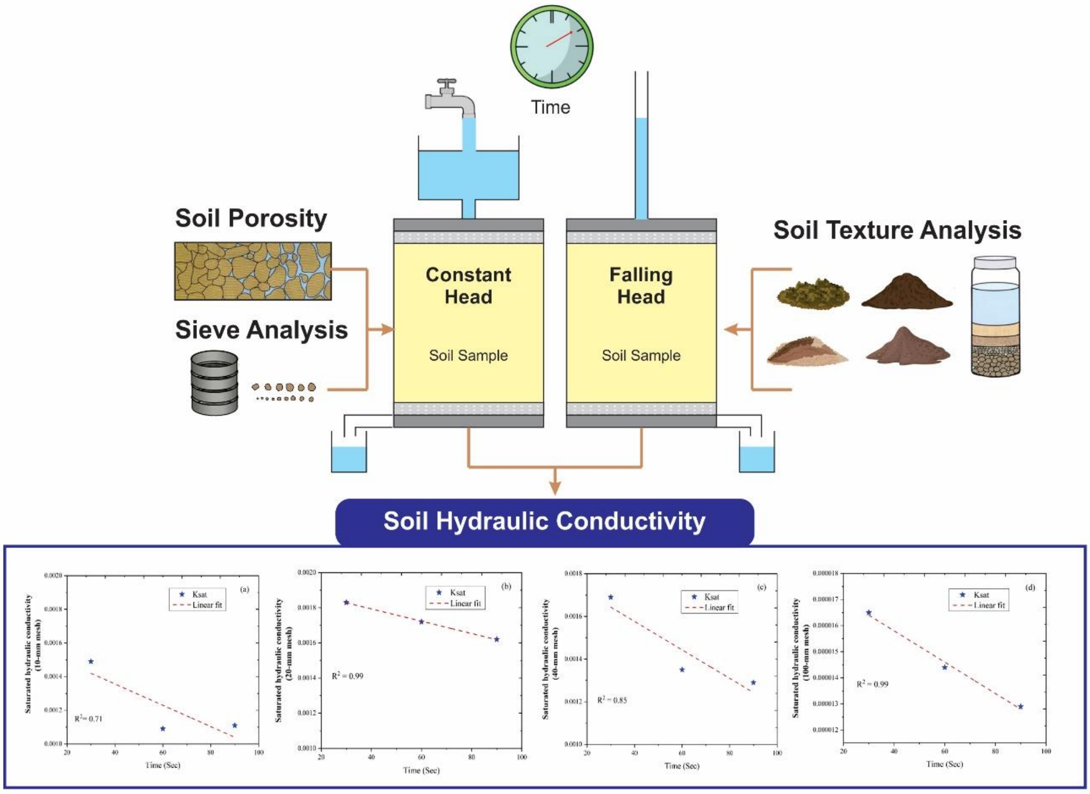
Assessment of Saturated Hydraulic Conductivity with Using Soil Particle Size Distribution: A Comparative Study of Constant Head and Falling Head Methods

Kashif Ali Solangi [1], Bilawal Abbasi [1], Farheen Solangi [2], Shahneela Khaskhali[3], Altaf Ali Siyal [1]*, Hassan Mehmood[4], Muhammad Irfan Akram[5], Rashid Iqbal[6]*, Abdullah Ahmed Al-Ghamdi[7], Mohamed S Elshikh[7]

[1] Faculty of Agricultural Engineering, Sindh Agriculture University Tandojam, Tandojam-70060, Pakistan; kashifsolangi73@gmail.com (K.A.S); 2018Y90100003@caas.cn (B.A); aasiyal@sau.edu.pk (A.A.S)
[2] Research Centre of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang 212013, China; 1000006244@ujs.edu.cn (F.S)
[3] Cereal Crops Institute, Hainan Academy of Agricultural Sciences Sanya Institute, Hainan Academy of Agricultural Sciences, Sanya, China; shahneela.gull@gmail.com (S.K)
[4] Department of Soil Science, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan; malikhassanbwp@gmail.com (H.M)
[5] Department of Entomology, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur-63100, Pakistan; drirfan@iub.edu.pk (M.I.A.)
[6] Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Bahawalpur 63100, Pakistan; rashid.iqbal@iub.edu.pk (R.I)
[7] Department of Botany and Microbiology, College of Science, King Saud University, P.O. 2455, Riyadh 11451, Saudi Arabia; aaalghamdiksu@gmail.com (A.A.A), melshikh@ksu.edu.sa (M.S.E)

*****Correspondence: aasiyal@sau.edu.pk, rashid.iqbal@iub.edu.pk

GRAPHICAL ABSTRACT



Abstract

The purpose of soil hydraulic conductivity is to retain soil water contents, and soil water pressure. In this study investigates two different methods to understand the soil hydraulic conductivity of loam and clay soils. The present research conducted a laboratory experiment to measure the saturated hydraulic conductivity (Ksat) using two different methods: the constant head and falling head methods. The constant head method utilized a soil column with a length of 8.5 cm, and three soil columns were occupied with various soil texture classes (%). The study results demonstrate that the classification of soil texture was predominantly sandy loam with porosity varying between 35%, 43%, and 50% within the clay soil category. Furthermore, the average value of K_{sat} for the soil samples using the constant head method was 0.00142 cm/sec, while the falling head method provides average values of 0.00123, 0.00172, and 0.00144 for sandy loam and 0.0000146 cm/sec for clay soil. It is concluded that the falling head method indicates greater accuracy, particularly evident in the concurrent analysis of three samples. This study suggested that determination of Ksat through laboratory method is suitable due to cost effectiveness and simplicity.

