Al-Azhar Engineering 16th International Conference

Vol. 19, No. 72, July 2024, 232 - 247

DETERMINING THE HYDRAULIC CONDUCTIVITY FOR POROUS MEDIA USING A MODIFIED EXPERIMENTAL METHOD

Omar Ibn Alkhattab M. Abu Al-Wafa*, Ahmed H. Mahmoud, Amir M. Mobasher, Anas M. El-Molla.

Irrigation and Hydraulics, Civil Engineering Department, Faculty of Engineering, Al-Azhar University, Cairo, Egypt.

***Correspondence:** OmarTaha.14@azhar.edu.eg

Citation:

O.I.M. Abu Alwafa, A.H. Mahmoud, A.M. Mobasher and A.M. El-Molla, " Determining The Hydraulic Conductivity For Porous Media Using A Modified Experimental Method", Journal of Al-Azhar University Engineering Sector, vol. 19, pp. 232 - 247, 2024.

Received: 09 December 2023

Revised: 30 January 2024

Accepted: 10 February 2024

DoI:10.21608/auej.2024.258828.1571

ABSTRACT

The primary factor influencing flow within recharge or discharge wells and groundwater dispersion is the soil hydraulic conductivity. Studying hydraulic conductivity and its variation is a basic condition for the understanding and modeling of flow and contaminant transport processes. Hydraulic conductivity is permitting water seepage through connected voids. Actually, determining the hydraulic conductivity, whether in laboratory or field experiments is sensitive and difficult. Accurate determination of the hydraulic conductivity still needs more studies. The main objective of this research is to present an experimental study for determining the hydraulic conductivity of porous media as a governing parameter which plays acritical role in studying groundwater flow through an in-depth exploration of soil hydraulic properties. To determine it, a specialized hydraulic model was devised based on the conventional Darcy's experiment. Experimental runs were carried out and measurements were determined. The validity of the device was confirmed and the results were approved and validated by making a comparison with standard values.

KEYWORDS: Determining of Hydraulic Conductivity – Porous Media Hydraulic Properties – Groundwater Movement.

تحديد التوصيلية الهيدروليكية للأوساط المسامّية باستخدام تجربة معملية معدّلة

عمر بن الخطاب محمد أبو الوفا*،أحمد حلمي محمود، أمير محمد مباشر، أنس محمد الملّا

شعبة الري والهيدروليكا بقسم الهندسة المدنية، كلية الهندسة، جامعة الأزهر، مدينة نصر، 11884، القاهرة، مصر.

***البريد الاليكتروني للباحث الرئيسي:** OmarTaha.14@azhar.edu.eg

الملخص

دراسة وتحديد التوصيلية الهيدروليكية له أهمية كبرى سواء في الدراسات الهيدروجيولوجية أو الجيوتقنية.العامل المؤثر الرئيسي في تصرف أبار سحب أو تغذية المياه الجوفية وكذلك سريانها وانتشارها هو قدرة التربة على التوصيلية الهيدروليكية خلالها.

قياس التوصيلية الهيدروليكية بدقة عالية في طبقات التربة يمثل تحديا وعلى الرغم من وجود عدة طرق عملية لتحديدها إلا إنها تختلف فيما بينها اختلافا كبيرا من حيث دقة النتائج. بناء على ما سبق لدراسة هيدروليكية السريان يتعيّن تحديد خصائص التربة وأهمها التوصيلية الهيدروليكية.تم تجهيز نموذج هيدروليكي لتعيين التوصيلية الهيدروليكية لأنواع التربة المختلفة.تم إجراء التجارب بوضع اسطوانة عينة التربة أفقيا لتطبيق محورها على خط المقارنة لتحقيق ثبات سرعة تسرب المياه خلال التربة عبر مسافة طول العينة،وليشير منسوب الماء في البيزومترات مباشرة إلى الضاغط الهيدروليكي فقط مع تجنب اختلاف وضع القطاعات العرضية على محور العينة بالنسبة لخط المقارنة الأفقي. تمت مقارنة النتائج بالنتائج القياسية والتأكد من صلاحية جهاز التجربة واعتماد نتائجها لتعيين التوصيلية الهيدروليكية للأوساط المسامية.

الكلمات المفتاحية : سريان المياه الجوفية، الخصائص الهيدروليكية لأنواع التربة، طرق تعيين التوصيلية الهيدروليكية.

1. INTRODUCTION

Many tools for the laboratory and field investigation of the parameter of hydraulic conductivity exist. used formulas were compared for the determination of hydraulic conductivity from grain size data for a range of sediment types and to evaluate these methods' predicting for hydraulic conductivity, using sonic sampling [1]. A pumping test, slug test and numerical modelling were used to evaluate hydraulic conductivity from grain size distribution [2]. Hydraulic conductivity was estimated using infiltration tests and borehole dilution [3]. A broad approaches'overview was given including slug tests, pumping tests, laboratory analyses of core samples, borehole flowmeter tests, and hydraulic tomography [4]. The difficulty of obtaining reliable hydraulic conductivity estimates in complex structured deposits was demonstrated [5,6]. Governing factors of the parameter of hydraulic conductivity are grain- and pore size distribution, grain and pore shape, tortuosity, specific surface, and porosity [7]. Earth materials' hydraulic conductivity can be determined in the laboratory using permeameters. Darcy made the first study of water movement through a porous medium In which original equipment was actually vertically oriented [8]. This research experiment is horizontally carried out to determine the hydraulic conductivity for porous media .

