



## Comparison of Unsaturated Hydraulic Conductivity of Sandy Loam and Clay Soils Estimated through Inverse Modeling using Hydrus-1D

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The research compared the unsaturated hydraulic conductivity of various soils by conducting double-ring infiltrometer experiments at different locations in KCAET, Tavanur campus in the Malappuram district of Kerala, India. Readings were taken from two different locations with distinct soil types. HYDRUS 1-D software was used to determine the unsaturated hydraulic conductivity by solving Richard's equation for water flow. The cumulative infiltration flux over time was fed to the software as the input to optimize soil hydraulic parameters. These optimized parameters were fitted to the empirical models proposed by van Genuchten (1980) to determine the unsaturated hydraulic conductivity (K) of the soils under investigation. The conclusion of the study highlighted that the sandy loam soil exhibited a higher unsaturated hydraulic conductivity compared to the clay soil. The unsaturated hydraulic conductivity for sandy loam soil was observed to range from 0.001 cm day<sup>-1</sup> to 0.178 cm day<sup>-1</sup>, corresponding to a moisture content between 0.105 and 0.193, respectively. The unsaturated hydraulic conductivity of clay soil was found to range from 0.002 cm day<sup>-1</sup> to 0.007 cm day<sup>-1</sup>, corresponding to a moisture content of 0.106 to 0.193, respectively. The results clearly demonstrated a direct relationship between moisture content and unsaturated hydraulic conductivity.

(*Key words: Hydrus-1D, Infiltration, Inverse modeling, Unsaturated hydraulic conductivity*)

Infiltration is the entry of water into the soil due to gravity, influenced by the forces exerted by soil particles on the water. This nonlinear and time-dependent process is crucial for irrigation, drainage, water harvesting, and groundwater recharge. Initially, the infiltration rate is highest, gradually decreasing and stabilizing at a constant value known as the basic or steady-state infiltration rate.

Hydraulic conductivity, which gauges the water transmission capability of a porous medium, can be assessed under both saturated and unsaturated conditions. Saturated hydraulic conductivity measures how easily water moves horizontally and vertically through saturated soil below the water table. On the other hand, unsaturated hydraulic conductivity, a vital parameter in agricultural and environmental studies, assesses the ability of soil to retain water in its pore spaces when not fully saturated. This occurs when water flow is vertical and takes place above the water table.

Unsaturated soil hydraulic conductivity is a measure of water movement (Fatehnia *et al.*, 2014), and

its determination is a challenging task, requiring costly, time-consuming, and skilled experimentation (Wosten and Van Genuchten, 1988; Malaya and Sreedeeep, 2013). Several techniques have been developed to evaluate unsaturated hydraulic conductivity, applicable in both laboratory and field environments (Klute and Dirksen, 1989). Laboratory techniques for measuring hydraulic conductivity can be categorized as either steady or unsteady. A constant flow rate or hydraulic gradient is applied under a specified metric suction in the steady methods. The unsteady methods are often less tedious to perform and require less testing time. Field methods used for obtaining the relationship between unsaturated hydraulic conductivity and water potential include the instantaneous profile method, steady-flux methods, sorptivity measurements, and the use of tension infiltrometers. To address the limitations associated with both field and laboratory methods, various models have been introduced. Simunek and van Genuchten (1996) estimated the unsaturated soil hydraulic properties from tension disc infiltrometer data by numerical inversion technique. Kodesova (2003), determined the hydraulic

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properties of unsaturated soil using a modified cone penetrometer by inverse modeling. Simunek and van Genuchten (1999), used the Hydrus -1D and Hydrus -2D codes for estimating unsaturated soil hydraulic and solute transport parameters.

Hydrus-1D, an interactive graphics-based user interface computer program and software package is found to be an effective tool for simulating water, heat and solute movement in one-dimensional variably saturated media. The HYDRUS program numerically solves the Richard's equation and includes a Marquardt-Levenberg (Marquardt, 1963) type parameter optimization algorithm for inverse estimation of hydraulic parameters. The program may be used to analyze water and solute movement in unsaturated porous media through inverse modeling of numerical models. HYDRUS-1D enables the simulation of water movement through unsaturated soils by incorporating various boundary conditions, soil types, and hydraulic parameters while effectively integrating both field and laboratory data. This precise modeling provides more accurate results compared to other indirect methods, making HYDRUS-1D a highly effective tool for such simulations. Additionally, the program's solute transport module offers opportunities for further research into soil-water-solute interactions within unsaturated soil layers.

