Vertical Hydraulic Conductivity of Unsaturated Zone by Infiltrometer Analysis of Shallow Groundwater Regime (KUISG)

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Abstract

A hydrogeologic model was developed and carried out in Taleaa district of 67km^2 . The study adopted a determination of KUISG depends upon the double rings infiltrometer model. The tests were carried out in a part of Mesopotamian Zone which is covered with quaternary deposits . In general the groundwater levels are about one meter below ground surface. Theoretically, the inclination angle of the saturated water phase plays an important role in the determination of KUISG. The experimental results prove that the angle of inclination of the saturated phase is identical to the angle of internal friction of the soil. This conclusion is supported by the comparison of the results that obtained from falling head test and infiltrometer measurements for estimating the hydraulic conductivitiy values for ten locations within the study area. The determination of vertical hydraulic conductivity by current infiltrometer model is constrained to only the shallow groundwater regime.7

Keywords: Infiltration Model, Angle of Inclination, Falling Head Permeameter, Saturated Water Phase, Direct Shear Test.

الخلاصه

تم تطوير نموذج هيدروجيولوجي وتنفيذه في ناحية الطليعة وعلى مساحة 67 كم^2 . أعتمدت الدراسة تحديد (KUISG)اعتماداً على موديل للإنفلتروميتر ثنائي الحلقة. وأجريت الاختبارات في جزء من منطقة ما بين النهرين التي تغطيها الرواسب الرباعية. وبصفة عامة، فإن مستويات المياه الجوفية تبلغ حوالي 1 متر تحت سطح الأرض .نظريا، زاوية الميل لطور المياه المشبعة تلعب دوراً هاماً في تحديد (KUISG). النتائج التجريبية تثبت أن زاوية ميل المرحلة المشبعة متطابقة مع زاوية الاحتكاك الداخلي للتربة .ويدعم هذا الاستنتاج مقارنة النتائج التي حصل عليها من فحص المنسوب المتغيير وقياسات الإنفلتروميتر لتقدير قيم التوصيلية الهيدرولوجية لعشرة مواقع داخل منطقة الدراسة .إن تحديد الموصلية الهيدروليكية العمودية من خلال نموذج الإنفلتروميتر الحالي مقيد بنظام المياه الجوفية الضحلة فقط.

الكلمات المفتاحية:- موديل الترشيح ، زاوية الميل ، جهازفحص النفاذية المتغيير ، طور المياه المشبعة ، فحص القص المباشر.

Introduction

Hydraulic conductivity measurements of soil directly in the field are favorable rather than laboratory test because the sampling disturbance of the tested samples is minimized and keeping natural soil conditions (Bouma ,1982)

Hydraulic conductivity of soil formations has a spatial variable due to the heterogeneity and large numbers of measurements are needed to determine these hydraulic conductivities in a field. So there is a need to put cheaper and quicker ways to define the hydraulic parameters of a soil. (Zeleke and Bing , 2005) reported that the falling head infiltration model can be used to determine the hydraulic conductivity (k). Accurate methods of soil hydraulic properties measurements are required to improve in the understanding of hydraulic processes of soil. For example, we need assessment and understanding of non- equilibrium in water flow and which scale the familiar equation process model provides an effective process representation for water transport in the unsaturated zone. Soil is the porous matter with three dimensional arrangement of open voids that form complex pore system. The challenge of estimation of soil hydraulic properties is interconnected pores system (Durner and

Lipsius , 2005). The vertical saturated k in the isotropic media is 4.75 times greater than in anisotropic media and the vertical saturated is 125 times smaller than the horizontal saturated k (Refloch *at.el.*,2017) .An infiltration rate is the basic task of a water management facility and a permeability(k) of subsurface conditions “ subsoil”. (Das , 1997) defined the property that controls the movement of fluids through its connected pore space . Permeability directly depends on the physical properties of subsurface conditions. The range of soil permeability can vary from $4.2*10^{-4}$ m/day to $1*10^{-6}$ feet/day (Cedergren ,1977). Infiltration rate is affected by volume of water runoff and hydraulic head (Assouline , 2007). A accurate ring infiltrometer values of hydraulic conductivity can be obtained with a water depth (10 cm), ring Diameter (7.6 cm), soil moisture(0.4%) and the duration (240 min) until reach steady state condition(Bagarello *et.al.*,2016). The double ring infiltrometer designs are better than the other designs as single ring infiltrometer. In single ring the wetting front spreads laterally and vertically but in the double ring the wetting front progresses in one direction toward the groundwater (Amreeta, 2014).