2. THEORETICAL APPRAUCH

Figure (1) demonstrates the principle of the experiment, illustrating flow through a horizontal cylinder filled with soil. Water is applied at A and Hydraulic head at this point could be observed by means of vertical pipe. Another piezometer is presented to measure the hydraulic head at the other point B. The discharge is proportional to water height difference and inversely proportional to the length of flow [8].
The flow is also obviously proportional to the pipe cross-sectional area, A. This concept results in the following expression (Darcy's law):

$$Q = -KA\left(\frac{ha - hb}{L}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(1)$$

It is necessary to identify the difference between discharge and seepage velocity. The flow velocity (v) is the water flow rate per unit of total cross sectional area (A). The actual velocity through voids will be greater than discharge velocity [9].

Therefor: $q = A.\mathrm{v} = \mathrm{v}_s.A_v$ $\quad \ldots \mathrm{v}_s = \frac{\mathrm{v}}{n} \quad \ldots\ldots\ldots..(2)$

Where: v_s : The fluid seepage velocity through area of voids.

A_v : Area of voids, and n : Porosity.

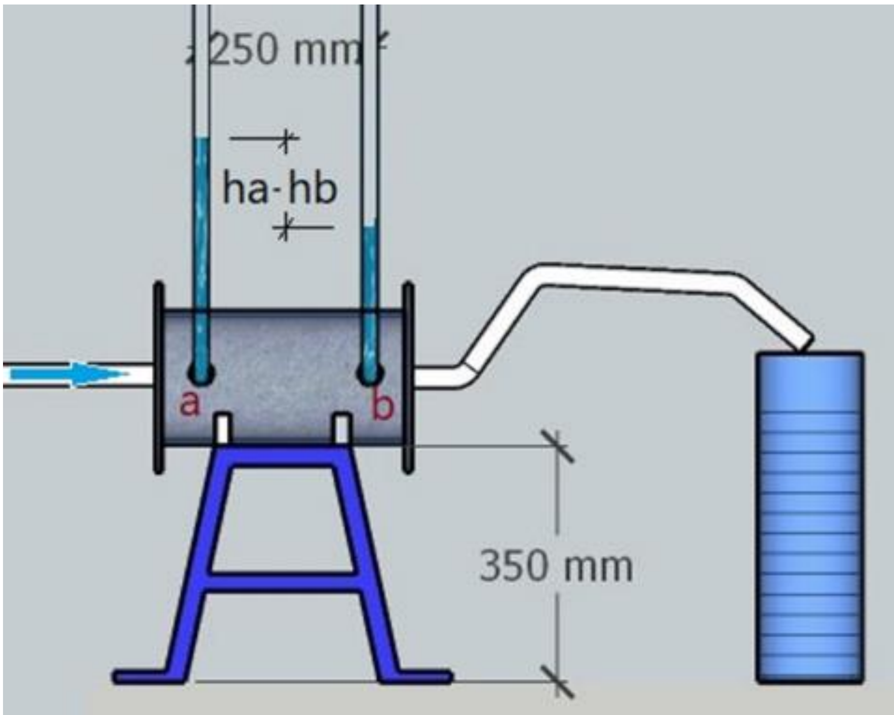

Figure (1). Hydraulic Gradient Through A Horizontal Soil Sample Pipe

Hydraulic conductivity is characterized by velocity dimensions (L/T) and is typically quantified in units of cm/sec or m/day. It is a combined property of the medium and the flowing fluid.

3. EXPERIMENTAL SETUP

The experimental model was set up in the irrigation and hydraulics laboratory in civil engineering department at the faculty of engineering, AL-Azhar University to determine the hydraulic conductivity for porous Media, **figures (2,3).** The system consists mainly of two acrylic cylindrical tanks with dimensions, (D) 10cm in diameter and (H) 35cm in height for both of them.

The first cylinder is filled with water at a constant head. This tank is supplied with water by feeding tank through a pipe connected to a submersible pump, **figure(4).**

Water cylindrical tank recharges the soil sample under constant head and water flows at a steady rate. There is a pipe to let excess water exit from water level at this head.

The second acrylic cylinder is considered the sample tank. This tank contains a soil sample which its hydraulic conductivity is targeted to be determined. A syphon was installed at the out let of the sample cylinder to ensure that the water flow covers the entire cross sectional area.

