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Theoretical Analysis of Seepage through Homogeneous and Non-homogeneous Saturated-Unsaturated Soil

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ABSTRACT

In this research, the program SEEP / W was used to compute the value of seepage through the homogenous and non-homogeneous earth dam with known dimensions. The results show that the relationship between the seepage and water height in upstream of the dam to its length for saturated soil was nonlinear when the dam is homogenous. For the non-homogeneous dam, the relationship was linear and the amount of seepage increase with the height of water in upstream to its length. Also the quantity of seepage was calculated using the method of (Fredlund and Xing, 1994) and (Van Genuchten, 1980) when the soil is saturated – unsaturated, the results referred to that the higher value of seepage when the soil is saturated and the lowest value of seepage when using Van Genuchten method for both homogeneous and non-homogeneous earth fill dams. Also relationship for the seepage (Q) with the curve fitting parameter (a) for sand, silt and clay soil was nonlinear when the dam is homogenous with constant variables (n, m) and the amount of seepage increase with increasing value of (a). The amount of seepage for a nonhomogeneous dam with a different value of (K_{shell} to K_{core}) was calculated and then compared with the value of ($K_{equivalent}$) which was equal to average (K_{shell} and K_{core}) for the homogenous dam. The results show that when the average between (K_{shell} and K_{core}) is ≤ 100 the difference was small between the quantity of the seepage calculated. For simplicity of the solution process, it can be replaced non-homogeneous dam by a homogenous dam with (K_{eq}) when the values of K_{shell} and K_{core} are less than or equal to 100.

Keywords: seepage, homogenous, nonhomogeneous, saturated-unsaturated soil, curve fitting parameters

تحليل نظري للتسرب خلال تربة مشبعة–غير مشبعة متجانسة وغير متجانسة

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الخلاصة

في هذا البحث تم استخدام البرنامج SEEP/W لمعرفة قيمة التسرب خلال سد ترابي متجانس وغير متجانس بأبعاد معلومة. حيث وجد ان العلاقة بين ارتفاع الماء في مقدمة السد الى طوله من نهاية ارتفاع الماء الى نهاية السد للتربة المشبعة ليست خطية عندما يكون السد متجانس اما السد الغير متجانس فكانت العلاقة خطية وان مقدار التسرب يزداد مع ازدياد ارتفاع الماء امام السد. كذلك تم ايجاد مقدار التسرب بموجب طريقة (Fredlund and Xing1994) و (Van Genuchten1980) عندما تكون التربة مشبعة -غير مشبعة وبينت النتائج ان اعلى قيمة للتسرب عندما تكون التربة مشبعة كليا وأوطأ قيمة

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للتسرب كانت باستخدام طريقة (Van Genuchten) لكلا النوعين من السدود الترابية (المتجانسة والغير متجانسة) . كذلك تم ايجاد علاقة بين التسرب (Q) مع المتغير (a) للتربة الرملية والغرينية والطينة حيث كانت غير خطية عندما يكون السد متجانس مع ثبوت المتغيرات (m, n). وان مقدار التسرب يزداد مع ازدياد قيمة (a) للترب الرملية والغرينية والطينية . تم ايجاد كمية التسرب لسد غير متجانس لقيم مختلفة من (K_{shell} وK_{core}) وقورنت مع القيم المحسوبة عندما تكون قيمة النفاذية تساوي القيمة المكافئة التي هي معدل قيمة (K_{shell} وK_{core}) لسد متجانس وقد بينت النتائج انه عندما يكون المعدل بين القيمتين 100 فان الفرق قليل بين قيم التسرب المحسوبة وعليه لتسهيل التحليل يمكن التعويض عن السد الغير متجانس بسد متجانس بنفاذية مكافئة عندما يكون (Kshell /Kcore≤ 100)

الكلمات الرئيسية : التسرب، متجانس، غير متجانس، تربة مشبعة-غير مشبعة، معاملات مسار المنحني.

1. INTRODUCTION

Several factors affect to seepage in the soil which is hydraulic conductivity of the soil and the pressure gradient, essentially the combination of factors acting on water. The homogenous and non-homogeneous earth fill dams have seepage existent from water percolating slowly of the dam and its foundation. Many problems from seepage and failures of earth-fill dams have occurred due to inadequate seepage control **Omofunmi, et al., 2017.** Therefore, many numbers of theories have been used for the solution of seepage problems, Dupuit's, Schaffernak-VanIterson, Casagrande's and other solutions to determine the quantity discharge through 2D homogeneous earth fill dams when the bases are impervious. **Jairry, 2010.**

The first figure who proposed the solution of the linear partial differential equation of flow was by Casagrande in 1937 the method known as "the graphical flow net method". According to this method, the soil is homogeneous and isotropic and that water flows only in the saturated zone. The boundaries of the flow region must be defined in terms of head or no flow. By Casagrande proposed the flow net solution. It was for simple unconfirmed flow cases without flux boundary conditions. The digital computer to solve complex seepage problems has appeared in late 1960. The development and application of such a thing take place. Proposed an alternative model of flow through both saturated and unsaturated soil regions. Developing this device and its combination with the finite element method help to solve the steady-state and transient saturated-unsaturated seepage problems. The computer programs are intended to solve saturated-unsaturated modeling in engineering practice, examples being, MODFLOW and SEEP/W seepage analysis for unsaturated soils is characterized by a partial differential equation that is non- linear and soil properties that can be highly non-linear .