Objectives

1- Estimation the vertical hydraulic conductivity by double-ring infiltrometer analysis in shallow groundwater regime.
2- Determine the angle of inclination of saturated water phase with the mechanical properties.

Infiltration Model

Saturated hydraulic conductivity can be obtained experimentally by the model of Eq.1 based on double ring infiltrometer concept:

$$k = \frac{z(csc\emptyset'+1)\,D_i^2}{2t(D_i^2+2zD_i cot\emptyset'+2z^2cot^2\emptyset')} ln\frac{h_0+z}{h_1+z} \quad \text{..............(1)}$$

Where:

D_i : Inner diameter of double ring infiltrometer, $\emptyset'$: Angle of water Phase inclination, h_o: Initial infiltrometer water head at steady infiltration capacity at zero time, h_1: water head after time t, z: depth of groundwater beneath soil surface.

Theoretical Background of the Model

Darcy's Law can be applied if the boundary conditions are defined and justified. The model is mathematically based on two assumptions:-

1- The cross sectional area of the zone of saturation is taken as the average area of the inner infiltrometer ring cross sectional area and the contact area of the zone of saturation and the groundwater.
2- The length of the flow lines within the zone of saturation is taken as the average length of flow lines which is taken as:

$$L = \frac{z}{2}(csc\emptyset + 1) \quad \text{...........(2)}$$

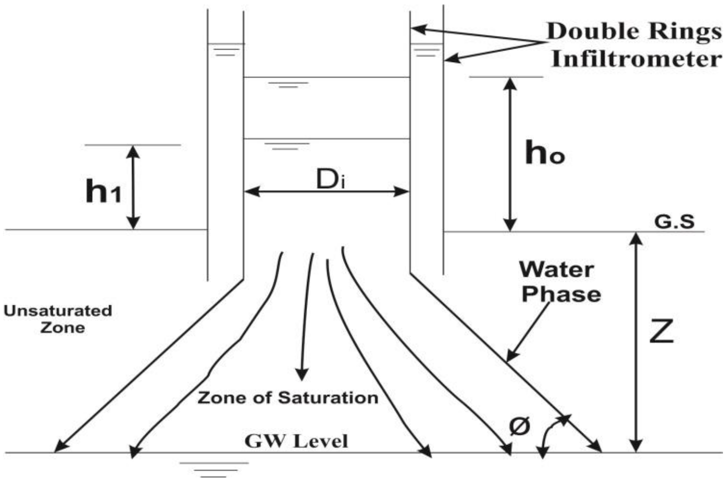

Fig.(1) Infiltration Model

On the basis of the infiltrometer geometry and conditions of (Darcy ,1856):

$adh = k\frac{h}{L}Adt$ …………………………..(3)

Where a: is an infiltrometer inner cross sectional area, K is the coefficient of permeability, h: is the applied water head, A is the average cross sectional area of a saturated zone and z is the groundwater depth and assumed equal to average flow lines length (Chow,1964).