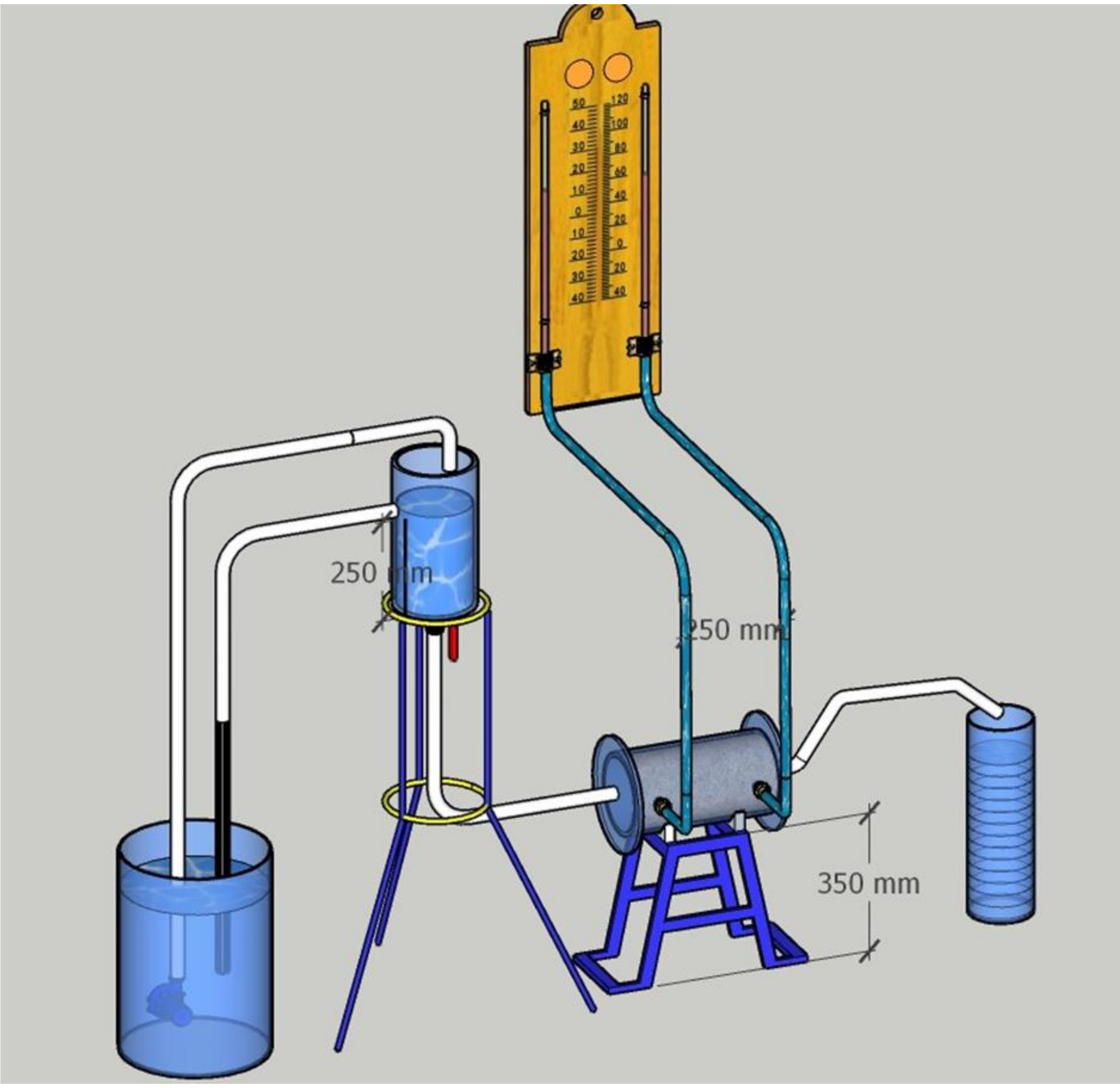

Figure (2). 3d Definition Sketch for the Experimental Model.

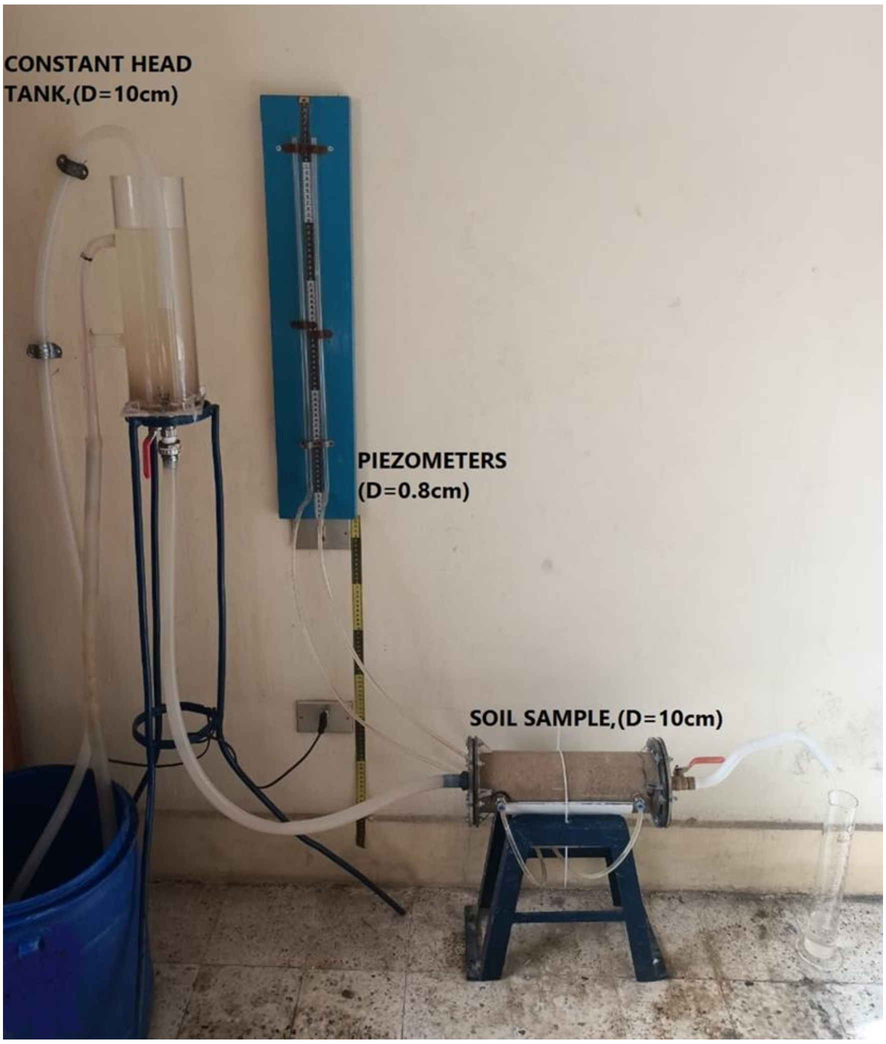

Figure (3): The Experimental Model.

