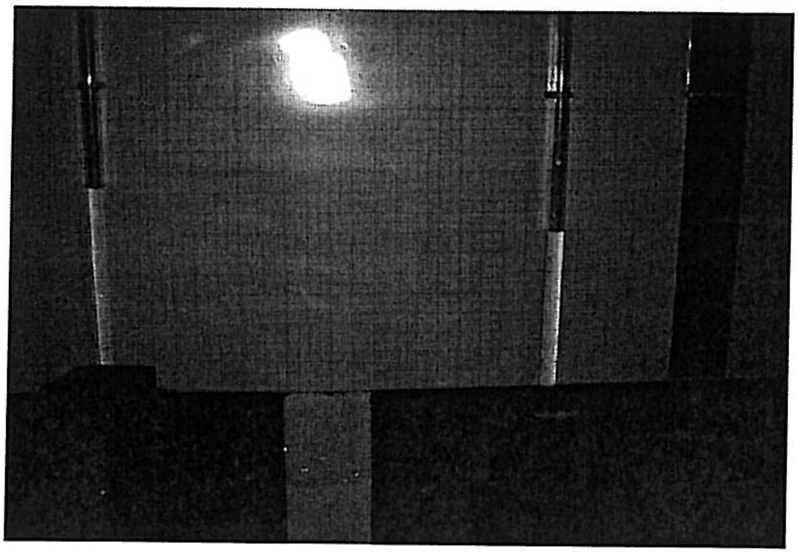


Figure 3.16. Difference in manometer reading between two points inside the peat soil column during the experiment.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

The purpose of this project was to show that Darcy's Law is inaccurate for flow through peat soil column by comparison between the velocity predicted by Darcy's Law and the measured velocity (through experiment). From the result of the experiment, by fitting the Izbash's Law, the velocities calculated by this law were compared to the actual velocity from the experiment to determine the suitability of this law in predicting the flow through a peat soil column. Beside that, the effect of different degree of decomposition/organic content with the deviation from Darcy's Law has been quantified. A relationship between hydraulic conductivity, K values with different degree of decomposition/organic content has also been established.

4.1 Result from Von Post Scale Determination On-site

Figures 4.1, 4.2 and 4.3 show the Von Post scale determination by squeezing a sample of peat in the hand, allowing liquids and soft solids to ooze out for the depth of 0 cm – 15 cm, 15 cm – 30 cm and 30 cm – 45 cm respectively. The appearance of the material squeezed out and the material retained is then compared to the Von Post scale of humification (Table 2.1, section 2.1 b) of this report). From the Von Post scale determination it is concluded that for depth 0 cm – 15 cm, it is of H7 in the Von Post scale of humification; for depth 15 cm – 30 cm is of H6 and for depth 30 cm – 45 cm is of H5.

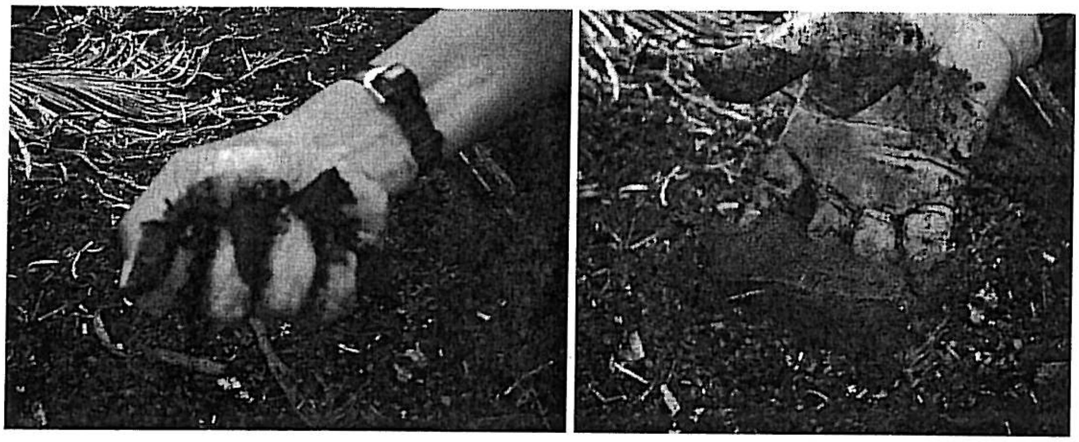


Figure 4.1. Von Post scale determination for depth 0 cm – 15 cm; it is concluded that for this layer it is of H7.

Figure 4.2. Von Post scale determination for depth 15 cm – 30 cm; it is concluded that for this layer it is of H6.

Figure 4.3. Von Post scale determination for depth 30 cm – 45 cm; it is concluded that for this layer it is of H5.

4.2 Result of On-site Hydraulic Conductivity Determination Using Guelph Permeameter

To determine the hydraulic conductivity on-site, holes have been made at depths 12.5 cm, 22.0 cm and 37.0 cm to represent the hydraulic conductivities at depths 0 cm – 15 cm, 15 cm – 30 cm and 30 cm – 45 cm respectively. The procedure for this test is mentioned in section 3.2. Appendix A at the end of this report shows the form that has been used in recording the permeameter readings and calculations. The result of this test is summarizes in Table 4.1.

Table 4.1: Summary of result from onsite guelph permeameter test.

Depth	Hydraulic conductivity, k (cm/s)
0 cm – 15 cm (holes at depth 12.5 cm)	0.002349
15 cm – 30 cm (holes at depth 22.0 cm)	-2.12×10^{-5}
30 cm – 45 cm (holes at depth 37.0 cm)	-0.001369

From the on-site testguelph permeameter , only the top layer (0 cm – 15 cm) has a positive value while the deeper layer has negative value. A negative value occurs, it indicates the presence of hydrologic discontinuity or holes. This may be true for deeper peat soil layer due to the presence of undecomposed plants matter such as branches and roots. While for the top layer, the presence of holes is minimal due to compaction. So, the reading from guelph permeameter is not that reliable.

4.3 Result of Moisture Content and Ash Content Determination

The determination of moisture content and ash content was done based on the procedure mentioned in section 3.3 of this report. Appendix B at the end of this report shows the table used for recording the data and calculation of moisture content and ash content. For moisture content, the result is as summarized in Table 4.2 while Figure 4.4 shows the difference in the structure of a sample of peat soil before and after oven-dried for moisture content determination purposes. From the result, it can be said that peat soil generally has a high moisture content which means high water holding capacity. When oven-dried, most of the weight of the peat sample will be lost because most of the weight of peat soil is made-up of water. This shows that peat soil has a spongy characteristic.