By separation of variables on both sides of Eq.3 and making the necessary integrals to a specified limit of $\int_{h_1+z}^{h_0+z} value\ of\ k$, One may obtain:

$k = \frac{aL}{At} ln\frac{h_0+z}{h_1+z}$. ……………..………(4)

In this system the cross sectional area of the porous media within the unsaturated zone is variable, accordingly to facilitate the analysis, the average cross sectional area of Fig.1 could be obtained by the form:

$A = \frac{\pi}{4}(D_i^2 + 2zD_i cot\emptyset + 2z^2cot^2\emptyset)$ …………………..…(5)

And a can be obtained by,

$a = \frac{\pi}{4}D_i^2$ ....………..……..………(6)

A substitution of Equations (5, 6 &2) in Eq.(4) leads to Eq.1

The model of Eq.1 can only be applied in a saturated media and this term is fulfilled when the infiltration rate becomes in a steady state condition. Fig.2 represents the relationship between the infiltration rate and duration of infiltrometer test. The curve consists of two parts a) the unsteady unsaturated water flow at which the conditions of unsaturated zone are occurred, whereas b) steady saturated water flow reach at which the conditions of saturated flow and Darcy's law are fulfilled. In reaching (b) since a saturation is fulfilled because the infiltrated flow lines become in contact with top of groundwater level, the model is can be applied.

It is obviously clear that the infiltration rate at the end of a rain storm and/or infiltrometer test reaches its steady infiltration capacity. This phenomena occurs only at saturation soil condition beneath the soil surface which is exposed to water infiltration. Correspondingly and because the saturation condition obtained at such circumstances.

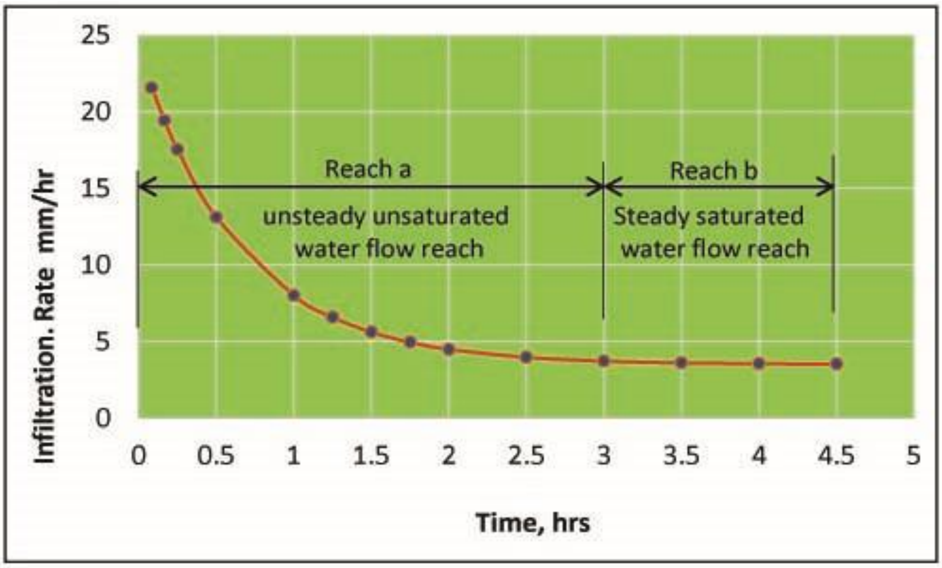

Fig.(2) Steady state saturated flow reach of arbitrary example

Theoretical Consideration of Inclination Angle

The saturated water phase or the wetted parameter is induced by the percolated water of infiltrometer which takes a hemi-elliptic shape and continuously expands downward, wetting front length under infiltrometer increases with the increasing of ring diameter (Chowdary *et.al.*, 2006) as in Fig.3. This part of wetting process represents reach (a) of Fig.2 But when the saturated water plume reaches the water table, the steady saturated water flow starts which represent reach (b) and the saturated water zone take the shape of Fig.1. Wetted plume would vary based on permeability and moisture distribution of soil (Alan ,1978) .