Figure (4): The Submersible Feeding Pump.

Direct determination of the hydraulic pressure head (P/ɣ) along the flow line was enabled through water level measurements in piezometers. Furthermore, maintaining the horizontal sample axis ensured a consistent seepage velocity across soil cross-sections, owing to the stability of the hydraulic head. This deliberate experimental configuration effectively mitigated measurement errors attributed to variations in the position head (Z) within the soil sample along the stream flow. In order to observe the flow hydraulic gradient, two filtered copper piezometers were installed. The length between these two piezometers is the soil sample length and equals 25cm. Two circular discs had been cut by C.N.C router machine and perforated with a high perforation ratio.

A disc=78.5cm^2, A perforation =24.5cm^2

Minimum perforation ratio = A perforation/ A disc =31%

These circular discs were covered with a permeable geotextile to enclose sediment sample granules and allow water to permeate without affecting on measurements accuracy.

The experimental runs were conducted for various soil types to determine the hydraulic conductivity for each one, **figures (5-7)** and **table (1).** The particle size distribution could be obtained by performing sieve analysis for the soil classification to determine engineering characteristics **figures (8-10)**.

Water is permitted to traverse a soil sample under a consistently maintained head. By ascertaining the sample's length (L), cross-sectional area (A), and quantifying the discharge (Q=V/t) of the flowing water, the hydraulic conductivity coefficient (K) can be deduced using equation (1).

The ingress of water is regulated through a valve originating from a reservoir with a constant head, and the effluent water is amassed in a graduated cylinder. The discrepancy in head is gauged between water surfaces topping the sample in a piezometric tube. The experiment is conducted multiple times with varying values of the hydraulic head. The mean value of hydraulic conductivity is subsequently computed.

Figure (5). Graded Sand Soil Sample.

Figure (6). Sandy Gravel Soil Sample.

Figure (7). Gravelly Sand Soil Sample.

Table (1) : Soil Samples Classification And Characteristics.

Soil Classification (M.I.T)	D_{50} mm
Graded Sand	0.57
Sandy gravel	2.8
Gravelly Sand	1

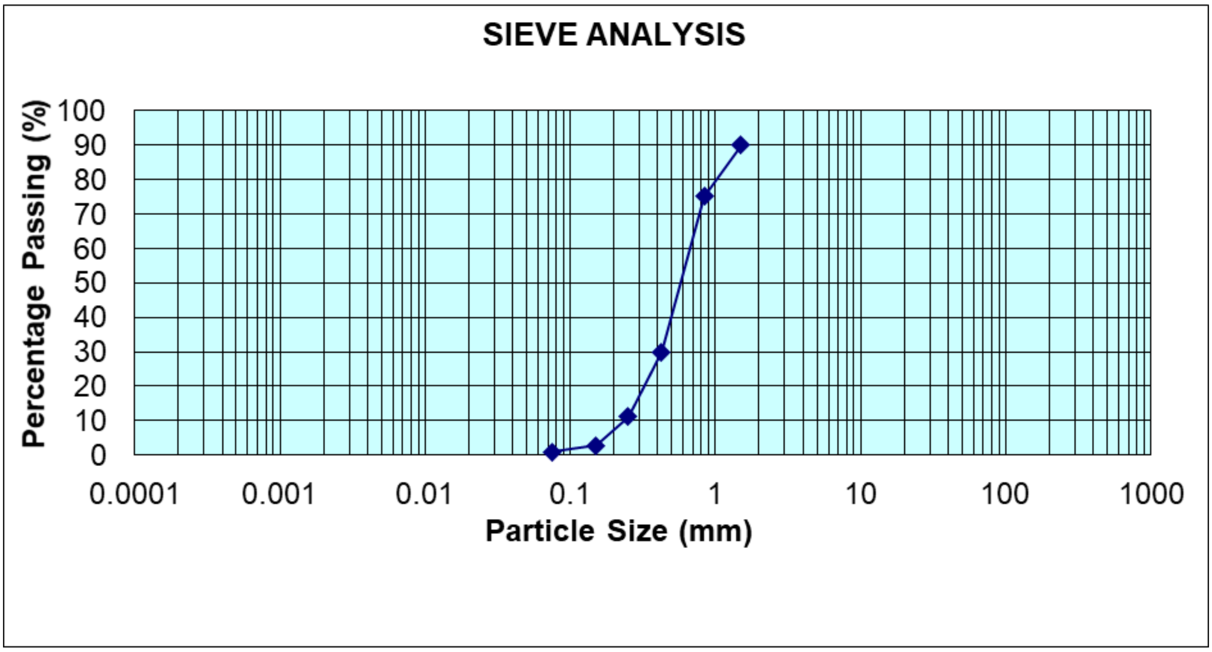

Figure (8). Grain Size Distribution Curve for Graded Sand Soil Sample.