Table 4.2: Summary of result from moisture content determination.

Depth (cm)	Moisture Content (%)
0 – 15	144.95
15 – 30	444.84
30 – 45	587.34

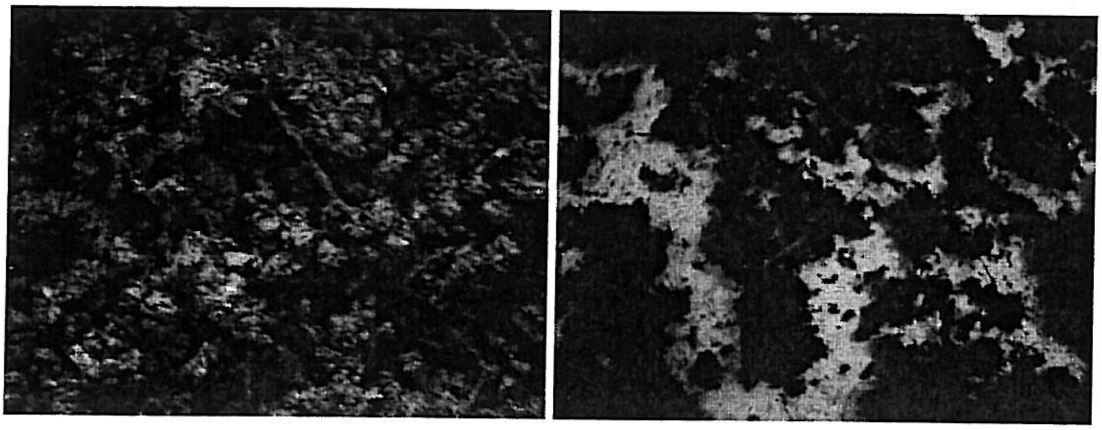


Figure 4.4: Difference between the structures of peat soil before oven-dried (left) and after oven-dried (right) for a sample taken at depth 30 cm – 45 cm.

For ash content, the result is summarized in Table 4.3. Figure 4.5 shows the difference for an oven-dried peat sample before the ash content test and after the test where the sample turns into ash which is lighter in colour. Based on the classification of peat and organic sediments by ash and organic content used by the Organic Sediments Research Center of the University of South Carolina, layer 0cm – 15cm is of high ash content, layer 15cm – 30cm is of low ash content and layer 30cm – 45cm is of medium ash content.

Table 4.3: Summary of result form ash content test.

Depth (cm)	Organic Content (%)	Ash Content (%)
0 – 15	75.67	24.33 (High Ash)
15 – 30	95.11	4.89 (Low Ash)
30 – 45	94.70	5.30 (Medium Ash)

Figure 4.5: Difference for an oven-dried peat sample before the ash content test (right) and after the test (left).

4.4 Result from Validity of Darcy's Law Test Through a Peat Soil Column Apparatus

The procedure for this test is as mentioned in section 3.4 of this report. From this test also, the average hydraulic conductivity, k values from the three different depths that represent the different degree of decomposition can be obtained. This k values have been used to calculate the velocity through the peat soil column by using Darcy's Law and also Izbash's Law. Table 4.4 shows the average k value (experimental) with depth.

The average hydraulic conductivity, K value (from experiment) seems to increase first than decrease as the layer becomes deeper.

Table 4.4. Average K value from the experiment.

Depth (cm)	Average experimental K value (m/s)
0 – 15	9.4×10^{-6}
15 – 30	0.00033
30 – 45	0.000173

This seems to conform the finding by Rizzuti et al. (2004) on core samples for peat taken across Peat Bay, South Carolina, where the hydraulic conductivities tended to increase with depth for the first 25 cm and then decrease with depth, perhaps as a result of either auto compaction of the peat or changes in original environments of deposition (climate, hydrology, etc.) that effected depositional processes swamp-wide and, consequently, physical composition of the organic sediments.

Appendix C shows the tabulated data from the peat soil apparatus test to check the validity of Darcy's Law. If the graph for observed velocities (from the experiment) against hydraulic gradient, i plotted on the same graph with the velocities predicted using Darcy's Law against hydraulic gradient, i (see Figure 4.6) for each of the different depth, there are some differences between these two graphs because Darcy's Law assumes a linear relationship between velocities and hydraulic gradient (straight line graph) while in real situation it may not be the case.