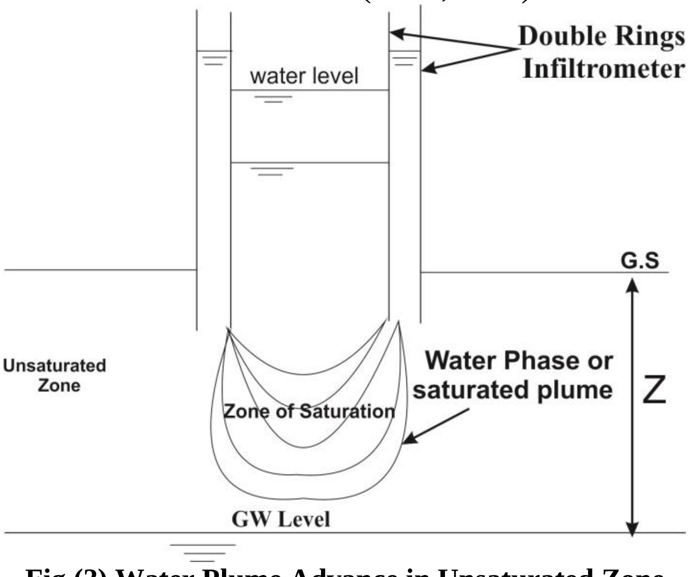

Fig.(3) Water Plume Advance in Unsaturated Zone

The inclination angle ($\emptyset'^{\circ}$)of the water phase (see Fig.1) is mainly depended on soil texture. Dense soil shows a reluctance to seepage flow lines which forcefully deviates away from vertical axis to the horizontal and this deviation process continues till the water phase shown in Fig.1, stabilize in a slope with what is called the angle of inclination. The angle of inclination certainly depends upon soil texture and gradation (Dukes *et.al*.,2005) . Therefore it ranges between (90-0) for coarse and fine particles respectively.

In other hand geotechnically it was stated that the angle of internal friction is also a parameter to soil texture and index for cohesion less soil. In short words, the small angle of internal friction means fine texture soil and inversely the large angle of internal friction the coarse texture soil.

It is concluded that there is a constant relationship between the angle of inclination and the angle of internal friction. This consideration was supported by different soil classification systems.

Location of The study Area

The study area lies in the Mesopotamia alluvial plain between latitudes ($32^{o}\ 10' - 32^{o}\ 16'N$) and longitudes ($44^{o}\ 42' - 44^{o}\ 49'E$) at south-east of Babylon Governorate central of Iraq. It covers an area of (67 km^2) within the administrative boundaries of Taleaa district. The area characterizes with non- clear topographic changes. Fig.4 shows the location map of Taleaa Area.