Consequently, the modeling of saturated and unsaturated soil systems becomes a challenge. The first challenge to face is to develop a numerical software package that ensures convergence in case of solving seepage problems with both saturated and unsaturated soil systems. This case lurks in solving problems unsaturated soil, **Fredlund, 1996.** Because of the fast development regarding computer in the last two decades for solving complex problems, unsaturated soil problem began to involve the soil properties that are highly non-linear, such as coefficient of permeability and water storage function. The partial differential equations to be solved become highly nonlinear and require the input from persons specially trained in the area of mathematics. This encourages the use of general partial differential equation solvers that are designed to solve equations from any area of engineering**, Thieu, et al., 2001.**

Kamanbedast and Delvari, 2012, used Ansys and Geo-Studio Software to analysis leakage and stability of Maroon dam that location north of Bahaman. The results showed that the seepage results in ANSYS were 18% lower than the results obtained from Geo-Studio. The slope stability results were similar for both programs.

Majeed, 2015, studied flow and deformation analysis of zone earth dam used finite element method. It concluded that finite element is the best tool for analyzing seepage flow in an earth-fill dam.

Jamel, 2016, studied the analysis and estimation of seepage through homogenous earth dam without a filter. Results show that when comparing the suggest equation with the artificial neural network (ANN) the error is less than 3% and with SEEP/W results less than 2% error, Dupuit's solution has more than 20% error and Casagrande's solution has more than 15% error.

The understanding of seepage flow makes it easier for designers to the selection of the type of dam that should be chosen according to use or purpose for which it was constructed for (storage or diversion or retention) the water.

The seepage through the soil depend on several factors, the most important of which is hydraulic conductivity, when the soil is saturated and their values considered a key for identifying the type of soil and constant for each type of soil but when the soil is saturated-unsaturated it can be calculated by method of Fredlund and Xing or Van Genuchten method.

The relationship between the water content and the matric suction represent a curve, the path of the curve can be defined by parameters (m, n. a) that value depends on the soil type.

The present study considered some important factors that affect seepage through earth dams such as the method of prediction of soil water characteristic curve and curve fitting parameter by using finite element method (FEM) in seepage analysis that makes the solution of seepage problems faster and complex leakage problems can be solved.

2. SEEP/W PROGRAM

SEEP/W can be defined as a finite element software product. It is a subprogram of Geo-Studio, used for analyzing groundwater seepage and access pore water pressure dissipation problems within porous materials such as soil and rock. Considering analyses ranging from simple saturated steady state problems to sophisticated, saturated and unsaturated time-dependent problems. For geotechnical, civil, hydrogeological and mining engineering projects SEEP/W is suitable and can be applied confidently**, Irzooki, 2016.**

The following equation used in the software program SEEP/W

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+Q=\frac{\partial \theta}{\partial t} \qquad (1)$$

Where:

h is total head

k_x is hydraulic conductivity in the x-direction.

k_y is hydraulic conductivity in the y-direction.

Q is applied boundary seepage

θ is volumetric water content

t is time

So that equation (1) modified to the following form for steady-state situations

$$\frac{\partial}{\partial x}(k_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(k\frac{\partial h}{\partial y})+Q=0 \qquad (2)$$

For steady state condition, the seepage entering and leaving an elemental volume at all time is a same. **Abbas, 2017,** SEEP/W program was used by many previous workers and they worked different seepage problems, **Irzooki, 2016.**

3. SOIL SUCTION

The development soil suction theories take place in relation to the soil–water plant system. The relation between suction and engineering properties of the soil increases importance of soil suction in the mechanical behavior of unsaturated soils. Another term is used alternatively to soil suction is the free energy state of soil water **Edlefsen and Anderson, 1943** cited in **Fredlund and Rahardjo, 1993.**

The partial vapor pressure of the soil water enables to measure the free energy of the soil water, this will prove the total connection or the relationship between relative humidity and soil suction which is equivalent suction derived from the measurement of the partial pressure of the water vapor in equilibrium with the free pore, **Sood, 2005.**

Soil suction has two components, a matric and matrix suction .Matric suction or capillary pressure refers to the difference between the pore- air pressure and the pore- water pressure (u_a-u_w). This suction is equal and is derived from the measurement of the partial pressure of water vapor in equilibrium with the soil water which is relative to the partial pressure of the water vapor in equilibrium with a solution identical in composition with the soil water. On the other hand, osmotic (or solute) component of free energy is the equivalent suction just like matric solution. The difference is that osmotic suction is relative to the partial pressure of water vapor in equilibrium with free pore water**, Fredlund and Rahardjo, 1993.** Acording to **Fredlund, 1994**, osmatic suction is a function of the amount of dissolved salts in the pore Fluid. For **Fredlund** and **Xing, 1994** at high suction (i-e greater than 1500 kPa), matric suction and total suction can be considered equivalent.