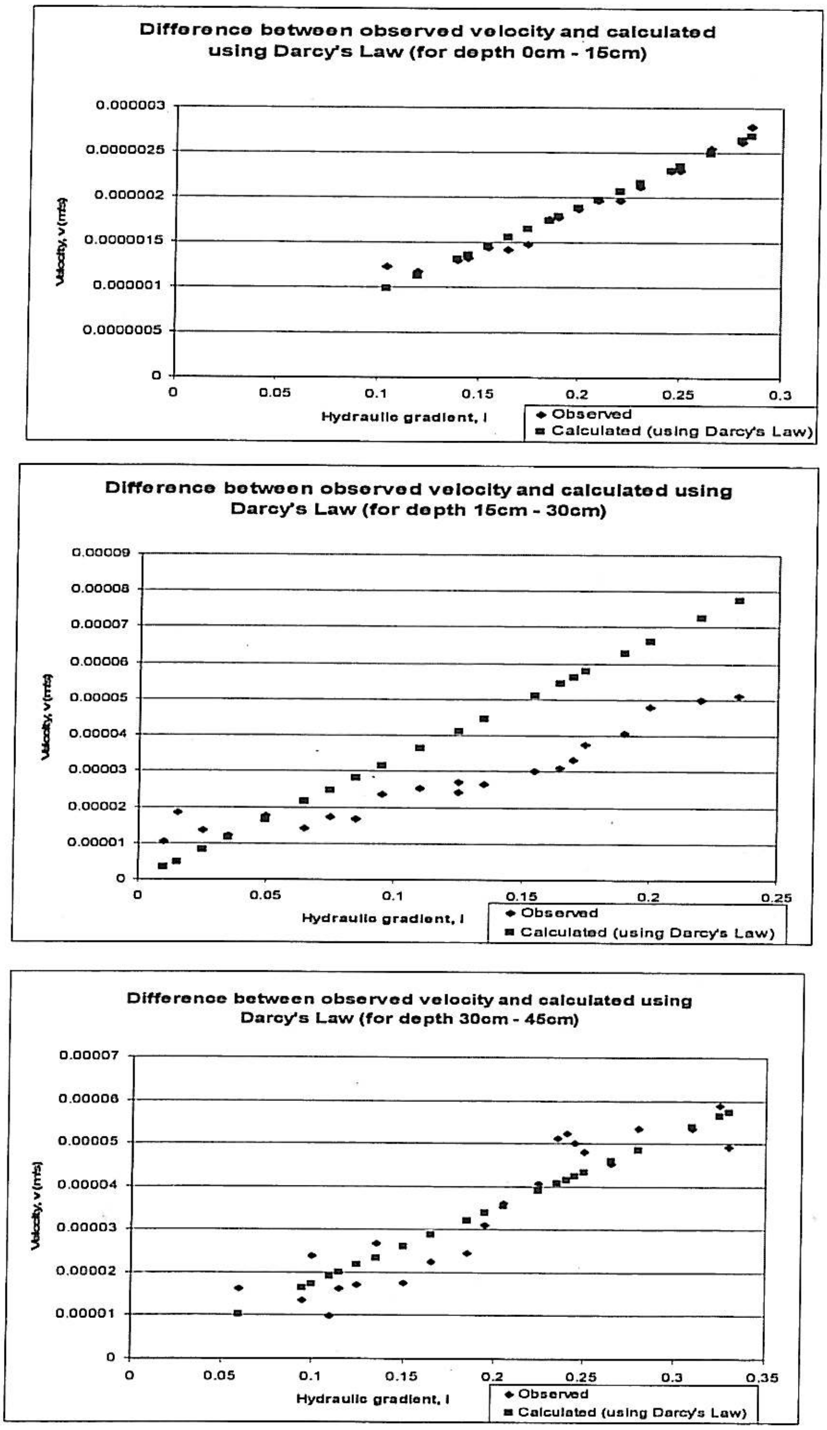


Figure 4.6. Difference between the observed velocity and the calculated velocity using Darcy's Law for the three different depths of peat soil column sample.

Table 4.5 shows the linear regression values, r^2 for the three different depths when the velocities observed are plotted against velocities calculated using Darcy's Law. If the linear regression r^2 value is closer to 1, this shows that velocities observed are closer to velocities calculated using Darcy's Law.

Table 4.5. Linear regression, r^2 values for the three different depths when observed velocities were plotted against velocities calculated using Darcy's Law.

Depth (cm)	Linear regression, r^2
0 – 15	0.9683
15 – 30	0.9035
30 - 45	0.8593

From the results, the r^2 value closest to 1 at the upper layer (depth 0cm – 15 cm) which is according to Hemond and Goldman (1985) where Darcy's Law is appropriate for upper unhumified layer. As the layer becomes deeper, the linear regression values reduced. This shows that at the deeper layers, deviation from Darcy's Law becomes larger. From this it can be said that Darcy's Law becomes less accurate when the peat layer becomes deeper. However, in this project, the linear regression values seem to be still within acceptable range for the three different depths which means that Darcy's Law still can be acceptable. This is because in this project low hydraulic gradients are being used, however, this may not be the case if high hydraulic gradients are being used where the effect of deviation from Darcy's Law will become larger, thus producing linear regression values that are far lesser than 1. In the next section, Izbash's Law was be used where a much better adjustment can be obtained. The linear regression values are higher when the observed velocities were plotted against the calculated velocities using Izbash's Law.

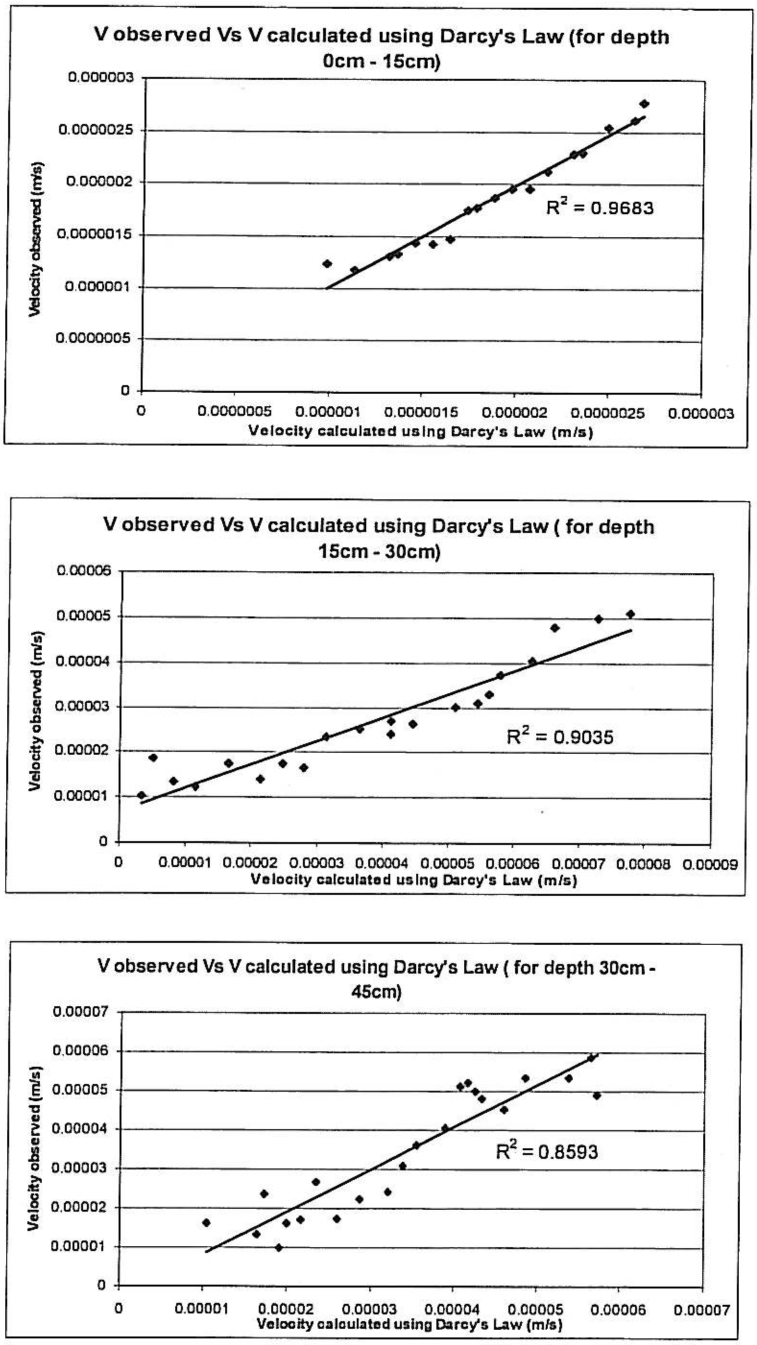


Figure 4.7: The observed against calculated velocities using Darcy's Law

against velocities calculated using Darcy's Law. This shows that Izbash's Law can provide a much better approximation of water flow through much deeper peat layer. Figure 4.7 shows the graphs when observed velocities are plotted against velocities calculated using Darcy's Law with the linear regression values for the three different depths

Table 4.6: Summary of the trial and error calculation for the linear regression, r^2 values.