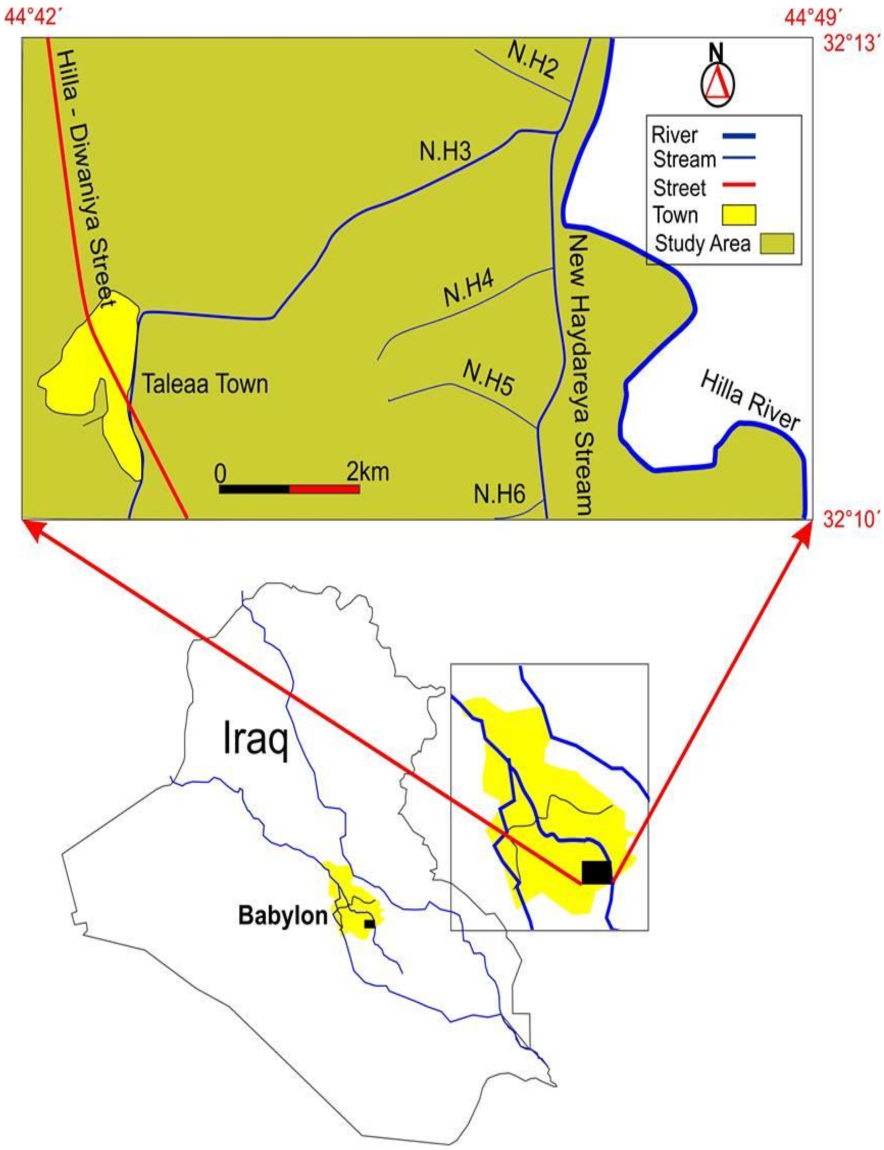

Fig.(4) Location Map of Taleaa

Geological and Hydrogeological Setting

A study area lies in Mesopotamian Zone .This zone is covered by quaternary sediments which were deposited by Tigris and Euphrates Rivers. The quaternary sediments are up to tens of meters in thickness. They include alternative beds of Flood Plain deposits such as sand, silt and clay, flood plain depression, sabkha and marsh.

The most important hydrological features is Hilla River, which represents the eastern border of the region. Hilla River is the main source of agricultural activities for the population by New Haydareya stream and its branches. The natural systems that forming deposits have been changed by human activities during a long time, for instance, artificial irrigation canals. So groundwater flow is a very complex system over whole Mesopotamia plain and changing from one region to another. Fig.5 indicates the most geological features in the area (Jassim and Goff , 2006) .

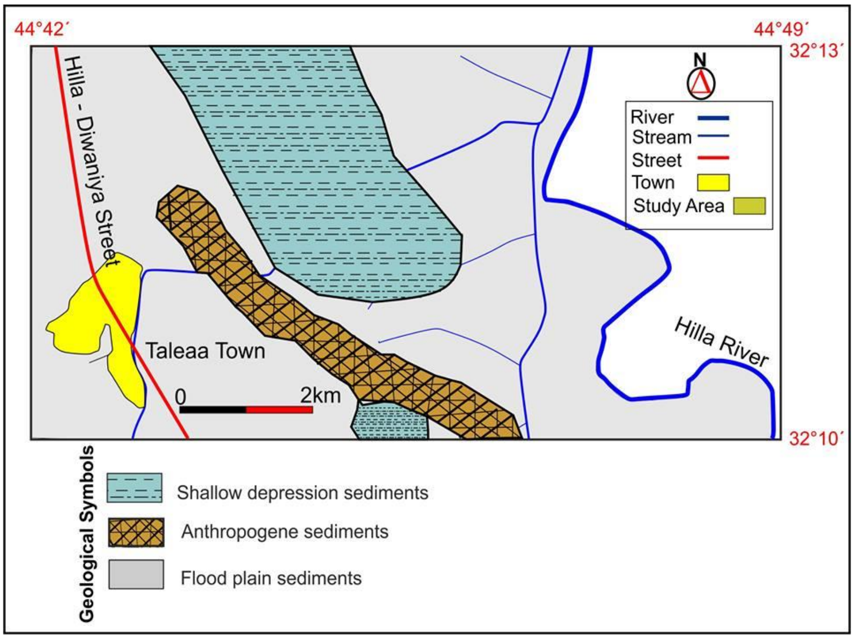

Fig.(5) Geologic Map (Modified of GEOSURV Map-Karbala Quadrangle, 1995)

Materials and Methods

Sampling and Testing procedures

Ten locations were selected within the study area to evaluate the hydraulic conductivity by a traditional method and double rings infiltrometer model according to (ASTM D 3385-09), they are shown in Fig. 6.