4. SOIL WATER CHARACTERISTIC CURVE

The relationship between water content and suction of a soil is known as "The soil-water characteristic curve" (SWCC). Form the hydraulic and physical point of view; it is the important parameter in the application of unsaturated soil mechanics to geotechnical and geoenvironmental engineering. SWCC or his parameter estimates the soil properties such as coefficient of permeability, shear strength and volume change to describe the engineering behavior of unsaturated soil. There are two types of (SWCC). The first is (desorption curves) when the soil transfers from the saturated state to drying state under the effect of suction pressure. The second type is the (adsorption curve) when the soil transfers from drying state to saturation state. Many designations have been used to measure the amount of water in the soil. There are three basic measures, the volumetric water content, θ_w, gravimetric water content, w, and the degree of saturation, S. Volumetric water content has most commonly used. **Fig. 1** shows the typical (SWCC) for silty soil. The (SWCC) contains three elements, the air entry value, the saturated volumetric water content (θ_s) and the residual volumetric water content (θ_r). The first stands for the value of suction pressure when the water starts to drainage out of the soil sample and represents the most significant point in (SWCC). The second element stands for the ratio between the volumes occupied by water to total volume, this values equal to soil porosity while the third stands for the water content at which a high suction pressure is required to dissipate additional water from soil sample, **Fig**. **1** shows these three**, Fredlund, et al., 1996.**

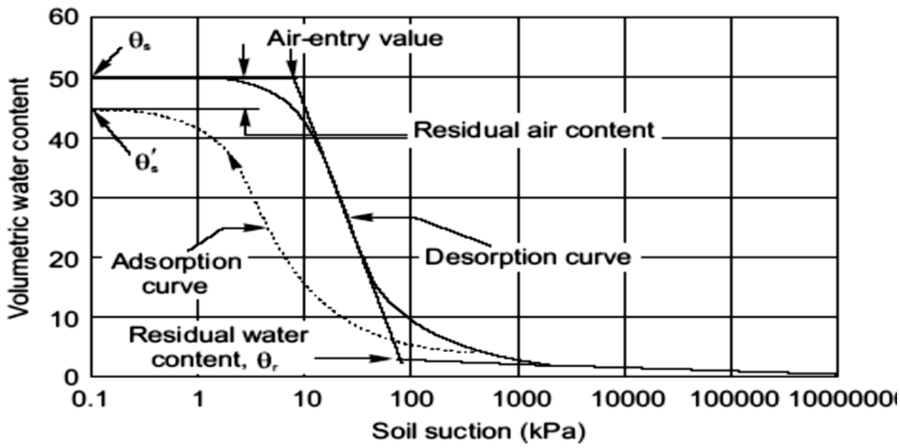

Figure 1. Typical soil- water characteristic curve for a silty soil (After **Fredlund and Xing, 1994**).

5. HYDRAULIC CONDUCTIVITY

The hydraulic conductivity of soils depends on several factors: fluid viscosity, pore-size distribution, grain- size distribution, void ratio, the roughness of mineral particles and degree of soil saturation. In clayey soils, structure plays an important role in hydraulic conductivity. Other major factors that affect the permeability of clays are the ionic concentration and the thickness of layers of water held to the clay particles. The value of hydraulic conductivity (*k*) varies widely for different soils. Some typical values for saturated soils are given in table (1), **Das, 2006.**

Table 1. Hydraulic conductivity of saturated soils.

Soil type	cm/sec	ft/min
Clean gravel	1.0-100	200-2.0
Coarse sand	0.1-1.0	2.0-0.02
Fine sand	0.01-0.001	0.02-0.002
Silty clay	0.001-0.00001	0.002-0.00002
Clay	<0.000001	< 0.000002

The hydraulic conductivity *(k*) of an unsaturated soil is not a constant and depends on the volumetric water content (θ_w) or the matric suction, (ψ), **Fattah, et al., 2014.**

The hydraulic conductivity in an unsaturated soil is considerably influenced by the extent of soil saturation (or the content of water). Water runs through the spaces of pores full of water, thus, the ratio of voids full with water is a vital factor. When the soil grows unsaturated, air initially

substitutes some of the water in the bigger pores which makes the water runs through the minor pores with an enlarged flow path sinuosity. Another matric suction increase of soil results in another reduction in the volume of pores filled with water. This results in additional resistance to the flow of water when the air-water line comes nearer and nearer to the particles of soil. Consequently, the hydraulic conductivity, in terms of the phase of liquid (water), declines quickly when the space existing for the flow of water decreases.
As **Fig. 2** shows, the desiccation (desorption) and/or the moistening (absorption) of most soils SWCCs results in hysteretic conduct**, Pham, et al., 2005,** for the similar value of suction, the soil may keep more water in the desiccating procedure than in the moistening procedure

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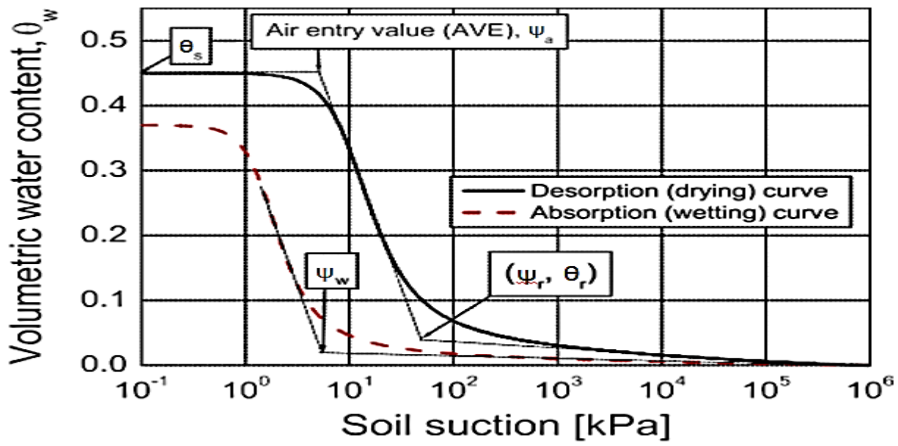

Figure 2. Typical soil-water characteristic curves (After **Gallage, et al., 2013**).