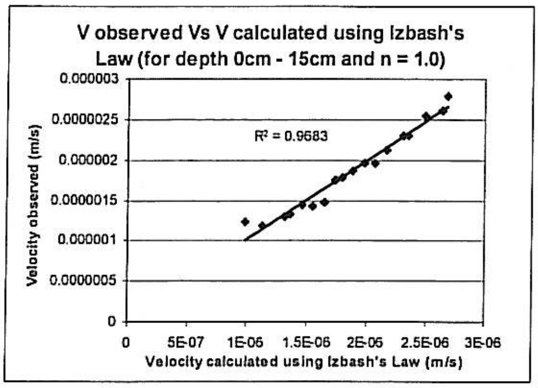
Depth (cm)	Izbash parameter, n	r^2
0 - 15	1	0.9683
15 - 30	0.9	0.8879
	1	0.9035
	1.1	0.9168
	1.2	0.9279
	1.3	0.9371
	1.4	0.9446
	1.5	0.9503
	1.6	0.9546
	1.7	0.9575
	1.8	0.9593
	1.85	0.9597
	1.9	0.9599
	2	0.9597
30 - 45	0.9	0.8581
	1	0.8593
	1.1	0.8595
	1.2	0.8588
	1.3	0.8571
	1.4	0.8547
	1.5	0.8514
	1.6	0.8474
	1.7	0.8426

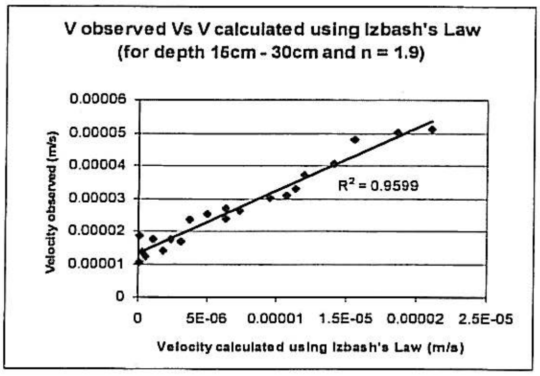
4.5 Izbash's Law ($v = ki^n$) and n Value (Izbash's Parameter)

By using trial and error for n values less than 2, the graph between velocity observed (from the experiment) against calculated velocity using the Izbash's Law were plotted and the graph with the best fit (linear regression, r^2 closest to 1), the n value for the graph is considered as the best value to represent the peat sample at that depth. Take note that the trial and error calculation has not been done for the upper layer of depth 0 cm – 15 cm because the Darcy's Law with linear regression value of 0.9683 (from section 4.4) is deem to be suitable to represent the flow of water through that layer because the linear regression value is very near to 1. Appendix D shows the trial and error calculation and Table 4.6 shows the summary of the trial and error calculation for the three different depths.

By using the Izbash's Law ($v = ki^n$) the suitable *n* and r^2 values are n = 1 and $r^2 = 0.9683$ for 0 cm to 15 cm depth, n = 1.9 and $r^2 = 0.9599$ for 15 cm to 30 cm depth and n = 1.1 and $r^2 = 0.8595$ for 30 cm to 45 cm depth. According to Basak (1977), the flow is at non-Darcy pre-linear zone if $n > 1$ and Darcian linear zone if n = 1. Figure 4.8 shows the graphs when observed velocities are plotted against velocities calculated using Izbash's Law for the most suitable n (Izbash's parameter value) with the linear regression values for the three different depths.

Figure 4.9 shows the graph for observed velocities (from the experiment) against hydraulic gradient, i plotted on the same graph with the velocities predicted using Izbash's Law against hydraulic gradient, i (for the most suitable n value) for each of the three different depths. From these graphs (Figure 4.9), it can be seen that by using the Izbash's Law to calculate the velocities, the shape of the graph is much closer to the shape of the graph for observed velocities compare to Darcy's Law method (Section 4.4). Thus, Izbash's Law provides a better approximation of water flow through much deeper peat layer.





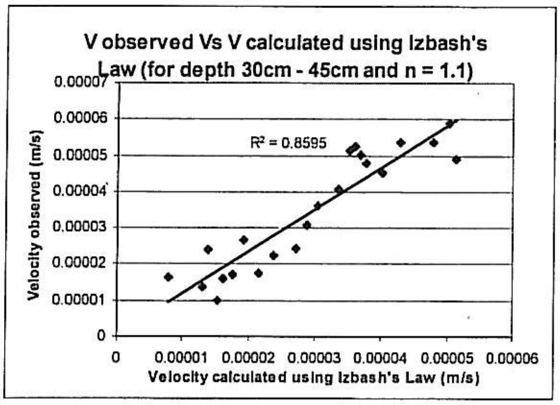


Figure 4.8. Observed against calculated velocities using Izbash's Law for the most suitable n (Izbash's parameter value) with the linear regression values for the three different depths.

4.6 Summary of the Findings

Table 4.7 below summarizes the findings of this project. Based on the results it can be concluded that the relationship between average K value and organic content/degree of decomposition is that higher organic content will produce higher average K value. As for the relationship between organic content/degree of

Table 4.7. Summary of the finding

Peat depth (cm)	Von Post Scale	K value (Guelph) (m/s)	K value (experiment) (m/s)	Moisture content (%)	Organic matter (%)	R2 V_{obs} versus V_{Darcy}	R2 V_{obs} versus V_{Izbash}	n
0-15	H7	0.002349	9.4×10^{-6}	144.90	75.70	0.96	0.96	1
15-30	H6	-2.12×10^{-5}	0.00033	444.80	95.10	0.90	0.95	1.9
30-45	H5	-0.001369	0.000173	587.30	94.70	0.85	0.85	1.1