Keywords: Hydraulic conductivity, Porosity, Constant head method, Falling head method.

1. Introduction

Saturated hydraulic conductivity (K_{sat}) is one of the major soil properties that can help regulate and determine the arrangements of the water flow process (Gupta et al. 2021). The assessment of K_{sat} is important for irrigation practices, such as runoff, infiltration rates, groundwater recharge rates, and drainage processes, which makes it of particular concern in forest management (Hao et al. 2019). Furthermore, K_{sat} evaluations can help guide resource management selections regarding irrigation, drainage, fertilizer use, water-saving measures, solute reduction, and plant development (Soares et al. 2023). By using simple laboratory and field methods like permeameter, slug, and pumping tests, it is possible to determine the K_{sat} (Soares et al. 2023; Vienken and Dietrich 2011). This vital soil property is linked with the behavior of the soil water flow pattern (Figure 1). Therefore, K_{sat} is a crucial property of soil that determines its capacity to allow the passage of water (Farid et al. 2023). Information of K_{sat} of the soil component facilitates accurate design for suitable structures for water control, improve flood and runoff forecasting, and provide earthen storage facilities(Jang, Narsilio, and Santamarina 2011). The soil hydraulic properties could be influenced by various management factors and its distribution, including pore size distribution, topography, slope gradient, pore continuity, and land use (Baranian Kabir et al. 2020). The bulk density and particle size fractions are frequently included in soil characterizations and are relatively easy to obtain, facilitating the assessment and comparison of K_{sat} determinations based on soil properties (Duan, Fedler, and Borrelli 2012).

Pakistan is an agricultural country situated in arid and semi-arid regions (Solangi et al. 2023). Agricultural loss in Pakistan Sindh province area is 31% due to waterlogging and salinity yearly (Baloch et al. 2023; Ahsan et al. 2022; Taratima et al. 2023). Hence, developing strategies for managing saline–alkali soil will be crucial in tackling the issue of limited crop soil and meeting the task of providing food security for the world's projected 10 billion people by 2050 (Akram et al. 2020; Victoria et al. 2023). It has the largest canals irrigation system, although over time, its efficiency has declined as a result of inadequate maintenance (Hasanuzzaman et al. 2014). Thus, groundwater is progressively revolving into the salt-water, along with an increasing depth of the water table (G. S. Solangi et al. 2019). These methods regularly produce different results, as K_{sat} is very sensitive to soil characteristics, flow geometry, and sample size. Therefore, all measurement methods are not precise for all soil types and their conditions (Nemes and Rawls 2004). A previous study by Phaneuf et al., (1999) reported that, irrespective of land practices, a large portion of water flow is transported by a small portion of the soil volume, demonstrating that the spatial hydraulic characteristics of soils are highly variable. The K_{sat} measurements should therefore be evaluated carefully to ensure that the values obtained are accurate and appropriate for the intended use (Abesh and Hubbart 2023).

The percentages of sand, silt, and clay particles in the soil refer to soil textural class (K. A. Solangi et al. 2019). The soil textural classes are often used to correlate K_{sat} standards with additional hydraulic properties of the soil, for example, drainable pore space and water-holding capacity (Hao et al. 2019). This characteristic is required to compute seepage through earth dams, beneath structures built on pervious layers, to compute the rate at which waste storage facilities (ponds, landfills, etc.) drain water and the rate at which clay soil deposits settle (Fakhari and Ghanbari 2013). The design, measurement, and implementation of subsurface drainage systems depend mostly on the K_{sat} of the soil (Hao et al. 2019). All drain spacing equations involve this parameter (Bakour et al. 2021).

Even if the particle size and dry density (void ratio) of the specimens remain stable, K_{sat} is likely to vary considerably due to the variation between these three specimen preparations techniques, which can differ by up to one order of magnitude. As such, it is difficult to precisely calculate the hydraulic conductivity based solely on data regarding solid particles. Theoretically, K_{sat} is associated with the pore structure; however, solid particles make it difficult to extract pore information. The average hydraulic conductivity of a saturated soil which is primarily based on the size, shape, and arrangement of the soil's particles presents the K_{sat} range (Liu et al. 2013; Bui et al. 2023). Temperature, viscosity, and water density of the soil are other factors that affect it. It needs to be mentioned that there are two methods for measuring K_{sat} in the laboratory. These two methods are mostly used to determine the K_{sat} in the laboratory, such as the constant head permeability test or the falling head permeability test. It is noted that the measured Ks of the remolded soil is generally based on a compacted specimen. It needs to be mentioned that the present study compares both different methods for measuring K_{sat} in the laboratory. For permeable soils (k > 10-4 cm/s), the constant head test method is employed, while the falling head test is mostly utilized for less permeable soils (k < 10-4 cm/s). The experiment aimed to provide comprehensive insights into the hydraulic conductivity of the soil under different textural compositions, offering valuable data for further research and practical applications in agricultural and environmental contexts.