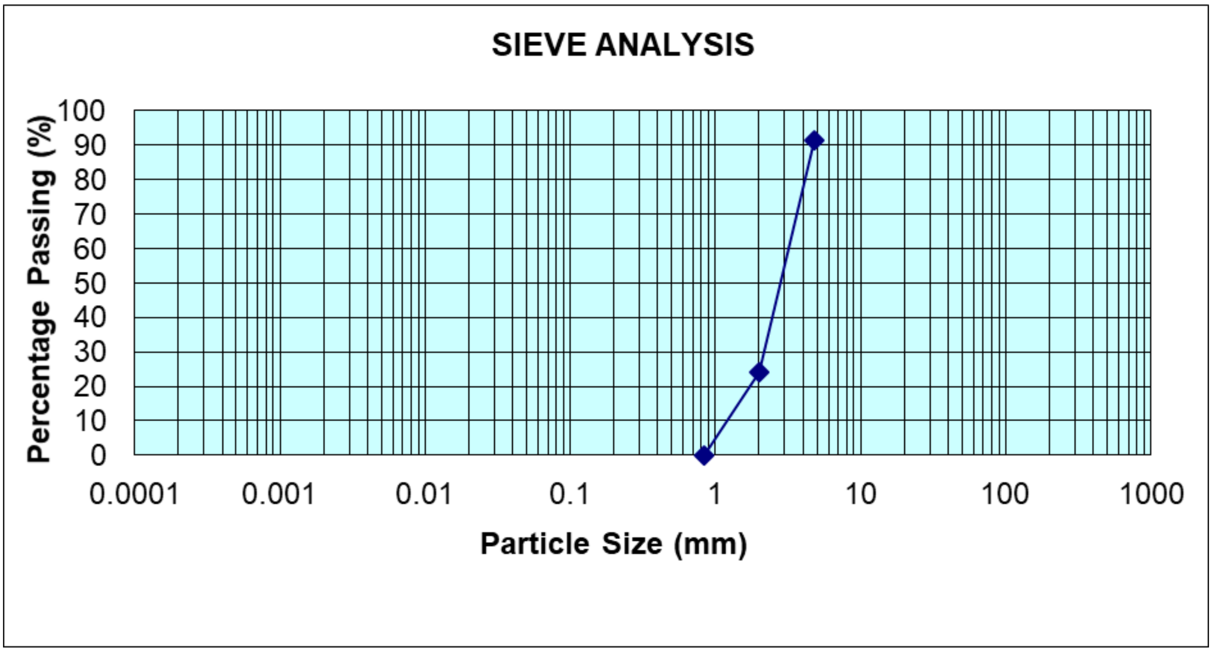

Figure (9). Grain Size Distribution Curve for Sandy gravel Soil Sample.

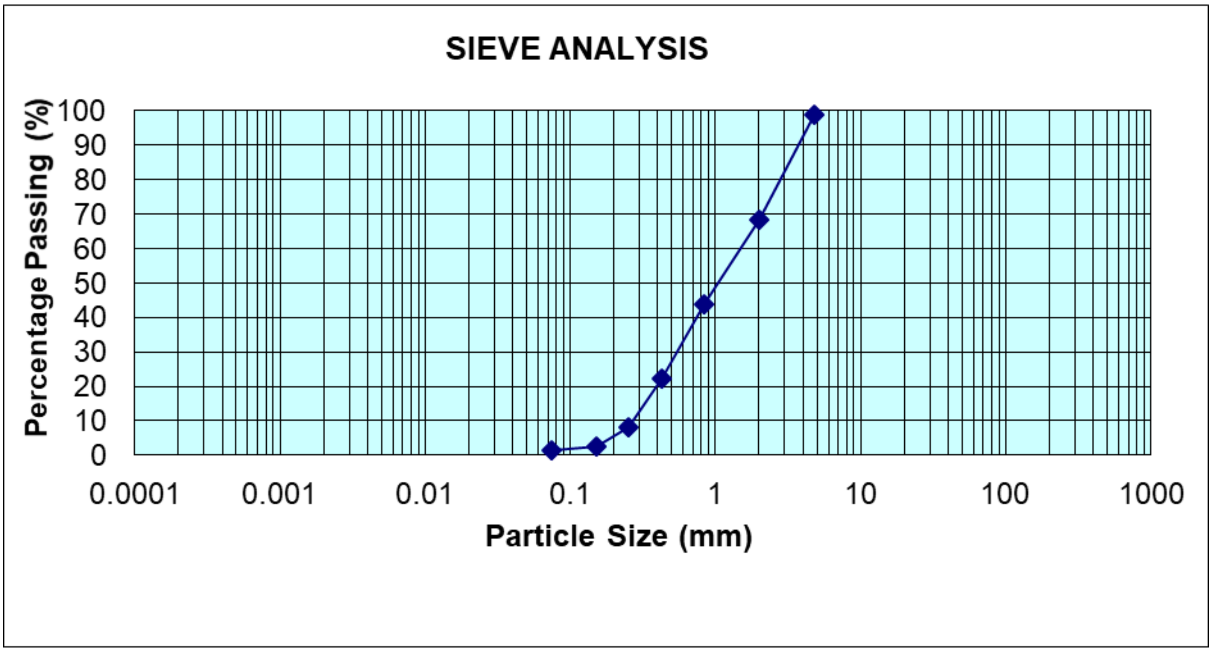

Figure (10). Grain Size Distribution Curve for Gravelly Sand Soil Sample.

4. RESULTS AND DISCUSSION

The experimental runs were carried out under the influence of different hydraulic pressure heads and the average readings were noticed. Results were compared with typical values of hydraulic conductivity to verify reliability.

The accumulative charts have been developed from the sieve analysis and the hydraulic conductivity results were obtained as follows:

The first experimental run was carried out on a sample of graded sand after performing sieve analysis which resulted in the accumulative chart as shown in **figure (8).** Water volumes were collected during a determined times through an indicated cross sectional area to determine the specific discharge values.The water levels between piezometers were measured through soil sample length to determine the average values of hydraulic gradient. Results were observed and plotted, **table (2)** and **Figure (11)**.

Table (2): Values Of Hydraulic Gradient And Specific Discharge For Sand Sample.