The present study aims to determine and compare the unsaturated hydraulic conductivities of different soil types available in the KCAET, Tavanur campus using the Hydrus-1D software package. Inverse modeling using tools like HYDRUS-1D has not been widely applied to estimate unsaturated hydraulic conductivity, especially in comparative studies involving soils with contrasting textures such as sandy loam and clay. Most prior research tends to focus on individual soil types and often utilizes direct measurement methods, which are typically labor-intensive, time-consuming, and susceptible to experimental inconsistencies. This study seeks to assess and compare the unsaturated hydraulic conductivities of sandy loam and clay soils, while also evaluating the precision and sensitivity of inverse modeling techniques across different soil textures.

## MATERIALS AND METHODS

### Study area

The field experiments were conducted at Kelappaji College of Agricultural Engineering and Technology (KCAET) campus, situated in Tavanur village along the southern banks of the sacred Bharathapuzha river. Encompassing around 40 hectares, the campus is situated at 10°51'5" North latitude and 75°59'14" East longitude in the Malappuram district of Kerala, India. Two sites with distinct soil types were selected for the study. Site-1 was an uncultivated land having undulating topography near the canteen having sandy clay soil whereas Site-2 was a paddy field in the farm having clay soil.

### Collection of data

#### *Double ring infiltrometer test*

A double ring infiltrometer of a 20 cm diameter inner ring and 30 cm diameter outer ring with a height 30 cm was used for the measurement of infiltration data at all selected locations. The infiltration data at different time periods were noted and cumulative infiltration was calculated for both the selected sites.

#### *Bulk density and soil texture*

The bulk density of the soil was determined by the core cutter method.

$$\text{Volume of the core cutter, } V = \pi \frac{d^2}{4} H \quad \dots(1)$$

where,  $d$  is the diameter of the cylinder, cm;  $H$  is the height of the cylinder, cm.

$$\text{Dry bulk density of the soil, } \rho_b = \frac{W}{V} \quad \dots(2)$$

where,  $\rho_b$  is the dry bulk density of soil,  $\text{Mg m}^{-3}$ ,  $W$  is the dry weight (mass) of soil, g;  $V$  is the volume of the core cutter,  $\text{m}^3$ .

The percentage of sand, silt and clay in the soil was estimated using sieve analysis and the texture of the soil was identified by examining the soil textural diagram.

### Methodology

#### *Hydrus -1D*

Hydrus-1D computer program was used in the study

to estimate the soil hydraulic parameters. The software uses the finite element numerical solution of Richard's equation for the optimization of the objective function for water flow. The transient flow through the unsaturated zone was simulated using the numerical model proposed by Richard (1931):

$$\frac{\partial \theta}{\partial x} = \frac{\partial [K \frac{\partial h}{\partial z} + \cos \alpha] - S}{\partial z} \quad \dots(3)$$

where,  $h$  is the water pressure head [L];  $\theta$  is the volumetric water content [ $L^3L^{-3}$ ];  $t$  is time [T];  $z$  is the spatial coordinate [L];  $S$  is the sink term [ $L^3L^{-3}T^{-1}$ ];  $\alpha$  is the angle between the flow direction and the vertical axis (*i.e.*,  $\alpha = 0^\circ$ , for vertical flow,  $90^\circ$ , for horizontal flow, and  $0^\circ < \alpha < 90^\circ$ , for inclined flow), and  $K$  is the unsaturated hydraulic conductivity function [ $LT^{-1}$ ].

The unsaturated soil hydraulic properties are generally nonlinear functions of the pressure head. HYDRUS software offers five models to describe the unsaturated hydraulic properties. The unsaturated soil hydraulic functions of van Genuchten's (1980) model were used in this study, as it performed better. This model provides specific functions that describe these properties as follows:

$$\text{Effective saturation,} \quad \frac{S_e}{1 - S_r} = \frac{1}{[1 + (-ah)^n]^m} \quad \dots(4)$$

$$\text{Also, } S_e = \frac{\theta_h - \theta_r}{\theta_s - \theta_r} \quad \dots(5)$$

where  $h$  is the pressure head, [L];  $S_e$  is the effective saturation;  $\theta_h$  is the volumetric moisture content, [ $L^3L^{-3}$ ];  $\theta_r$  is the residual volumetric water content, [ $L^3L^{-3}$ ];  $\theta_s$  is the saturated volumetric water content, [ $L^3L^{-3}$ ];  $m$  is an empirical coefficient,  $m = 1 - \frac{1}{n}$ ;  $n$  is a measure of pore size distribution.