Thus, the function of unsaturated soil hydraulic conductivity, measured after the desiccating and moistening procedure, would display hysteresis as exposed to the matric suction**, van Dam, et al., 1996.** Because of the large consumption of time necessary for measuring the function of hydraulic conductivity after the moistening procedure, it is usually measured after the desiccating procedure**, Agus, et al., 2005.**
In order to measure the hydraulic conductivity precisely and correctly at little suction values, thus, it is significant to get a parameter that utilizes the constant-state method and has a more costly and vigorous system of measurement. Nevertheless, measuring the unsaturated hydraulic conductivity in the laboratory is consuming time and expensive, because it needs special devices and equipment as well as the service of a skillful technical individual. Consequently, many theoretical (indirect) methods are suggested by scholars to forecast the unsaturated soils hydraulic conductivity, **Fredlund, et al., 1994 and van Genuchten, 1980.**

6. PARAMETRIC STUDY FOR HOMOGENEOUS EARTH DAM

After the construction of an earth dam according to a particular design, the height of the water is considered variable and the hydraulic conductivity is constant for the saturated soil but it is different in the saturated-unsaturated soil. From this principle, SEEP/W software program was used to study seepage when the soil is saturated and saturated-unsaturated through homogeneous earth dam. **Fig. 3** is the typical cross- section for homogenous earth dam considered in this study. From **Fig. 3,** the possible variables affecting the quantity of seepage (Q) are:

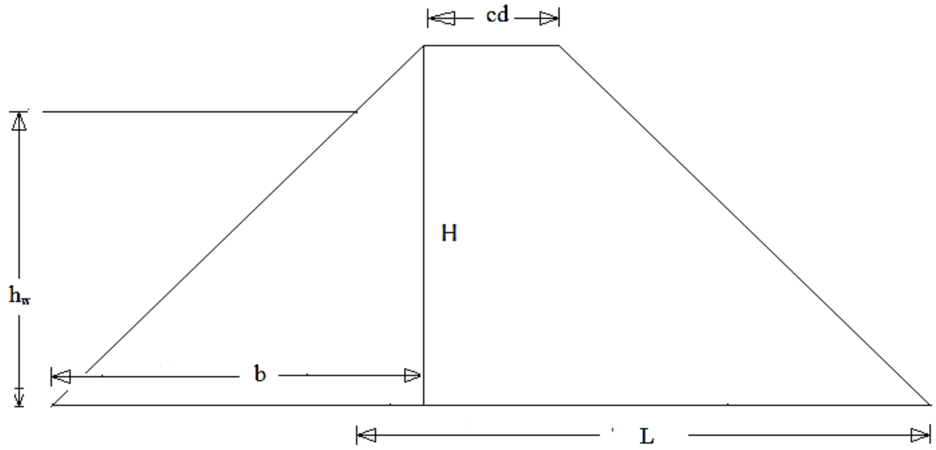

Figure 3. Typical cross-sections for homogenous earth dam profile.

H=higth of the earth dam (15m)

h_w=height of the water in the upstream (m)

L= Length from end height water to end dam

Cd=crest width of the dam (8m)

b= triangle base(26m)

In this research, the effect of heights of water in upstream (9, 10, 11, 12) and (L) (44.4, 42.667, 40.933, 39.2) was studied and the amount of seepage through the dam with constant hydraulic conductivity (k=0.1728 m/days) and saturated material was computed. Also, the analysis for saturated-unsaturated material using the data according to range value in **Table 2** are performed, where n and α refer to the soil- water characteristic curve and hydraulic conductivity function modeling constants, Sr is the residual degree of saturation and Ks is saturated hydraulic conductivity. The n parameter is required in many SWCC hydraulic conductivity function models to capture the pore size distribution of the soil.

Table 2. Representative Hydrologic parameter for sand, silt, and clay, **Ning Lu and William, 2004.**

Soil type	n(dimensionless)	α(kpa^{-1})	Sr (%)	Ks(m/s)
Sand	4 -8.5	0.1 – 0.5	5-10	10^{-2}-10^{-5}
Silt	2 -4	0.01-0.1	8-15	10^{-6}-10^{-9}
Clay	1.1 -2.5	0.001- 0.1	10-20	10^{-8}-10^{-13}

Three types of soil are used with curve fitting parameter. a, n, and m as shown in **Table 3.** Fredlund and Xing and van Geunchten methods were applied with different values of (a) parameter for each soil with constant n, m, and constant hydraulic conductivity according to **Table 3.**

Table 3. Curve fitting parameter of used soil, **Fredlund and Xing, 1994.**

Soil type	a	n	m(Fr)	Ks(m/day)	S_r
sand	1.799	4.524	1.157	o.864	0.08
Silt	1.948	2.708	1.084	0.00864	0.1
clay	15150	1.101	0.865	0.0000864	0.15

7. PARAMETRIC STUDY FOR NON-HOMOGENEOUS EARTH DAMS

One of the most important components in dam designing is the dam core. The dam core is a significant factor in caulking and controlling the dam body from seepage**, Karampoor, and Riazi, 2015. Fig.4** shows the sample models of a nonhomogeneous dam, the possible variables affecting the quantity of seepage (Q) are:

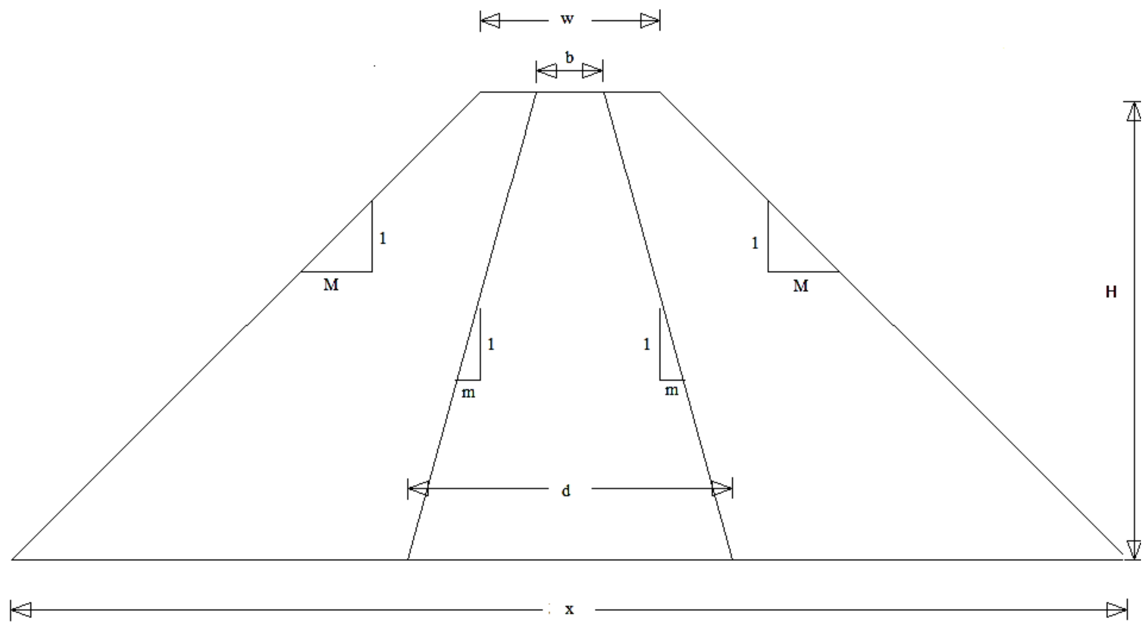

Figure 4. Sample model of non- homogeneous earth dam.

H= higth of the earth dam (15m)
w = crest width of the dam (8m)
x= width base of the dam (60m)
b= crest width of the dam core (3m)
d=width the base of the dam core (14m)
the effect of different heights of water in upstream (9, 10, 11, 12), with different values of (L) (44.4, 42.667, 40.933, 39.2) on amount of seepage through the dam with constant hydraulic

conductivity (Kshell=0.864 m/day and Kcore=0.0000864) m/day) for saturated soil was studied. Also, saturated-unsaturated analysis was calculated using the values shown in **Table 4.**

Table 4. Curve fitting parameter of used soils for the nonhomogeneous dam, **Fredlund and Xing, 1994.**

No	Soil type	a	n	m	Ks(m/day)	S_r
1-	Silt	1.948	2.708	1.084	0.0864	0.1
2-	Clay	15150	1.101	0.865	0.0000864	0.15

8. RESULTS AND DISCUSSION

The effect of each variable on amount seepage through homogeneous and non-homogenous earth dams can be seen as follows:

8.1 Effect of Head Boundary Condition for Saturated Soil.

Fig. 5 represents the relationship between the quantity of seepage with h to L ratio for homogeneous earth dam, the relationship is nonlinear but in non-homogenous earth dam the relationship linear between the quantity of seepage and h to L ratio **Fig. 7.** The seepage increases when the value of (h/L) increases (i.e. water in upstream of earth dam was high and the value of L is low) for both type of earth dam.

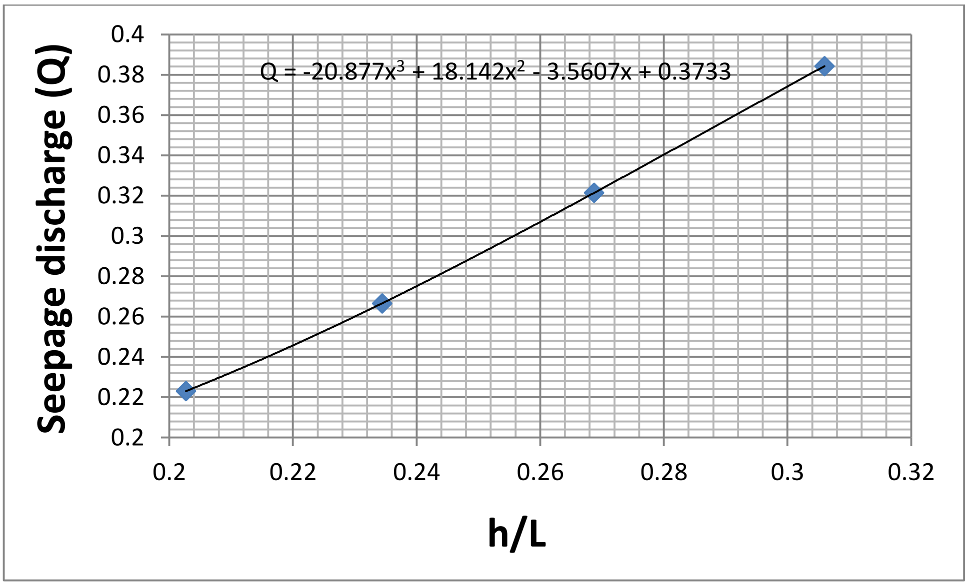

Figure 5. The relationship between Q with h/L for steady state homogenous earth dam.