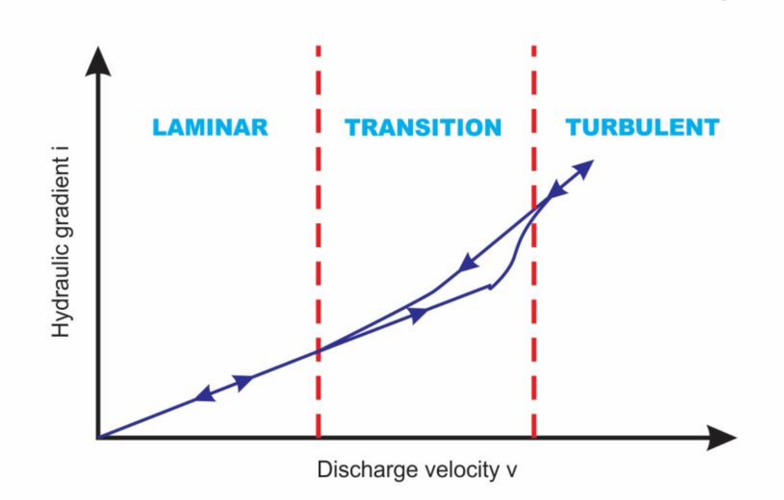


Figure 1. Different zones of turbulent and laminar flow

2. Material and Method

2.1 Study area and experimental description

The laboratory experiment was carried out in the Faculty of Agricultural Engineering, Sindh Agriculture University (SAU), Tando Jam, Department of Land Water Management situated in the Sindh province of southern Pakistan, at coordinates 25°42′34″ N and 68°54′08″ E, with an elevation of 75 ft (23 m) above sea level (Figure 2). The experiment was carried out on 12th November 2022 in the laboratory to assess hydraulic conductivity using two distinct methods: the constant head method and the falling head method. The soil samples were gathered from the different location fields of Latif Farm, located near SAU, at a depth of 0–20 cm. Soil samples were collected using a soil auger. The soil columns, each measuring 8.5

cm in length, were filled with soil of varying percentages of texture, specifically sandy loam soil. In the constant head method, K_{sat} was determined by maintaining a consistent hydraulic head at the tops of the sampled centers, which had been saturated with water in a previous laboratory experiments (Klute 1986).

The constant head method involves maintaining a stable hydraulic head at the sampling points, ensuring accurate measurements. Similarly, the falling head method, an alternative technique, was also applied to enhance the precision of the results. Detailed descriptions of these methods can be found in the experimental approach section 2.3.

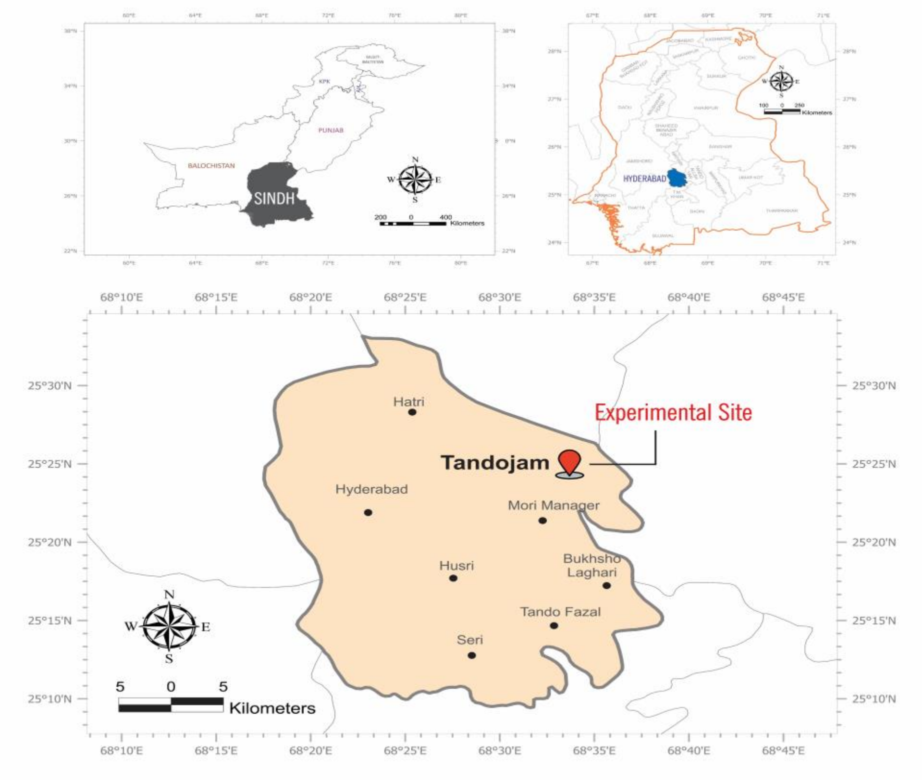


Figure 2. Location map of experimental site.