Unsaturated hydraulic conductivity,

$$K = K_s S_e^l [1 - (1 - S_e^{l/m})^m]^n \quad \dots(6)$$

where  $h$  is the soil water matric head [L];  $K_s$  is the saturated hydraulic conductivity [ $LT^{-1}$ ];  $l$  is the pore connectivity coefficient;  $\alpha$  is the inverse of air entry value, [ $L^{-1}$ ];  $m$  is an empirical coefficient. The pore-connectivity parameter  $l$  in the hydraulic conductivity function was estimated by Mualem (1976) to be 0.5 as an average for many soils.

### Inverse modeling

Inverse modelling is a numerical modelling approach which determines the causes of a problem based on observation of its effects. It is an alternative to direct measurement and can be used for indirectly estimating soil hydraulic parameters. The inverse modelling has three functional parts as follows: i. A controlled transient flow experiment in which boundary and initial conditions are prescribed and various flow variables are measured. ii. A numerical flow model simulates the transient flow regime of this experiment, using initial estimates of the parametric soil hydraulic functions. iii. An optimization algorithm which estimates the unknown parameters through minimization of the difference between observed and simulated flow variables (residuals) defined in an objective function ( $\emptyset$ ) through an iterative solution of the transient flow equation.

### Parameter estimation

Desired hydraulic parameters are determined by minimizing the differences between observed and simulated state variables. The total of these differences is expressed by an objective function ( $\emptyset$ ), which may be defined by Simunek *et al.* (1998) as:

$$\emptyset(b, q, p) = \sum_{j=1}^{m_q} v_j \sum_{i=1}^{n_{qj}} w_{ij} [q_j^*(x, t_i) - q_j(x, t_i, b)]^2 + \sum_{j=1}^{m_q} v_j \sum_{i=1}^{n_{qj}} w_{ij} [p_j^*(\theta_i) - p_j(\theta_i, b)]^2 + \sum_{j=1}^{n_b} v_j [b_j^* - b_j]^2 \quad \dots(7)$$

where,  $m_q$  is the number of different sets of measurements;  $n_{qj}$  is the number of measurements in a particular measurement set;  $q_j^*(x, t_i)$  represents the specific measurements at time  $t_i$  for the  $j^{\text{th}}$  measurement set at location  $x(r, z)$ ;  $q_j(x, t_i, b)$  is the corresponding model predictions for the vector of optimized parameters  $b$ ;  $v_j$  and  $w_{ij}$  is the weights associated with a particular

measurement set or point, respectively;  $m_p$ ,  $n_{pj}$ ,  $p_j^*(\theta_i)$ ,  $p_j(\theta_i, b)$ ,  $v_j$  and  $w_{i,j}$  have similar meanings to that of the first term, but now for the soil hydraulic properties;  $b_j^*$  is the prior knowledge of the soil hydraulic parameters;  $b_j$  is the final estimate of soil hydraulic parameters;  $n_b$  is the number of parameters with prior knowledge;  $v_j$  is the pre-assigned weight.

The first term on the right-hand side represents deviations between measured and calculated space-time variables, such as pressure heads, water contents, and/or concentrations at different locations and/or times in the flow domain, or actual or cumulative fluxes versus time across a certain boundary. The second term of equation (6) represents differences between independently measured and predicted soil hydraulic properties. The last term of the objective function represents a penalty function for deviations between prior knowledge of the soil hydraulic parameters and their final estimates.

In this study, the cumulative infiltration flux across a boundary at different periods was given as the input variable to optimize the soil hydraulic parameters through inverse modelling. Hydrus-1D computer program was used for the estimation of six soil hydraulic parameters *viz.* saturated water content ( $\theta_s$ ), residual water content ( $\theta_r$ ), saturated hydraulic conductivity ( $K_s$ ), soil water retention parameter ( $n$ ), the inverse of air entry value ( $\alpha$ ) and pore connectivity parameter ( $l$ ), which is optimized using Marquardt-Levenberg optimization algorithm. The initial estimates of these parameters for both soil types were found by the Rosetta Lite v 1.1 module in Hydrus-1D. Hydrus-1D refines its initial parameter estimates through multiple iterations to find the best parameter set. In our field experiment data analysis, the software underwent several iterations to optimize these parameters. Once the sum of squares (SSQ) couldn't be reduced further, indicating no more improvements, the iterations were halted, and the final outputs were obtained.

The optimized parameters were fitted to the empirical models proposed by van Genuchten (1980) for finding the unsaturated hydraulic conductivity ( $K$ ) of the proposed sandy loam soil and clay soil. Once the optimization was completed successfully, Hydrus-1D generates a set of simulated data for the observed cumulative infiltration data. The comparison of observed

and simulated data is generally termed as Residual Analysis.