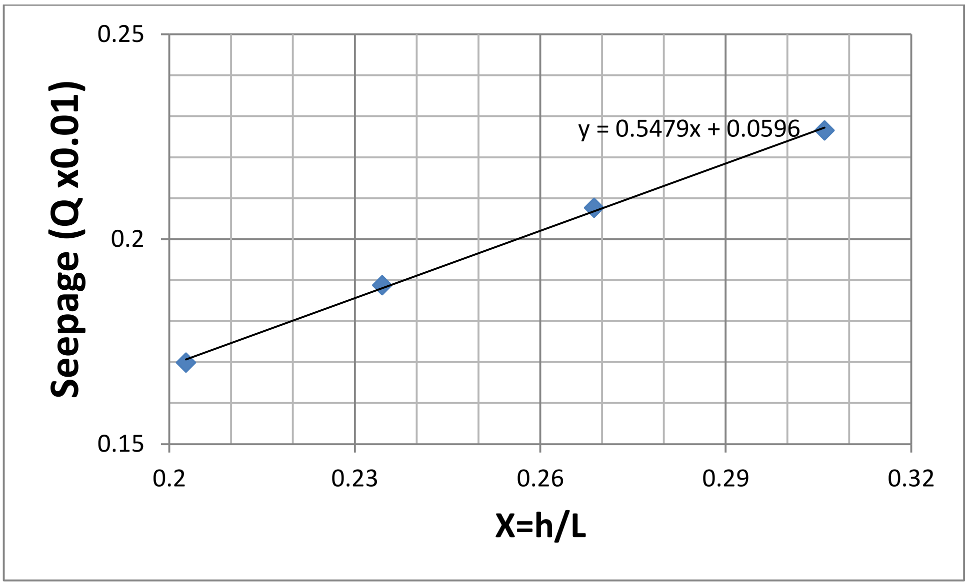

Figure 6. The relationship between (Q) with (H/L) for steady state non-homogenous earth dam.

8.2 Effect of Method of Prediction SWCC on Seepage through Soil.

For homogenous earth dam, **Fig.7** illustrates the relationship between the type of analysis with seepage (Q), the highest value of (Q) when the soil is saturated and smallest value is when using the method of (VG.) for all type of soil (sand, silt, and clay).

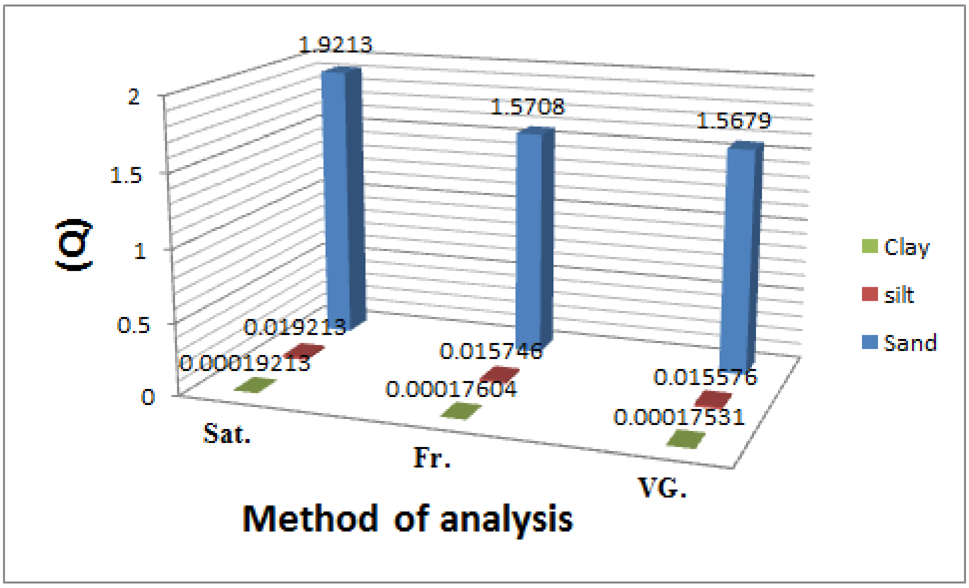

Figure 7. Comparison between methods of prediction of SWCC on seepage through saturated-unsaturated soil for different type of soil.

8.3 Effect of Type of Analysis

For non-homogeneous earth dam, **Fig. 8** represents the relationship between seepage (Q) with the method of analysis, the result shows that the value of seepage is highest for saturated and smallest value is obtained when using of Van Genuchten method.

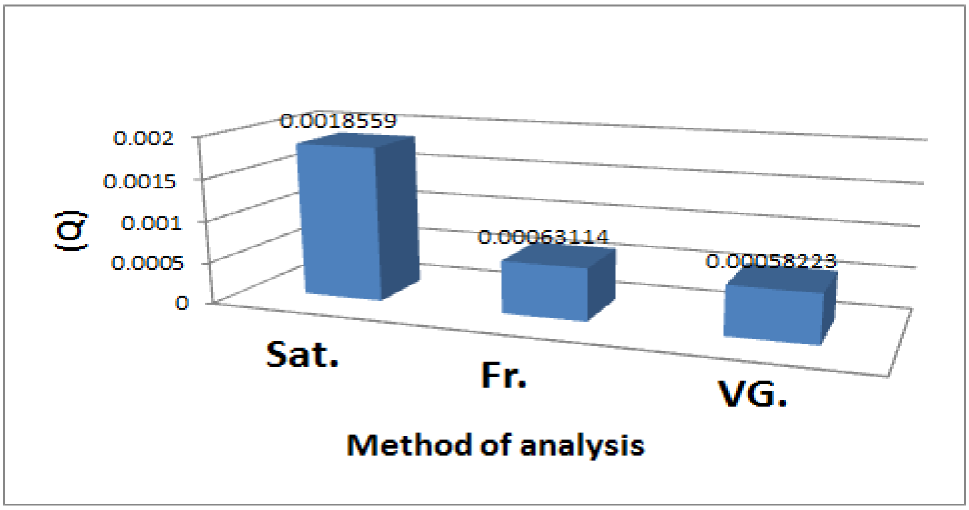

Figure 8. The relationship between seepage (Q) with the method of analysis.