2.2 Determination of soil textural analysis

The relative percentage of soil particles in the samples was evaluated using the method outlined by Bouyoucos (1936). A hydrometer method was used for this technique, which relies on the varying settling velocities of soil particles within a water column. The method operates on the principles of Stokes' law, considering the velocity of fall of spheres in a fluid, sphere diameter, specific weights of the sphere and fluid, and fluid viscosity. In this context, it takes 40 seconds for sand particles to settle 10cm, while silt particles require over 8 hours to cover the same distance.

In this context, a sand particle takes 40 seconds to settle down in the direction of the 10cm scale of a flask. As the soil particles settle, the density of the suspension at the top of the container diminishes. A rapid decrease indicates a high sand content, whereas a slow decrease signifies a clayey composition. By measuring suspension density at specific depths over time, the proportions of silt, sand, and clay in the soil samples were determined. Standardized hydrometers, operating with a 1-liter suspension containing 40 grams of soil, were employed for this purpose.

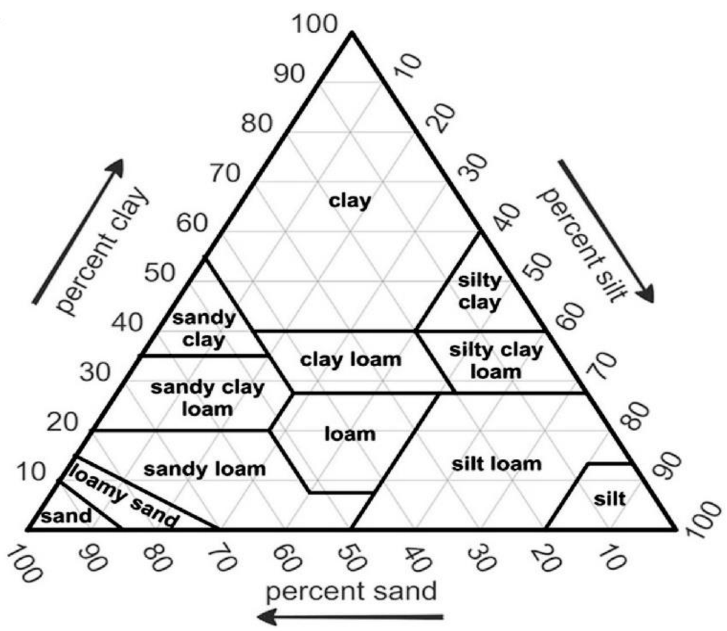


Figure 3. Soil USDA triangle used for Soil textural class (Moreno-Maroto and Alonso-Azcarate 2022).

Once the amounts of sand, silt, and clay were known, the USDA textural triangle was used to divide the soil into textural classes based on Figure 3, which depicted the proportions of these soil types. This method provided a comprehensive understanding of the soil's composition, essential for precise soil characterization and classification.

2.3 Soil Porosity determination

Porosity of soil refers to the void spaces or gaps between the soil particles themselves. Porosity is determined by the equation;

$$\eta = \frac{Vv}{Vt} \text{ x } 100 \qquad (1)$$

Where, η is the porosity of the soil samples (%), 100 is the unit conversion element, Vv is the volume of spaces in the soil sample (L3) soil bulk density (g cm^{-1}), and Vt is represents the samples total volume

The result is expressed in percentages. The soil porosity was analyzed based on the water pressure method, with the surface of the water located just below the tops of the soil cores (Sasal, Andriulo, and Taboada 2006). Every soil core was first measured and kept in a tray via filter paper until it reached a constant weight. After weighing, the soil samples were allowed to drain entirely under influence gravity. The soil samples were weighed again; their capillary water contents were examined by the differences in weight between the saturated and drained states.

2.4 Permeability Tests

This permeability test is a method used to quantify the velocity at which water moves through the pores of soil. In this experiment, water is tested with constant pressure and directed through a soil sample with specified dimensions, allowing for the measurement of the flow rate. The primary goal of this experiment is to assess the appropriateness of sands and gravels for drainage applications. It is conducted only on samples that have been changed. The examination is restricted to supplies with a coefficient of permeability value recorded at nearly 300 mm per day and higher (Wang and Tong 2014).

2.4.1 Constant Head Method

The constant-head approach is often used in the testing of granular soil, as illustrated in Figure 4. This experimental method facilitates the movement of water through soil under conditions of constant hydraulic head while simultaneously quantifying the volume of water passing by the soil samples over a specified period interval. The constant head approach for examining the coefficient of permeability (k) used equation 2:

$$K = \frac{QL}{Ath} \tag{2}$$

In this case, the coefficient of permeability is denoted by K, the amount of water discharged is represented by Q, the distance between manometers is indicated by L, the cross-sectional area of the specimen is denoted as A, the total time of discharge is represented by t, and the difference in head on manometers is denoted as H.