The unsaturated hydraulic conductivity and water retention properties of the selected soil types are also obtained after the successful run of the program. The results of both soils were compared to see the change in hydraulic properties of clay and sandy loam soil.

## RESULTS AND DISCUSSION

The present study was undertaken to estimate and compare the unsaturated hydraulic conductivity of different soils of KCAET. The bulk density of Site-1 was calculated as  $1.69 \text{ Mg m}^{-3}$  and that for Site-2 was  $1.47 \text{ Mg m}^{-3}$  and the soil type was found to be sandy loam and clay soil respectively. The cumulative infiltration versus time graph (Figs.1 and 2) for both soils were plotted to analyze the trend of infiltration with respect to time. Invariably, the cumulative infiltration curve consistently rises over time. The curve for sandy loam soil appears steeper when compared to clay. The shape of the cumulative infiltration curve is largely influenced by the clay content, the infiltration method and the organic carbon content of the soil (Pachepsky and Karahan, 2022). Thus, the distinction in the shape of the curve arises due to the higher presence of macro pores in sandy loam soil compared to clay, resulting in a higher infiltration rate for the former. On the other hand, the porosity of clay soil is determined mainly by the higher number of micropores, which in turn make it capable of holding water rather than transmitting it.

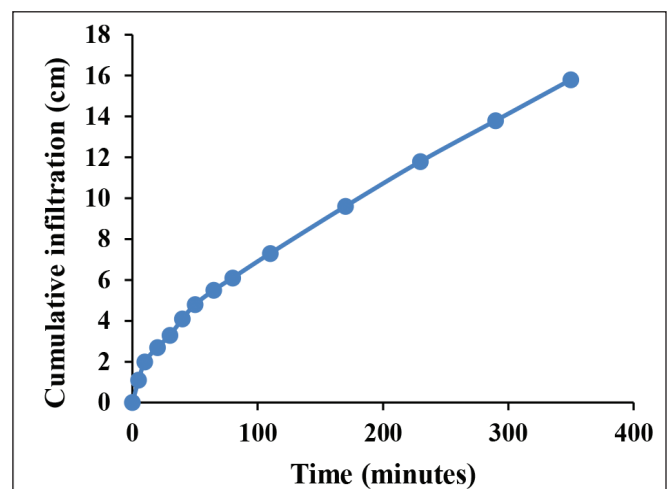


Fig. 1. Cumulative infiltration curve of sandy loam soil

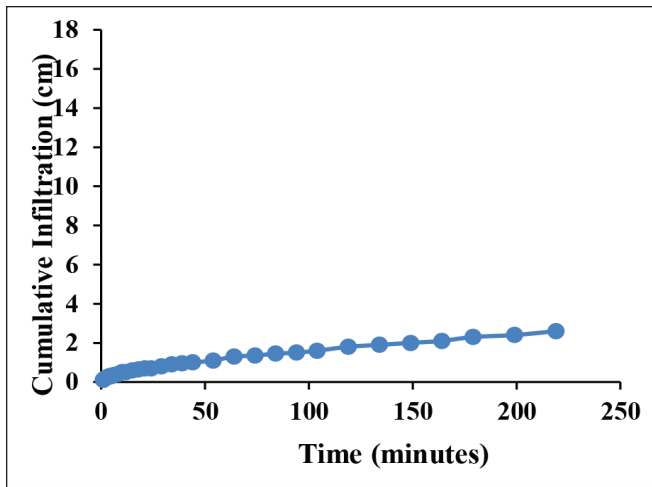


Fig. 2. Cumulative infiltration curve of clay soil

### Initial and final estimates of soil hydraulic parameters

Hydrus-1D software was used for the inversion of six soil hydraulic parameters. The initial estimates of these parameters for both soil types were found by the Rosetta Lite v 1.1 module in Hydrus-1D. Interestingly, for sandy loam soil, convergence was achieved within 8 iterations, while for clay soil, it took 12 consecutive iterations to reach convergence. The initial and final estimates of the six optimized parameters for sandy loam and clay soils are tabulated in Tables 1 and 2, respectively.