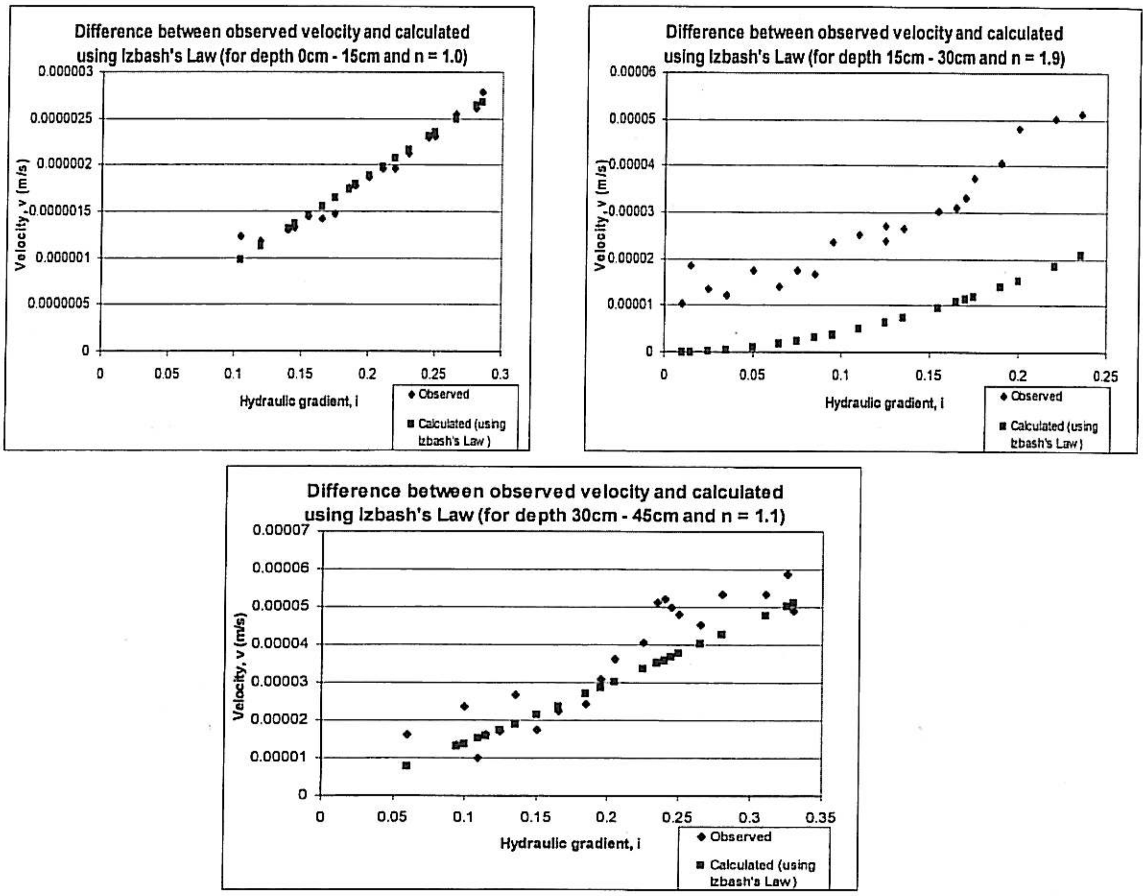


Figure 4.9: Observed velocities against hydraulic gradient, i plotted on the same graph with the velocities predicted using Izbash's Law against hydraulic gradient, i (for the most suitable n value) for three different depths.

decomposition and the deviation from Darcy's Law, there is no clear relationship that can be seen from the results. This is because the deviation from Darcy's Law is governs by many factors such as the structure of the peat soil and the hydraulic gradient and not just influenced by the degree of decomposition. However, what can be said is that peat soil with higher organic content will have the tendency to deviate from Darcy's Law than peat soil with lower organic content.

CHAPTER 5

CONCLUSIONS AND FUTURE RECOMMENDATIONS

5.1 Conclusions

From the data and results obtained, it can be concluded that,

a) The degree of peat humification based on Von Post scale varies with the soil depths. It seemed proportional to the soil depths. The 0-15cm belonged to H7, 15-30 cm is H6 and for 30 – 45 cm is H5.

b) Based on the classification of peat and organic sediments by ash and organic content used by the Organic Sediments Research Center of the University of South Carolina; the peat samples of the study area, layer 0cm – 15cm is of high ash content, layer 15cm – 30cm is of low ash content and layer 30cm – 45cm is of medium ash content.

c) The average hydraulic conductivity, K seems to increase first then decrease with depth which is according to the finding by Rizutti (2004) for the peat area at South Carolina, where the K values were increased for the first 25 cm then decrease.

d) When the observed velocity is plotted against calculated velocity using Darcy's Law, the r^2 value closest to 1 for the upper layer (depth 0cm – 15 cm) which is according to the findings by Hemond and Goldman (1985). In this case, the Darcy's Law is appropriate for upper unhumified layer. For the deeper soil layer the r^2 values became smaller, indicating that the deviation from Darcy's Law is more pronounced. From this particular finding, it can be said that Darcy's Law becomes less accurate at the lower peat profile and more appropriate method (law) is needed to predict flow through deeper peat layer.

e) By using the Izbash's Law ($v = ki^n$) the n values are; for depth 0 cm to 15 cm, n = 1 with r^2 = 0.9683; for depth 15 cm to 30 cm, n = 1.9 with r^2 = 0.9599 and for depth 30 cm to 45 cm, n = 1.1 with r^2 = 0.8595; which according to Basak (1977), the flow is at non-Darcy pre-linear zone if n >1 and Darcian linear zone if n = 1. The Izbash or Power Law provides a much better approximation of water flow through much deeper peat layer.

f) The relationship between average K value (hydraulic conductivity) and organic content/degree of decomposition is that the higher organic content produced higher average K value.

g) As for the relationship between organic content/degree of decomposition and the deviation from Darcy's Law, there is no clear relationship that can be seen from the results. This is because the deviation from Darcy's Law is governs by a lot of factor such as the structure of the peat soil and the hydraulic gradient and not just influence by the degree of decomposition. However, what can be said is that peat soil with higher organic content will have the tendency to deviate from Darcy's Law than peat soil with lower organic content.

5.2 Recommendations

Since the characteristics of flow through peat soil layer is not fully understood, it is suggested that the future studies should cover the following aspects.

a) A larger scale study should be carried out to cover other peat soil areas in Malaysia with a lot more sampling to check whether the present finding can e generalized for Malaysian peat soil hydraulic characteristics. By doing a large scale studies also, maybe a relationship between the n value (Izbash's parameter) and ash content/degree of decomposition can be developed; for example to get a certain value of n that can be used for flow calculation for certain ash content and degree of decomposition.

b) Although proper care has been taken in the sampling of peat soil in this project, to get an undisturbed peat soil sample is almost impossible. For future studies, it is suggested that a more proper method to get undisturbed peat soil sample should be investigated.