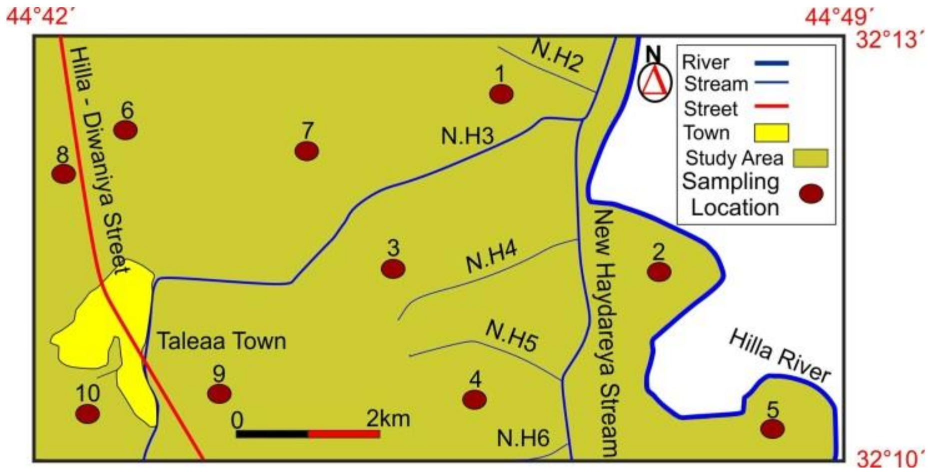

Fig.(6) Locations of sampling and Testing of GW and Soil Samples

Testing and sampling methodology initiates by removing 10 cm of top soil to avoid plant residues and three tests were carried out for each undisturbed sample.

1- Falling head permeameter:

10 core samples of undisturbed soil were brought to the lab for testing a falling head permeameter model according to the ASTM (D5084 – 03) as in Fig.7. The test was employed for undisturbed samples that obtained from ten locations in the considered area. Briefly, the permeability coefficient results and the corresponding used device shown in Table 1 and Fig 7 respectively.

Table(1) Falling Head Permeability Results

Location No.1	h_o(cm)	h_1(cm)	K (cm/min)
1	70	58	0.001421
2	70	62	0.000917
3	70	40	0.00423
4	70	64	0.000677
5	70	44	0.003509
6	70	51	0.002393
7	70	51	0.002393
8	70	62.7	0.000832
9	70	63.4	0.000748
10	70	58	0.001421

$A = 37.39cm^2, a = 0.2826cm^2, L = 30cm, t = 10min$

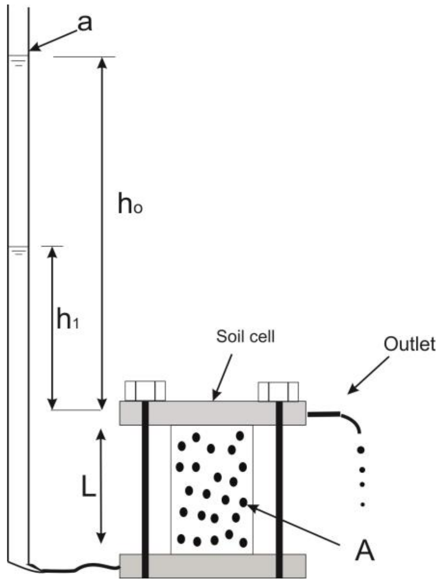

Fig.(7)Falling Head Permeameter

1- Direct Shear Force.

The field undisturbed samples were prepared to be tested by the direct shear test according ASTM (D3080/D3080M-11) to evaluate the angle of internal friction (ø) shown in Table 2.