Graded sand	
i (-dh/dl)	**q (mm min^{-1})**
1.17	9.34
1.98	16.13
2.33	19.2
2.82	23.3

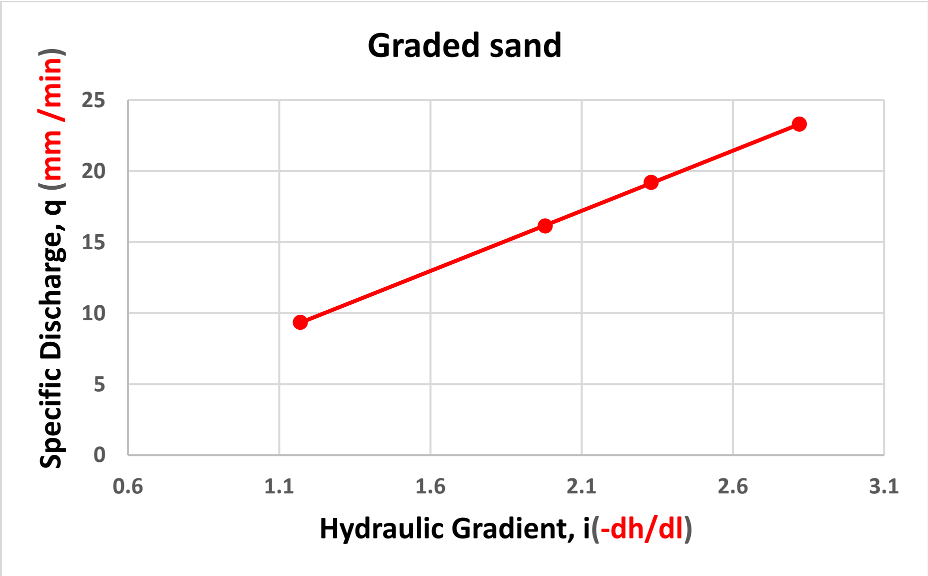

Figure (11): Hydraulic Conductivity Values Curve For Sand Sample.

From the chart of this sand soil type experimental results, hydraulic conductivity for it can be obtained which equals the slope of results trendline.

$$K = \frac{q}{i} = 8.473\, mm\, min^{-1} \;= 1.4 \times 10^{-2} cm/\sec \;\; = \; 12.2 m/day$$

This sand soil sample data was compared with Darcy's data for two different sands and showed compatibility, **figure (12)**.

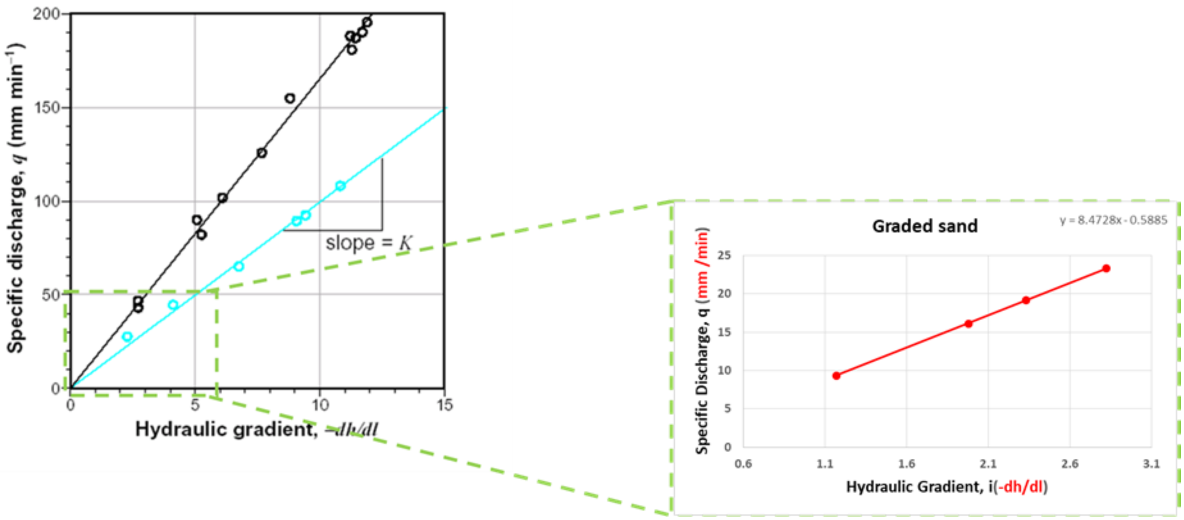

Figure (12): Comparison with Darcy's data for two different sands.

The experimental results were compared with standard values **Table (5)** and grain size-based Methods **Table (6)** and showed good agreement.

The second experimental run was carried out on a sample of sandy gravel. **Figure (9).** displays the sieve analysis accumulative chart for this type of soil. As in the previous sequence the specific discharge and Hydraulic Gradient values were obtained and plotted in **table(3) and figure(13)**. There is a clear difference in the specific discharge range between gravel and sand samples because of the great difference in particle size, shape, and internal surface area of the particles.

Table (3): Values Of Hydraulic Gradient And Specific Discharge For Sandy Gravel Sample.