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APPENDIX A. HYDRAULIC CONDUCTIVITY MEASUEREMENT USING GUELPH PERMEAMETER

GP FIELD DATA SHEET

Date :	19/5/2005		Investigator :		Charles Bong
					Depth of Well Hole
Reservoir Constants: (See label on Permeameter)					
Combined Reservoirs X		35.33	cm2		v
Inner Reservoir Y		2.21	cm2		

1st Set of Readings with height of water in well (H1) set at 5 cm

Reading number	Time	Time interval (min)	Water level in reservoir, (cm)	Water level change (cm)	Rate of water level change R1 (cm/min)
1	0	-	1.8	-	-
2	2	2	2.7	0.9	0.45
3	4	2	3.4	0.7	0.35
4	6	2	4.3	0.9	0.45
5	8	2	5.1	0.8	0.4
6	10	2	6.1	1	0.5
7	12	2	6.8	0.7	0.35
8	14	2	7.5	0.7	0.35
9	16	2	8.3	0.8	0.4
10	18	2	9.1	0.8	0.4
11	20	2	9.9	0.8	0.4
12					
					R1 = 0.4

2nd Set of Readings with height of water in well (H2) set at 10 cm

Reading number	Time	Time interval (min)	Water level in reservoir, (cm)	Water level change (cm)	Rate of water level change R2 (cm/min)
1	0	-	13.5	-	-
2	1	1	15.2	1.7	1.7
3	2	1	16.7	1.5	1.5
4	3	1	18.2	1.5	1.5
5	4	1	19.7	1.5	1.5
6	5	1	21.2	1.5	1.5
7					
					R2 = 1.5

CALCULATIONS

R, the steady state of flow, is achieved when R is the same in three consecutive time inter

For the 1st Set of Readings, R1 = (0.4) / 60 = 0.0066667
R1

For the 2nd Set of Readings, R2 = (1.5) / 60 = 0.025
R2

Kfs = [(0.0041) (35.33) (0.025)] - [(0.0054) (35.33) (0.006667)] =
Field Saturated — Reservoir R2 — Reservoir R1

GP FIELD DATA SHEET

Date : 19/5/2005 Investigator : Charles Bong

Depth of Well Hole 22.0

Reservoir Constants: (See label on Permeameter)

Combined Reservoirs X		[redacted]	cm2		Check Reservoir
Inner Reservoir Y		[redacted]	cm2	v	Used

1st Set of Readings with height of water in well (H1) set at 5 cm

Reading number	Time	Time interval (min)	Water level in reservoir, (cm)	Water level change (cm)	Rate of water level change R1 (cm/min)
1	0	-	27.4	-	-
2	2	2	28.4	1	0.5
3	4	2	29.5	1.1	0.55
4	6	2	30.6	1.1	0.55
5	8	2	31.8	1.2	0.6
6	10	2	33	1.2	0.6
7	12	2	34.2	1.2	0.6
8					
					R1 = [redacted]

2nd Set of Readings with height of water in well (H2) set at 10 cm

Reading number	Time	Time interval (min)	Water level in reservoir, (cm)	Water level change (cm)	Rate of water level change R2 (cm/min)
1	0	-	61.1	-	-
2	2	2	61.9	0.8	0.4
3	4	2	63.4	1.5	0.75
4	6	2	64.7	1.3	0.65
5	8	2	66	1.3	0.65
6	10	2	67.3	1.3	0.65
7					
					R2 = [redacted]

CALCULATIONS

R, the steady state of flow, is achieved when R is the same in three consecutive time intervals.

For the 1st Set of Readings, R1 = (0.6) / 60 = [redacted] cm/sec
(R1)

For the 2nd Set of Readings, R2 = (0.65) / 60 = [redacted] cm/sec
(R2)

Kfs	= [(0.0041)	(2.21)	(0.010833)] -	[(0.0054) (2.21)	(0.01)] =	-2.11792E-05
Field Saturated Hydraulic Conductivity		Reservoir Constant	R2	Reservoir Constant	R1	

?m	= [(0.0572)	(2.21)	(0.01)] -	[(0.0237) (2.21)	(0.010833)] =	0.011137783
Matric Flux Potential		Reservoir Constant	R1	Reservoir Constant	R2	

Date :	19/5/2005		Investigator :		Charles Bong	
					Depth of Well Hole	37.0
Reservoir Constants: (See label on Permeameter)						
Combined Reservoirs X			[redacted]	cm2	v	Check Re
Inner Reservoir Y			[redacted]	cm2		Used

1st Set of Readings with height of water in well (H1) set at 5 cm

Reading number	Time	Time interval (min)	Water level in reservoir (cm)	Water level change (cm)	Rate of water level change R1 (cm/min)
1	0	-	5.2	-	-
2	2	2	6.8	1.6	0.8
3	4	2	8.5	1.7	0.85
4	6	2	10.2	1.7	0.85
5	8	2	12	1.8	0.9
6	10	2	13.5	1.5	0.75
7	12	2	15.2	1.7	0.85
8	14	2	17	1.8	0.9
9	16	2	18.7	1.7	0.85
10	18	2	20.7	2	1
11	20	2	22.3	1.6	0.8
12	22	2	24.3	2	1
13	24	2	26.3	2	1
14	26	2	28.3	2	1
15					
					R1 = [redacted]

2nd Set of Readings with height of water in well (H2) set at 10 cm

Reading number	Time	Time interval (min)	Water level in reservoir (cm)	Water level change (cm)	Rate of water level change R2 (cm/min)
1	0	-	31.8	-	-
2	2	2	33.8	2	1
3	4	2	35.8	2	1
4	6	2	37.8	2	1
5	8	2	39.2	1.4	0.7
6	10	2	41.2	2	1
7	12	2	42.7	1.5	0.75
8	14	2	44.2	1.5	0.75
9	16	2	45.7	1.5	0.75
10					
					R2 = [redacted]

CALCULATIONS

R, the steady state of flow, is achieved when R is the same in three consecutive time i

For the 1st Set of Readings, R1 = (0.4) / 60 = [redacted] cm/sec
R1

For the 2nd Set of Readings, R2 = (1.5) / 60 = [redacted] cm/sec
R2

Kfs	= [(0.0041) (35.33) (0.0125)] - [(0.0054) (35.33) (0.016667)] =					-0.00137
Field Saturated		Reservoir	R2	Reservoir	R1	
Hydraulic		Constant		Constant		
Conductivity						

?m	= [(0.0572) (35.33) (0.016667)] - [(0.0237) (35.33) (0.0125)] =					0.02321
Matric Flux		Reservoir	R1	Reservoir	R2	