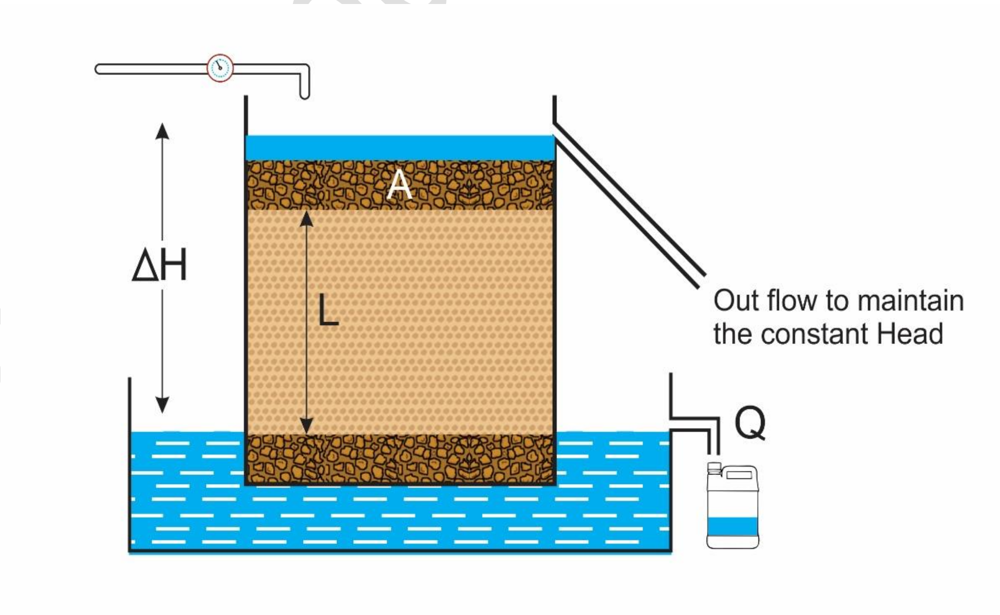


Figure 4: Demonstrates the measurement the saturated hydraulic conductivity using constant head method.

2.4.2 Falling Head Method

In the initial setup, the falling-head method is also the same as the constant-head technique, which is presented in Figure 5. The falling-head method is mostly used for fine size soils. Initially, samples of soil were soaked under the specified hydraulic head conditions. Subsequently, water is permitted to permeate the soil without the imposition of a consistent pressure gradient. The determination of the coefficient of permeability (k) using the falling head technique has been performed by employing the next calculation:

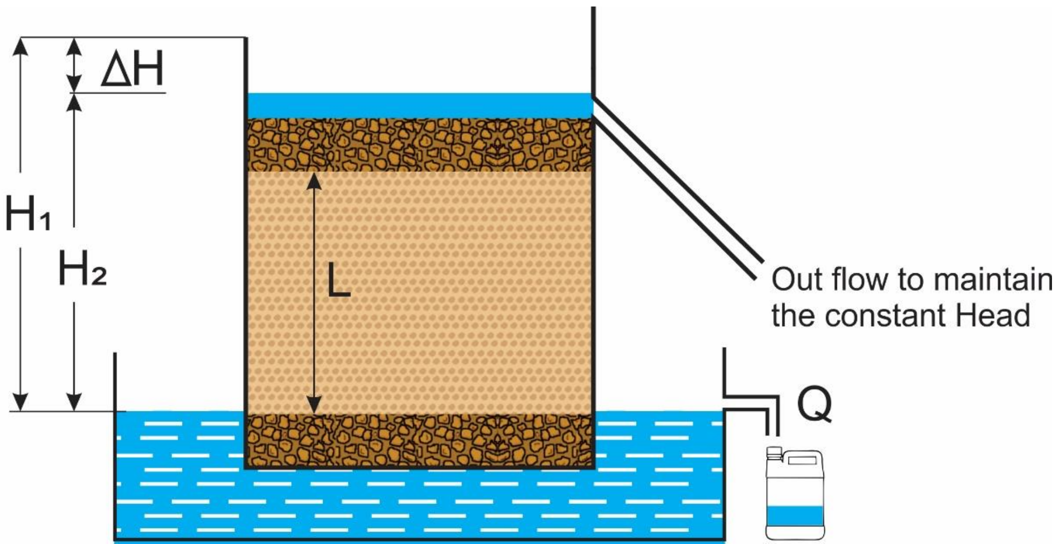
$$K = \frac{aL}{At} Ln[\frac{\text{ho}}{\text{h1}}] \qquad (3)$$

Where a represents the cross-sectional area of the soil column, L denotes the length of the standpipe, t signifies the time interval until the head drops, h0 represents the total head prior to the test, and h1 represents the total head after the test.

Figure 5. Demonstrates the measurement of the saturated hydraulic conductivity using falling head method.

2.5 Data analysis.

To assess the saturated hydraulic conductivity in different types of soil samples with a 0-



20 cm depth on the K_{sat} and other soil characteristics, an analysis of variance (ANOVA) was performed. The figures were prepared with photoshop software version CS6.

3. Results

3.1 Soil texture classes

Table 1 displays the experimental results that showed the classification of soil samples based on texture classes. The analysis of soil particle size revealed that, when samples passed through a 10-mesh sieve, the percentages of clay, silt, and sand were 18%, 17%, and 65%, respectively. Although there were differences noted, soil texture classifications primarily fell into the sandy loam category.. Moreover, 20-mesh and 40-mesh passed soil samples mostly fall in the sandy loam soil texture class.. Contrastingly, the distribution of 100-mesh sample percentages indicated 79% clay, 5% silt, and 16% sand, with the soil texture falling into the clay percentage class.