Sandy Gravel	
i (-dh/dl)	q (mm min^{-1})
1.455	103.29
1.12	88.88
0.68	57.9

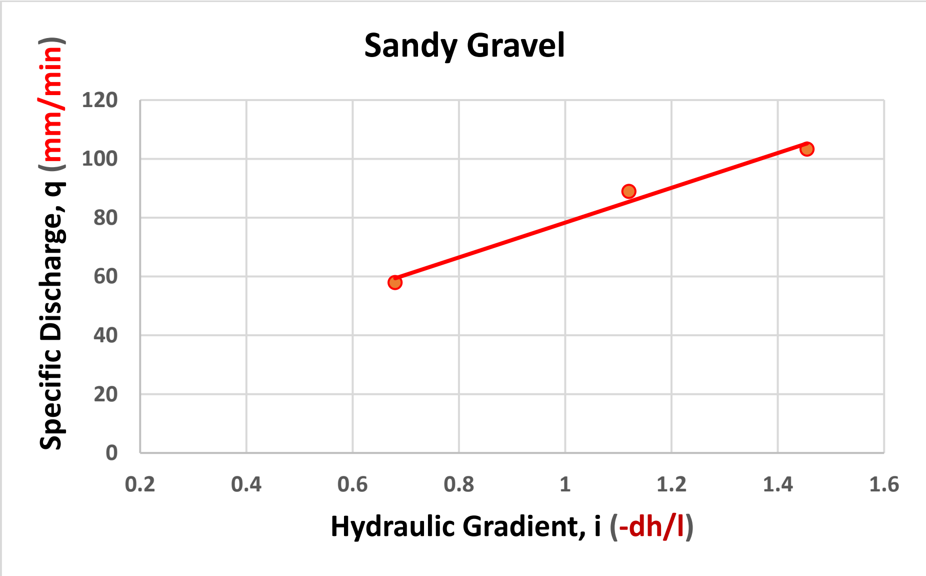

Figure (13): Hydraulic Conductivity Values Curve For Sandy Gravel Sample.

The average value of hydraulic conductivity for the sandy gravel sample can be determined.

$$k = \frac{q}{i} = 59.171\, mm\, min^{-1} = 9.86 \times 10^{-2} cm/\sec$$

There is a good agreement with typical hydraulic conductivity values, **table (5).**

The last experimental run was carried out on a sample of gravelly sand. The sieve analysis accumulative chart for this soil is shown in **figure (10).** Under the influence of different hydraulic heads the average results were noticed and plotted, **table(4) and figure(14)**.

Table (4): Values Of Hydraulic Gradient And Specific Discharge For Gravelly Sand Sample.

Gravelly sand	
i (-dh/dl)	**q (mm min^{-1})**
1.58	1.408
2.74	2.593
3.31	3.25

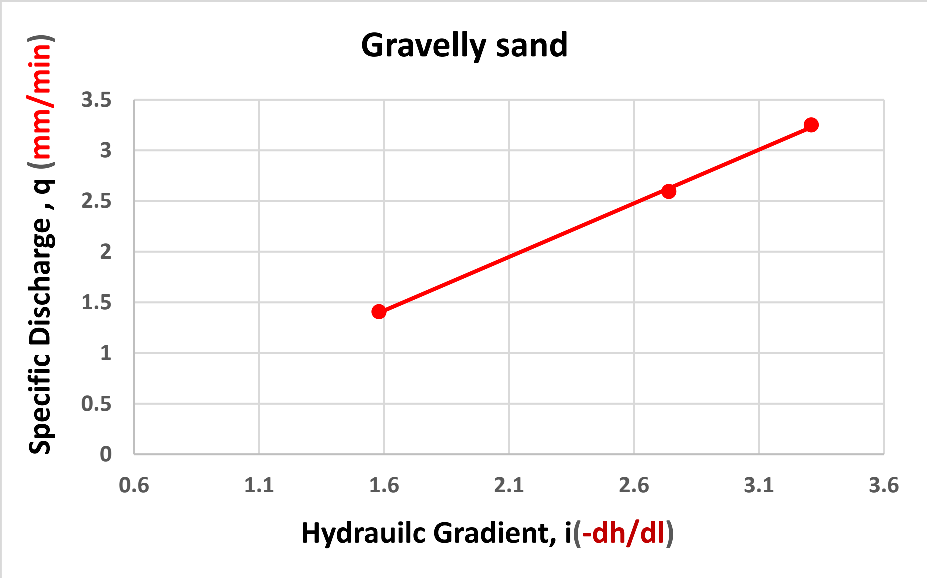

Figure (14): Hydraulic Conductivity Values Curve For Gravelly sand Sample.

The flow rate in this sample is much lower, because of the increase in standard deviation which results in the interaction between sand and gravel grains resulting in a diminished effective cross-sectional area of voids orthogonal to the direction of flow and thus increases friction and resistance to flow.

From the results trendline chart get the hydraulic conductivity as follows:

$$k = \frac{q}{i} = 1.0584\, mm * min^{-1} = 1.76 \times 10^{-3}\, cm/\sec$$

Table (5). Common Soil Hydraulic Conductivity Values [9].

Soil Type	Hydraulic Conductivity (cm/sec)
Clean Gravel	>1
Clean Coarse Sand	$1 \quad to \quad 1 \times 10^{-2}$
Fine Sand	$5 \times 10^{-2} \quad to \quad 1 \times 10^{-3}$
Silty Sand	$2 \times 10^{-3} \quad to \quad 1 \times 10^{-4}$
Silt	$5 \times 10^{-4} \quad to \quad 1 \times 10^{-5}$
Clay	$< 1 \times 10^{-6}$

Table (6). Compilation Of Outcomes From Grain Size Analysis Alongside The Conductivity (K) Values Expressed In Meters Per Day, As Determined For The Aquifer Materials Through Empirical Methods [10].