APPENDIX B. Soil moisture and ash content of the tested samples

Determination of Moisture Content.					
Depth (cm)	Mass of Container (g)	Mass of container + peat (wet) (g)	Mass of peat (wet) (g)	Mass of container + peat (dry) (g)	Mass of peat (dry) (g)
0 - 15	260.64	501.06	240.42	358.79	98.15
15 - 30	250.92	724.77	473.85	337.89	86.97
30 - 45	223.65	701.97	478.32	293.24	69.59

Ash Content Determination.						
Depth (cm)	Mass of Container (g)	Mass of Container + oven-dried peat (g)	Mass of oven-dried peat (g)	Mass of Container + oven-dried peat (after ashing) (g)	Mass of ash (g)	% ash content
0 - 15	21.01	31.63	10.62	23.55	2.54	23.93
	21.73	32.37	10.63	24.36	2.62	24.66
	20.90	31.83	10.93	23.57	2.67	24.41
					Average	24.33
15 - 30	21.01	31.13	10.13	21.49	0.48	4.74
	21.74	31.95	10.21	22.24	0.50	4.93
	20.90	31.11	10.21	21.41	0.51	4.99
					Average	4.89
30 - 45	21.01	28.58	7.57	21.50	0.49	6.46
	21.73	29.31	7.57	22.09	0.36	4.72
	20.90	28.92	8.03	21.28	0.38	4.72
					Average	5.30

APPENDIX C. RAW DATA OF THE EXPERIMENT

Peat soil at 0 cm - 15 cm depth (24/5/2005)

Distance between 2 piezometer = 0.20 m

H1(mm)	H2(mm)	?H(m)	t(s)	Volume in measuring cylinder (ml)	Q (m3/s)	Area (m2)	v(m/s)	i	k(m/s)
166	117	0.049	205	1	4.88E-09	0.00212	2.3E-06	0.245	9.4E-06
188	138	0.05	204	1	4.9E-09	0.00212	2.3E-06	0.25	9.2E-06
199	143	0.056	180	1	5.56E-09	0.00212	2.6E-06	0.28	9.3E-06
203	146	0.057	169	1	5.92E-09	0.00212	2.8E-06	0.285	9.8E-06
214	161	0.053	185	1	5.41E-09	0.00212	2.5E-06	0.265	9.6E-06
120	99	0.021	382	1	2.62E-09	0.00212	1.2E-06	0.105	1.2E-05
162	138	0.024	399	1	2.51E-09	0.00212	1.2E-06	0.12	9.8E-06
197	169	0.028	361	1	2.77E-09	0.00212	1.3E-06	0.14	9.3E-06
228	199	0.029	354	1	2.82E-09	0.00212	1.3E-06	0.145	9.2E-06
259	228	0.031	326	1	3.07E-09	0.00212	1.4E-06	0.155	9.3E-06
312	279	0.033	331	1	3.02E-09	0.00212	1.4E-06	0.165	8.6E-06
342	307	0.035	320	1	3.13E-09	0.00212	1.5E-06	0.175	8.4E-06
369	332	0.037	268	1	3.73E-09	0.00212	1.8E-06	0.185	9.5E-06
385	347	0.038	265	1	3.77E-09	0.00212	1.8E-06	0.19	9.4E-06
410	370	0.04	252	1	3.97E-09	0.00212	1.9E-06	0.2	9.3E-06
421	379	0.042	240	1	4.17E-09	0.00212	2E-06	0.21	9.3E-06
433	389	0.044	240	1	4.17E-09	0.00212	2E-06	0.22	8.9E-06
445	399	0.046	222	1	4.5E-09	0.00212	2.1E-06	0.23	9.2E-06
								Average	9.4E-06

Velocity Calculated by Darcy's Law

i	k(m/s) (average)	vDL(m/s) Calculate Darcy's Law	vobs(m/s) Observed
0.245	9.4E-06	2.3E-06	2.3E-06
0.25	9.4E-06	2.4E-06	2.3E-06
0.28	9.4E-06	2.6E-06	2.6E-06
0.285	9.4E-06	2.7E-06	2.8E-06
0.265	9.4E-06	2.5E-06	2.5E-06
0.105	9.4E-06	9.9E-07	1.2E-06
0.12	9.4E-06	1.1E-06	1.2E-06
0.14	9.4E-06	1.3E-06	1.3E-06
0.145	9.4E-06	1.4E-06	1.3E-06
0.155	9.4E-06	1.5E-06	1.4E-06
0.165	9.4E-06	1.6E-06	1.4E-06
0.175	9.4E-06	1.6E-06	1.5E-06
0.185	9.4E-06	1.7E-06	1.8E-06
0.19	9.4E-06	1.8E-06	1.8E-06
0.2	9.4E-06	1.9E-06	1.9E-06
0.21	9.4E-06	2E-06	2E-06
0.22	9.4E-06	2.1E-06	2E-06
0.23	9.4E-06	2.2E-06	2.1E-06

Peat soil at 15 cm - 30 cm depth (25/5/2005)									
Distance between 2 piezometer = 0.20 m									
H1(mm)	H2(mm)	?H(m)	t(s)	Volume in measuring cylinder (ml)	Q (m3/s)	Area (m2)	v(m/s)	i	k(m/s)
70	55	0.015	135	5	3.7E-08	0.00212	1.7E-05	0.075	0.000232
130	123	0.007	192	5	2.6E-08	0.00212	1.2E-05	0.035	0.00035
270	267	0.003	127	5	3.9E-08	0.00212	1.9E-05	0.015	0.001236
50	33	0.017	141	5	3.5E-08	0.00212	1.7E-05	0.085	0.000196
260	247	0.013	166	5	3E-08	0.00212	1.4E-05	0.065	0.000218
200	198	0.002	227	5	2.2E-08	0.00212	1E-05	0.01	0.001037
110	105	0.005	174	5	2.9E-08	0.00212	1.4E-05	0.025	0.000541
180	161	0.019	100	5	5E-08	0.00212	2.4E-05	0.095	0.000248
330	320	0.01	134	5	3.7E-08	0.00212	1.8E-05	0.05	0.000351
335	310	0.025	98	5	5.1E-08	0.00212	2.4E-05	0.125	0.000192
380	353	0.027	89	5	5.6E-08	0.00212	2.6E-05	0.135	0.000196
40	15	0.025	87	5	5.7E-08	0.00212	2.7E-05	0.125	0.000216
100	78	0.022	93	5	5.4E-08	0.00212	2.5E-05	0.11	0.00023
302	271	0.031	78	5	6.4E-08	0.00212	3E-05	0.155	0.000195
310	277	0.033	76	5	6.6E-08	0.00212	3.1E-05	0.165	0.000188
318	284	0.034	71	5	7E-08	0.00212	3.3E-05	0.17	0.000195
326	291	0.035	63	5	7.9E-08	0.00212	3.7E-05	0.175	0.000214
330	292	0.038	58	5	8.6E-08	0.00212	4.1E-05	0.19	0.000214
353	313	0.04	49	5	1E-07	0.00212	4.8E-05	0.2	0.00024
360	316	0.044	47	5	1.1E-07	0.00212	5E-05	0.22	0.000228
380	333	0.047	46	5	1.1E-07	0.00212	5.1E-05	0.235	0.000218
								Average	0.00033