8.4 Effect of Curve Fitting Parameter on the Seepage

To study the effect of curve fitting parameters on seepage through different types of soil, different values of a parameter for each soil are used with constant n and m and constant hydraulic conductivity as show in **Table 4**.

Table 4. Curve fitting parameter of used soils for homogenous dam

Soil type	a (kPa)	n	m(Fr.)	K_s m/day	S_r
Sand	0.1	4.524	1.157	0.864	0.08
	1				
	1.799				
Silt	1.948	2708	1.084	0.00864	0.1
	10				
	25				
Clay	625	1.5	1	0.0000864	0.15
	1000				
	1500				

Fig. 9, Fig. 10, and Fig. 11 illustrates the relationship between parameter (a) with seepage (Q). It is noted that (Q) increases when parameter (a) increases and the relationship is nonlinear for sand, silty and clay soil.

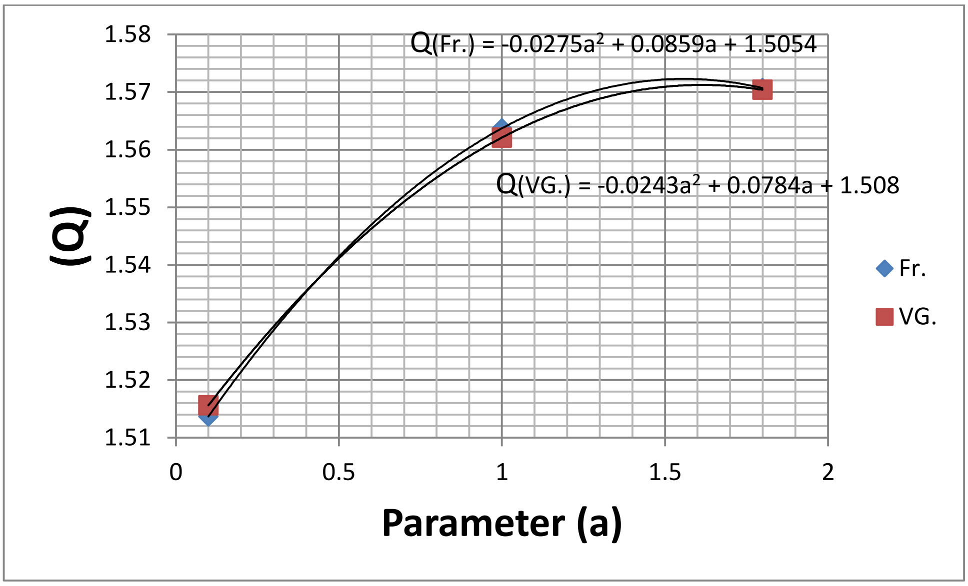

Figure 9. The relationship between quantity of seepage with a value of (a) for sand soil.

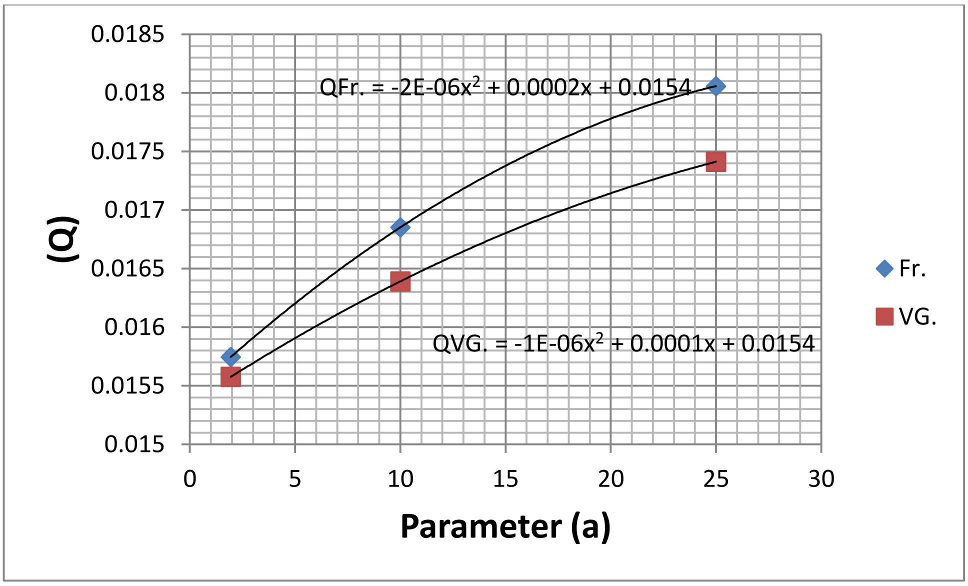

Figure 10. The relationship between quantity of seepage with a value of (a) for silt soil.