Table 1. Presented the textural classes (%) of different samples.

No	Samples (mm)	Clay (%)	Silt (%)	Sand (%)	Textural class
1	10	18	17	65	Sandy loam
2	20	14	15	71	Sandy loam
3	40	17	12	70	Sandy loam
4	100	79	05	16	Clay

3.2 Soil porosity

According to the calculation, the soil porosity results indicated that when soil particles were sieved from the 10, 20, and 40 mesh range, the porosity was noted at 35.33%, 43.42%, and 39.16%, respectively, and the average value of porosity was 39.30%. While for the 100-mesh range of porosity it was 50.16%. These findings not only provide valuable insights into the soil's particle composition but also offer essential data regarding its porosity characteristics (Table 2). Understanding these parameters is essential for a comprehensive evaluation of soil quality and its suitability for various applications, ranging from agriculture to environmental engineering.

S. No	Sample (mm)	FW (g)	DW(g)	CV (cm^{-3})	P (%)
1	10	105.6	92.5	37.07	35.33
2	20	103.3	85.3	41.45	43.42
3	40	89.5	74.8	37.53	39.16
4	100	102.3	87.2	30.1	50.16

Table 2. Soil porosity (%) in soil samples at different mesh ranges.

Note: FW (fresh weight), DW (dry weight), CV (core volume) and P (porosity)

3.3 Constant head methods

The study highlights the remarkable permeability of soil, particularly gravel and sands, which necessitates conducting constant head tests both in field settings and laboratories. Table 3 presents the outcomes of the hydraulic conductivity measurements obtained through the constant head method. The saturated hydraulic conductivity values were recorded as 0.00166 cm/sec, 0.00148 cm/sec, and 0.00113 cm/sec respectively, with a mean value (K_{avg}) of 0.00142 cm/sec. These findings underscore the significant water flow capacity of the soil, providing crucial insights for various engineering and environmental applications.

Table 3. The K_{Sat} values of constant head approach for the samples of 10, 20 and 40 meshes.

Parameters S.no	**OV (cm^3)**	**L (cm)**	**T (minutes)**	**AOS (cm^2)**	**TCH (cm)**	**K_{sat} cm/sec**
1	299	8.5	5	181.76	h1 (100-69)	0.001504

2	603	8.5	10	181.76	h2 (69-38)	0.001516
3	860	8.5	15	181.76	h3 (38-0)	0.001176

Note: OV (outflow volume), L (length), T(Time), AOS (Area of Sample), and TCH (Total Constant Head).

Figure 6 illustrates the relationship between K_{sat} as measured by the constant head permeameter, across various sample materials. The high correlation coefficient ($R^2 = 0.966$) indicates a strong relationship, demonstrating the robustness of the measured permeability values. This significant correlation underscores the method's effectiveness in capturing variations in different soil sample materials over time, affirming its reliability and applicability in diverse soil analyses.

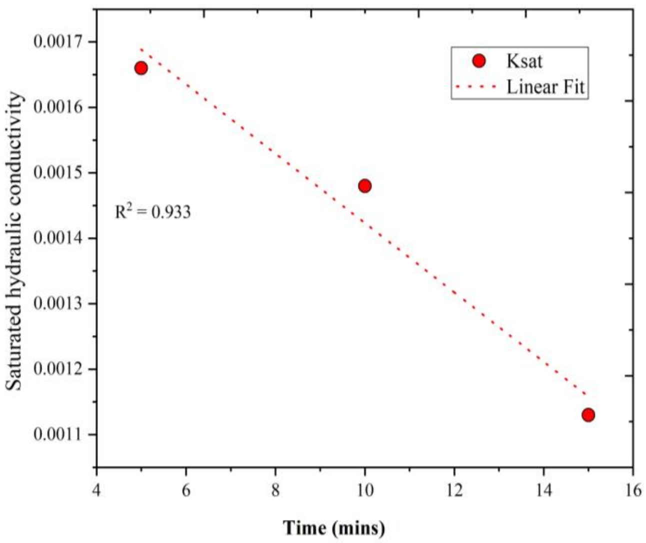


Figure 6. The constant head approach used to measure the hydraulic conductivity with different stages of time samples passed through 10, 20, and 40mm mesh range.

3.4 Falling head method

The K_{sat}, also known as permeability, of the collected soil samples was determined using the falling head method for the 10-sieve number. The measured values of K_{sat} for varying head and time were 0.00149 cm/sec, 0.00109 cm/sec, and 0.00111 cm/sec. Their average (K_{avg})

was calculated as 0.00123 cm/sec for the 10 mesh samples (Table 4). For the 20 mesh samples, the observed hydraulic conductivity values were 0.00183 cm/sec, 0.00172 cm/sec, and 0.00162 cm/sec, with an average (K_{avg}) of 0.00172 cm/sec. Similarly, for the 40 mesh samples, the results were 0.00169, 0.00135 cm per second, and 0.00129 cm per second, and the normal (K_{avg}) was 0.00144 cm per second (Table 4).