:ulated by Darcy's Law

i	k(m/s) (average)	v(m/s) Calculate by Darcy's Law	v(m/s) Observed
0.075	0.00033	2.48E-05	1.7E-05
0.035	0.00033	1.16E-05	1.2E-05
0.015	0.00033	4.95E-06	1.9E-05
0.085	0.00033	2.81E-05	1.7E-05
0.065	0.00033	2.15E-05	1.4E-05
0.01	0.00033	3.3E-06	1E-05
0.025	0.00033	8.26E-06	1.4E-05
0.095	0.00033	3.14E-05	2.4E-05
0.05	0.00033	1.65E-05	1.8E-05
0.125	0.00033	4.13E-05	2.4E-05
0.135	0.00033	4.46E-05	2.6E-05
0.125	0.00033	4.13E-05	2.7E-05
0.11	0.00033	3.63E-05	2.5E-05
0.155	0.00033	5.12E-05	3E-05
0.165	0.00033	5.45E-05	3.1E-05
0.17	0.00033	5.61E-05	3.3E-05
0.175	0.00033	5.78E-05	3.7E-05
0.19	0.00033	6.27E-05	4.1E-05
0.2	0.00033	6.61E-05	4.8E-05
0.22	0.00033	7.27E-05	5E-05
0.235	0.00033	7.76E-05	5.1E-05

Peat soil at 30 cm - 45 cm depth (26/5/2005)

Distance between 2 piezometer = 0.20 m

H1(mm)	H2(mm)	?H(m)	t(s)	Volume in measuring cylinder (ml)	Q (m3/s)	Area (m2)	v(m/s)	i	k(m/s)
260	241	0.019	174	5	2.9E-08	0.00212	1.4E-05	0.095	0.00014
289	266	0.023	146	5	3.4E-08	0.00212	1.6E-05	0.115	0.00014
352	307	0.045	58	5	8.6E-08	0.00212	4.1E-05	0.225	0.00018
380	327	0.053	52	5	9.6E-08	0.00212	4.5E-05	0.265	0.00017
383	336	0.047	46	5	1.1E-07	0.00212	5.1E-05	0.235	0.00022
392	343	0.049	47	5	1.1E-07	0.00212	5E-05	0.245	0.0002
395	345	0.05	49	5	1E-07	0.00212	4.8E-05	0.25	0.00019
402	354	0.048	45	5	1.1E-07	0.00212	5.2E-05	0.24	0.00022
413	357	0.056	44	5	1.1E-07	0.00212	5.4E-05	0.28	0.00019
492	430	0.062	44	5	1.1E-07	0.00212	5.4E-05	0.31	0.00017
473	408	0.065	40	5	1.3E-07	0.00212	5.9E-05	0.325	0.00018
565	499	0.066	48	5	1E-07	0.00212	4.9E-05	0.33	0.00015
137	125	0.012	145	5	3.4E-08	0.00212	1.6E-05	0.06	0.00027
205	183	0.022	236	5	2.1E-08	0.00212	1E-05	0.11	9.1E-05
159	139	0.02	99	5	5.1E-08	0.00212	2.4E-05	0.1	0.00024
135	110	0.025	138	5	3.6E-08	0.00212	1.7E-05	0.125	0.00014
145	115	0.03	134	5	3.7E-08	0.00212	1.8E-05	0.15	0.00012
210	177	0.033	105	5	4.8E-08	0.00212	2.2E-05	0.165	0.00014
234	197	0.037	96	5	5.2E-08	0.00212	2.5E-05	0.185	0.00013
253	212	0.041	65	5	7.7E-08	0.00212	3.6E-05	0.205	0.00018
262	223	0.039	76	5	6.6E-08	0.00212	3.1E-05	0.195	0.00016
307	280	0.027	88	5	5.7E-08	0.00212	2.7E-05	0.135	0.0002
								Average	0.00017

ulated by Darcy's Law

i	k(m/s) (average)	v(m/s) Calculate by Darcy's Law	v(m/s) Observed
0.095	0.00017	1.6E-05	1.4E-05
0.115	0.00017	2E-05	1.6E-05
0.225	0.00017	3.9E-05	4.1E-05
0.265	0.00017	4.6E-05	4.5E-05
0.235	0.00017	4.1E-05	5.1E-05
0.245	0.00017	4.2E-05	5E-05
0.25	0.00017	4.3E-05	4.8E-05
0.24	0.00017	4.2E-05	5.2E-05
0.28	0.00017	4.9E-05	5.4E-05
0.31	0.00017	5.4E-05	5.4E-05
0.325	0.00017	5.6E-05	5.9E-05
0.33	0.00017	5.7E-05	4.9E-05
0.06	0.00017	1E-05	1.6E-05
0.11	0.00017	1.9E-05	1E-05
0.1	0.00017	1.7E-05	2.4E-05
0.125	0.00017	2.2E-05	1.7E-05
0.15	0.00017	2.6E-05	1.8E-05
0.165	0.00017	2.9E-05	2.2E-05
0.185	0.00017	3.2E-05	2.5E-05
0.205	0.00017	3.6E-05	3.6E-05
0.195	0.00017	3.4E-05	3.1E-05
0.135	0.00017	2.3E-05	2.7E-05

APPENDIX D. Izbash's parameter computation

zbash's Law	
vDL(m/s) Calculated by Izbash's's Law	vobs(m/s) Observed
2.30569E-06	2.29664E-06
2.35274E-06	2.3079E-06
2.63507E-06	2.61562E-06
2.68213E-06	2.78587E-06
2.49391E-06	2.54493E-06
9.88152E-07	1.23249E-06
1.12932E-06	1.17998E-06
1.31754E-06	1.30419E-06
1.36459E-06	1.32998E-06
1.4587E-06	1.44421E-06
1.55281E-06	1.42239E-06
1.64692E-06	1.47129E-06
1.74103E-06	1.75676E-06
1.78808E-06	1.77665E-06
1.88219E-06	1.8683E-06
1.9763E-06	1.96171E-06
2.07041E-06	1.96171E-06
2.16452E-06	2.12077E-06