2- Infiltrometer Analysis

The hydraulic conductivity enables us to understand subsurface hydrology and irrigation design. It varies with T, irrigation ways and soil types (Chen, 2013).Double ring infiltrometer is accurate tool in physical properties measurements of soil(Paul, 2004).So a double ring infiltrometer model was used to obtain the relationship between the infiltration rate in (mm/hr) versus time in (hrs) for ten samples. Infiltration rate of ponded soil conditions decreases until reaching a steady state or an equilibrium state. The results were represented graphically in Fig.8 and then used for estimation of hydraulic conductivity of surface soil according to the current model of Eq.1 and indicated in Table 2.

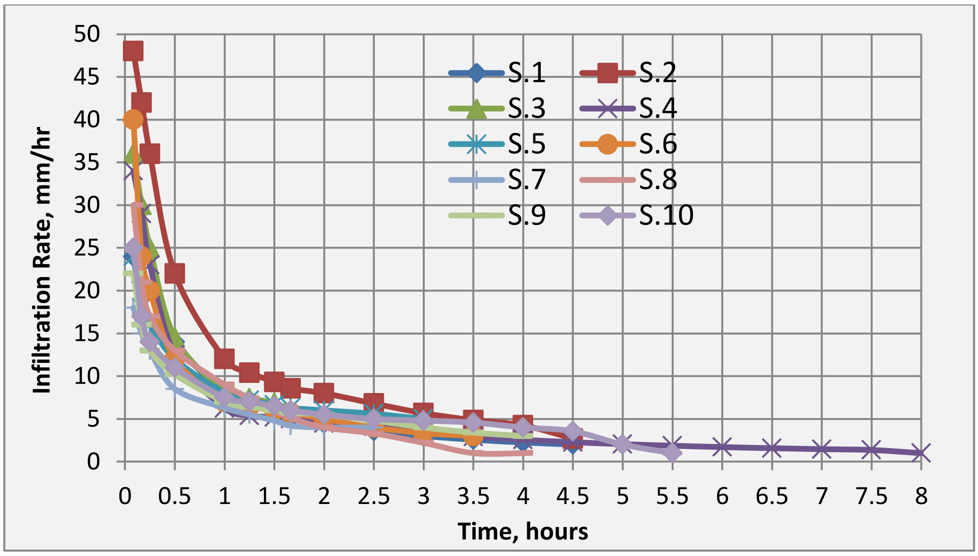

Fig.(8) Infiltrometer Results

Table (2) Infiltrometer Analysis Results

Location No.	$\emptyset'^{\circ}$	$\emptyset^{\circ}$	Z(cm) Or	t(min)	$D_i(cm)$	h_o(cm)	h_1(cm)	K (cm/min)
1	33	32.5	102	30	30	4	0	0.001436
2	20	20.07	100.3	30	30	3	0	0.000929
3	33	32.65	96	30	30	2	0	0.004483
4	32	32.1	101	30	30	2	0	0.000692
5	31	31	98	30	30	3	0	0.003315
6	34	33.89	99	30	30	2	0	0.002324
7	29	30	100	30	30	4	0	0.002347
8	36	35.91	102	30	30	3	0	0.000841
9	28	27.1	102	30	30	5	0	0.000787
10	21	21	104	30	30	1	0	0.001436

Discussion of the results and Methodology of Estimation

The angles of internal friction ($\emptyset^{\circ}$)are substituted in the infiltrometer model (Eq.1) instead of the angle of inclination of the saturated water phase to estimate the KISUG. The angles of internal frictions were calibrated and adjusted corresponding to the hydraulic conductivity values of Table 1. The hydraulic conductivity values and the angles of inclination of the saturated water phase obtained by the infiltrometer model are listed in Table 2.

It is found that the angles of internal friction obtained from the direct shear test were extremely identical to the angles of inclination of the saturated water phase. as shown in Table 2.

Conclusions:

The main conclusions are:-

1- The double ring infiltrometer can be used as a field method for hydraulic conductivity estimation for unsaturated surface soil in the shallow groundwater regime.

2- The angle of inclination of the saturated water phase is identical to the angle of internal friction.

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