In the case of the 100 mesh samples, the hydraulic conductivity values were 0.0000165, 0.0000144 and 0.0000129 cm per second, with an average of 0.0000146cm per second. Additionally, the correlation factors corresponding to these measurements were 0.71, 0.99, 0.85, and 0.99 respectively, as shown in Figure 7. These results provide a comprehensive understanding of the soil's permeability characteristics across different mesh sizes, aiding in precise soil analysis and groundwater flow predictions.

Table 4. Soil Hydraulic conductivity values were determined by using falling head method for the sample in the 10, 20, 40 and 100mm mesh ranges.

				10mm-mesh sample			
Test	**ho**	**h1**	**CAS (cm^2)**	**SCL (cm)**	**CASC (cm^2)**	**T (sec)**	**K_{sat} (cm per second)**
1	99	88	0.342	15	31.65	30	0.029446
2	99	76	0.342	15	31.65	60	0.044064
3	99	63	0.342	15	31.65	90	0.061634
				20mm-mesh sample			
1	99	78	0.342	15	31.65	30	0.059603
2	99	66	0.342	15	31.65	60	0.067578
3	99	53	0.342	15	31.65	90	0.085204

40mm-mesh sample							
1	99	81	0.342	15	31.65	30	0.050168
2	99	69	0.342	15	31.65	60	0.060169
3	99	53	0.342	15	31.65	90	0.098716
100mm-mesh sample							
1	99	92	0.342	15	31.65	30	0.018333
2	99	89	0.342	15	31.65	60	0.017747
3	99	84	0.342	15	31.65	90	0.022405

Note: CAS (cross-section area of stand-pipe), SCL (soil column length), CASC (cross-section area of soil column, T (Time).

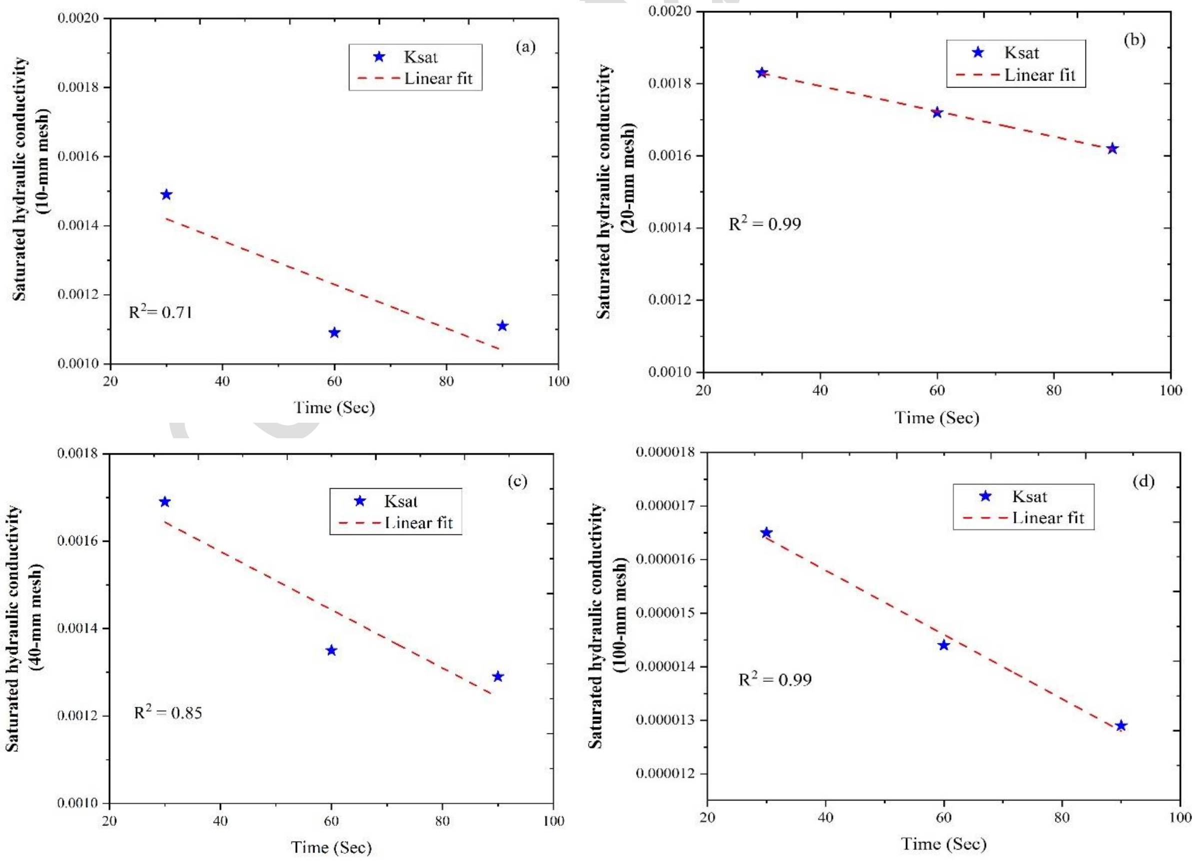


Figure 7. The correlation between K_{sat} and the falling head method is investigated with different time stages for samples of 10, 20, 40, and 100mm mesh.