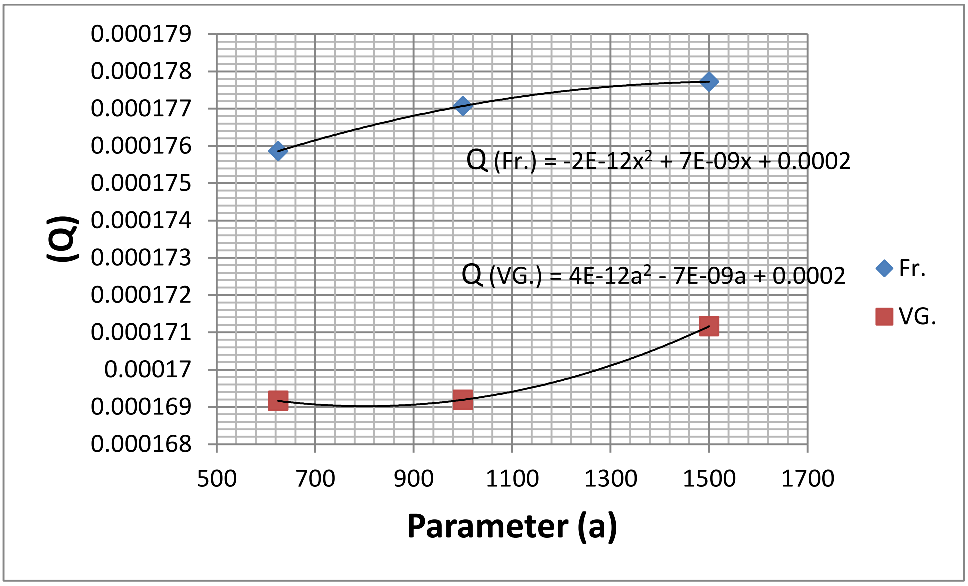

Figure 11. The relationship between the quantity of seepage with a value of (a) for clay soil.

8.5 Effect of (K_{shell}/K_{core}) of Soil

The values of hydraulic conductivity of shell and core soil for nonhomogeneous dam within the limit shown in **Table 6** are compared with an equivalent (K_{equ}) = ($K_{shell}+K_{core}$)/2. **Fig. 12** illustrates the relationship between the quantities of seepage (Q) with hydraulic conductivity. The result shows that the difference is high for the first and second case (42% and 202%) whereas the difference is very low in case three when (K_{shell} and K_{core}) =100 (4%) therefore, for simplicity equivalent hydraulic conductivity can be used successfully when $K_{shell}/K_{core} \leq 100$.

Table 6. Hydraulic conductivity of shell and core of used soils.

Soil type of shell	K_{shell}(m/day)	Soil type of core	K_{core}(m/day)	K_{shell}/K_{core}	K_{equ}(m/day)
Find sand	0.864	Clay	0.0000864	10000	0.4320432
Silt clay	0.0864		0.0000864	1000	0.0432432
	0.00864		0.0000864	100	0.0043632

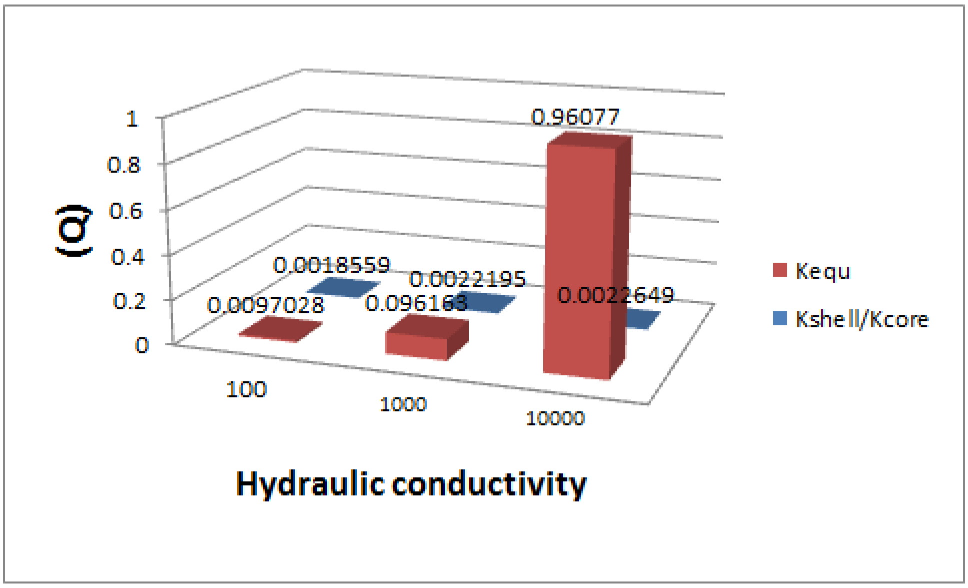

Figure 12. The relationship between the quantity of seepage with a value of hydraulic conductivity

9. CONCLUSIONS

The following main conclusions can be summarized as:-

- The quantity of seepage through homogeneous and non-homogeneous earth dam is increased with increasing ratio of height water in upstream to length (from the end of water height to end of earth fill dam).
- The highest amount of seepage through homogeneous and non-homogeneous earth dam is for saturated soil and lowest value when using van Genuchten method
- The quantity of seepage is increased when increasing the parameter (a) in sand, silt, and clay.
- The quantity of seepage is increased when increasing the value K_{shell}/K_{core}.

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