Depth Range of boreholes (m)	Sand Size Parameters (d_{50} mm)	Sand Type*	HAZ	BREY	SLIT	TERZ	KOZ	USBR	A&S
(A) Karnamepur 44–50	0.87	cs	45	46	13	29	36	36	6
50–68	0.65	cs	48	46	15	34	44	20	19
(B) Bharauli 56–69	0.85	cs	38	39	11	23	28	20	6
69–103	0.65	cs	42	41	13	28	36	15	16
130–144	0.42	ms	39	36	14	30	41	9	25
(C) Nargada Narayanpur 146–178	0.55	cs	38	36	12	26	34	11	18
210–247	0.61	cs	46	42	15	34	44	17	19
(D) Paharpur 75–82	0.73	cs	50	48	16	35	45	24	16

HAZ = Hazen; BREY = Breyer; SLIT = Slitcher; TERZ = Terzaghi; KOZ = Kozeny-Carman; USBR = U.S. Bureau of Reclamation; A&S = Alyamani and Sen. * ms = medium sand; cs = coarse sand.

The empirical methods equations used for determination of hydraulic conductivity according to grain size distribution are listed in **table (7)**.

Table (7). Concise Overview Of The Empirical Approaches Employed In Ascertaining Hydraulic Conductivity [10].

Author	Empirical Formula	Coefficients	Porosity Function	Effective Grain Diameter
Hazen	$(g/v)Ch\ f(n)d_{10}^2$	$Ch = 6 * 10^{-4}$	$1 + 10(n - 0.26)$	d_{10}
Breyer	$(g/v)Cb\ d_{10}^2$	$Cb = 6 * 10^{-4} \log 500/Uc$	1	d_{10}
Slitcher	$\frac{g}{v} \times 1 \times 10^{-2} \times n^{3.287} d10^2$	0.01	$n^{3.287}$	d_{10}
Terzaghi	$\frac{g}{v} \times \beta_\gamma (n - \frac{.13}{\sqrt[3]{(1-n)}})^2 d10^2$	$\beta_\gamma = 10.7 * 10^{-3}$ for smooth grains, $6.1 * 10^{-3}$ for large grains.	$(n - \frac{.13}{\sqrt[3]{(1-n)}})^2$	d_{10}
Kozeny-Carman	$(g/v)Ck\ f(n)d_{10}^2$	$Ck = 8.3 * 10^{-3}$	$n3/(1 - n)^2$	d_{10}
USBR	$0.36(d20^{2.3})$	0.36	1	d_{20}
A&S	$1300[Io + 0.025(d50 - d10)]^2$	1	1	d_{10}, d_{50}

5. Conclusion

Indeed, it was demonstrated that the experimental apparatus utilized in this research is apt for the estimation of hydraulic conductivity in granular materials. Calculations of hydraulic conductivity coefficient obtained from the present experimental runs are considered within the accepted ranges for this type of material.

In this way, it is considered that this device setup has a correct construction and validation. This experimental study has a guiding significance for the similar analysis as a modified and reliable research that considerably improves the hydraulic conductivity estimates for porous media that influences groundwater movement study.

References

[1] T. Vienken and P. Dietrich, "Field evaluation of methods for determining hydraulic conductivity from grain size data," Journal of Hydrology, vol. 400, no. 1–2, pp. 58–71, Mar. 2011, doi: 10.1016/j.jhydrol.2011.01.022.

[2] J.-Y. Cheong, S.-Y. Hamm, H.-S. Kim, E.-J. Ko, K. Yang, and J.-H. Lee, "Estimating hydraulic conductivity using grain-size analyses, aquifer tests, and numerical modeling in a riverside alluvial system in South Korea," Hydrogeol J, vol. 16, no. 6, p. 1129, Sep. 2008, doi: 10.1007/s10040-008-0303-4.

[3] T. Vienken, "Critical evaluation of vertical high resolution methods for determining hydraulic conductivity.," Environmental Science, Engineering, Geology, 2010.

[4] J. J. Butler, "Hydrogeological Methods for Estimation of Spatial Variations in Hydraulic Conductivity," in Hydrogeophysics, vol. 50, Y. Rubin and S. S. Hubbard, Eds., in Water Science and Technology Library, vol. 50. , Dordrecht: Springer Netherlands, 2005, pp. 23–58. doi: 10.1007/1-4020-3102-5_2.

[5] G. E. Rehfeldt, C. C. Ying, D. L. Spittlehouse, and D. A. Hamilton, "Genetic Responses to Climate in Pinus contorta: Niche Breadth, Climate Change, and Reforestation," Ecological Monographs, vol. 69, no. 3, p. 375, Aug. 1999, doi: 10.2307/2657162.

[6] E. A. Sudicky, "A natural gradient experiment on solute transport in a sand aquifer: Spatial variability of hydraulic conductivity and its role in the dispersion process," Water Resources Research, vol. 22, no. 13, pp. 2069–2082, Dec. 1986, doi: 10.1029/WR022i013p02069.

[7] P. A. C. Raats, "Dynamics of Fluids in Porous Media: By J. Bear. American Elsevier Publishing Company, Inc., 52 Vanderbilt Avenue, New York, N.Y. 10017 or Elsevier Publishing Company, 335 Jan Van Galenstraat, P.O. Box 221, Amsterdam, The Netherlands. 764 p. 1972." Soil Science Soc of Amer J, vol. 37, no. 4, Jul. 1973, doi: 10.2136/sssaj1973.03615995003700040004x.

[8] C. W. Fetter, Applied hydrogeology, 4th ed. Upper Saddle River, N.J: Prentice Hall, 2001.

[9] A. Radwan, Fundmental of Soil Mechanics, Seventh. 2007.

[10] S. Sahu and D. Saha, "Empirical Methods and Estimation of Hydraulic Conductivity of Fluvial Aquifers," Environmental & Engineering Geoscience, vol. 22, no. 4, pp. 319–340, Nov. 2016, doi: 10.2113/gseegeosci.22.4.319.