4. Discussion

Current research evaluates the K_{sat} with two separate methods, which are significantly enhanced soil infiltration can be greatly affected by soil compaction (Romero - Ruiz et al. 2022). These method reduces porosity and increases bulk density, which may substantially reduce soil infiltration (Inam et al. 2019; Rachman et al. 2003; Sindesi et al. 2023). The generation of macrospores and channels by root penetration through soil tends to form special flow paths, thus enhancing soil infiltration and reducing runoff and soil erosion (Benegas et al. 2014; Li et al. 2011). In the current study, K_{sat} showed fluctuations is determining the different meshes. However, fluctuations in soil hydraulic conductivity were found to be associated with the first 10 years of restoration (Ren et al. 2016). Previous studies have shown that soil moisture is closely related to soil physical properties such as infiltration performance, particle size distribution, and pore condition (Shaikh et al. 2022; Yuan et al. 2020) An other former studies reported that plant physiological parameters also very important because these parameters directly or indirectly its effect on soil physical properties (Solangi et al. 2021; Tunio et al. 2020). Salt sress also important factor which change the soil physical properties (Ali Solangi et al. 2022). This study examined the influence of soil aggregate dimensions on the hydraulic conductivity (K_{sat}) and observed a positive relationship between K_{sat} and soil organic matter (SOM) content, which was further related with larger soil aggregate size (Tunio et al. 2022). The influences of pore size and its distribution can also effects on K_{sat} (Dexter and Richard 2009). At the field scale, the physical and chemical parameters of soils are not always significantly correlated with K_{sat} (Chen et al. 2009).

The results presented in this study provide valuable insights into the soil's particle composition, porosity characteristics, and hydraulic conductivity across various mesh sizes. The soil samples predominantly fell within the sandy loam category, indicating a balanced mixture of sand, silt, and clay. The porosity analysis revealed varying values, with the soil showing higher porosity in the 20 and 100-mesh samples, suggesting potential differences in water retention capacities. The results of the constant head method lie between 0.145-0.203, which is consistent with the previous study by Rawls et al., (1998).

The study's findings concerning soil permeability are significant. It is important to evaluate hydraulic conductivity values using both methods, including the constant head and falling head methods (Batezini and Balbo 2015). The results demonstrated significant water flow capacities for the soil samples, emphasizing their potential for various engineering and environmental applications. The correlation between permeability and time, especially evident in the constant head method, further supported the reliability of the measurements, highlighting the consistency of the soil's hydraulic conductivity over time.

When comparing the obtained results to earlier studies, it is clear that soil hydraulic conductivity is a factors multifaceted parameter, shaped by various influencing factors. Soil compaction, porosity, root penetration, and chemical characteristics such as organic matter content play pivotal roles in determining hydraulic conductivity (Nawaz, Bourrie, and Trolard 2013). The fluctuations observed in hydraulic conductivity across different mesh sizes indicate how complicated nature of soil behavior, emphasizing the need for comprehensive analyses incorporating various parameters (Yu, Gui, and Laguna 2023). The previous research, confirms that it is important to of understand the soil properties for effective land use planning and environmental management (Akram et al. 2023; Chapuis 2012).

Soil characteristics, including particle composition, porosity, and permeability, directly impact water infiltration, runoff, and erosion(Pan et al. 2021; Abd El-Fattah et al. 2022). A pervious study by Clapp & Hornberger, (1978) which support the results of porosity which fluctuated between 0.35-0.43% of sandy loam soil. Therefore, these findings hold practical implications for agriculture, environmental engineering, and watershed management. This information also contributes valuable data to the existing body of knowledge concerning soil behavior. By comprehensively analyzing soil properties, this research enhances our understanding of soil-water interactions, providing a foundation for sustainable land use practices and environmental conservation efforts.

5. Conclusions

In conclusion, the soil samples collected from various locations within Latif Farm predominantly exhibited a sandy loam texture, determined using the Boucyoucs hydrometer method for soil textural classification. The study revealed a fluctuation in soil porosity ranging between 35% and 43% across all samples. The analysis of saturated hydraulic conductivity (Ks) percentages gave an average value of 0.00142 cm/sec using the constant head method. In contrast, the falling head method produced varying results with average values of 0.00123 cm/sec, 0.00172 cm/sec, and 0.00144 cm/sec for different samples, while clay particles exhibited an average value of 0.0000146 cm/sec. It was observed that hydraulic conductivity values increased in average to coarse-textured soil layers and decreased in fine-textured soil layers. Comparing the two methods, the falling head method demonstrated greater accuracy, particularly evident in the analysis of three samples concurrently. Soil texture and structure significantly influenced both saturated hydraulic conductivity and porosity. Thus, field experiments employing methods like the auger-hole and inverse auger-hole techniques are recommended for a comprehensive understanding of soil properties. This research contributes valuable data for predicting hydraulic conductivity accurately. The study underscores the importance of soil characteristics, especially in sandy soils, providing crucial insights for hydrological studies in landscapes with similar soil qualities. Furthermore, future research should focus on refining modeling techniques, especially in areas where particle size data is available. Such kind of advancements can enhance the precision of Ks estimations, aiding in informed decisions regarding water resource management.

Acknowledgment:

The authors extend their appreciation to the Researchers Supporting Project number (RSPD2024R941), King Saud University, Riyadh, Saudi Arabia.

Competing interests

The authors stated that they had no interest which might be perceived as posing a conflict or bias.

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