It is evident from Tables 1 and 2 that there is a good correspondence between the initial and optimized

Table 1. Initial and final parameter estimates of sandy loam soil

Parameters	Initial estimate	Final estimate
Residual water content, $\theta_r$ ( $\text{cm}^3 \text{cm}^{-3}$ )	0.038	0.058
Saturated water content, $\theta_s$ ( $\text{cm}^3 \text{cm}^{-3}$ )	0.348	0.354
Inverse air entry value, $\alpha$ ( $\text{cm}^{-1}$ )	0.031	0.020
Soil water retention function, $n$ (-)	1.383	1.535
Saturated hydraulic conductivity, $K_s$ ( $\text{cm min}^{-1}$ )	0.016	0.028
Pore connectivity parameter, $l$ (-)	0.500	0.500

Table 2. Initial and final parameter estimates of clay soil

Parameters	Initial estimates	Final estimates
Residual water content, $\theta_r$ ( $\text{cm}^3 \text{cm}^{-3}$ )	0.095	0.034
Saturated water content, $\theta_s$ ( $\text{cm}^3 \text{cm}^{-3}$ )	0.456	0.174
Inverse air entry value, $\alpha$ ( $\text{cm}^{-1}$ )	0.014	0.016
Soil water retention function, $n$ (-)	1.325	1.290
Saturated hydraulic conductivity, $K_s$ ( $\text{cm min}^{-1}$ )	0.004	0.004
Pore connectivity parameter, $l$ (-)	0.500	0.500

parameter estimates of  $\theta_r$ ,  $\theta_s$ ,  $\alpha$ ,  $n$  and  $K_s$ . The optimized parameter values for  $\alpha$ ,  $n$  and  $K_s$  were mostly very close or only slightly different from the initial parameter values. The close correspondence of the initial and final estimates of  $K_s$  lends further credibility to the accuracy of double-ring infiltrometer data for the sandy loam soil and clay soil used in this study.

Table 3 shows the comparison between the final

estimates of the parameters of sandy loam soil and clay soil. Clay soil exhibits higher residual water content ( $\theta_r$ ) and saturated water content ( $\theta_s$ ) due to its micro pores retaining more water even under high tension. The parameter  $\alpha$ , the inverse of the air entry value (bubbling pressure), signifies this entry of air into the soil. Finer soils with more pores have higher air entry values and thus lower  $\alpha$  values. Consequently, clay

soils have a lower  $\alpha$  pH compared to sandy loam soils. The parameter 'n' represents the empirical soil water retention function. Saturated hydraulic conductivity ( $K_s$ ) signifies the constant infiltration rate. In comparison, clay soil generally has lower  $K_s$  than sandy loam soil due to the higher presence of micropores that retain water

instead of allowing transmission. The impact of the pore connectivity parameter (l) on the objective function was noted to have a minor influence. Namitha and Ravikumar (2018) investigated the parameter variations by keeping l constant, affirming the earlier observation regarding its limited effect.

**Table 3.** Comparison of final estimates of sandy loam soil and clay soil

Parameters	Sandy loam soil	Clay soil
Residual water content, $\theta_r$ ( $\text{cm}^3 \text{cm}^{-3}$ )	0.058	0.034
Saturated water content, $\theta_s$ ( $\text{cm}^3 \text{cm}^{-3}$ )	0.354	0.174
Inverse air entry value, $\alpha$ ( $\text{cm}^{-1}$ )	0.020	0.016
Soil water retention function, n (-)	1.535	1.290
Saturated hydraulic conductivity, $K_s$ ( $\text{cm min}^{-1}$ )	0.028	0.004
Pore connectivity parameter, l (-)	0.500	0.500

### Observed and simulated cumulative infiltration

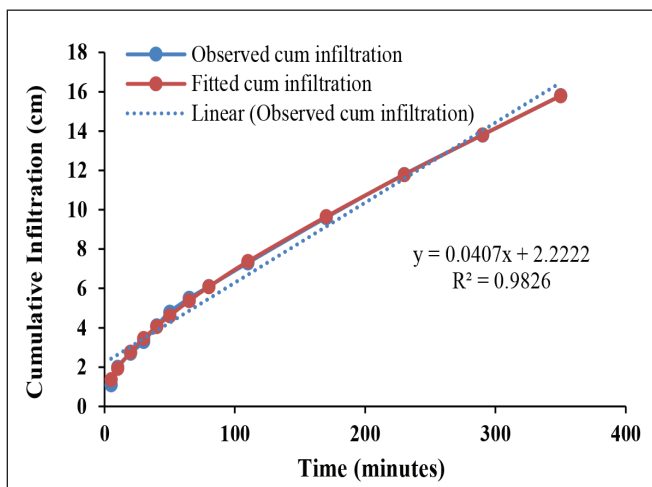
The observed cumulative infiltration data obtained from the infiltrometer experiment is compared with simulated cumulative infiltration from Hydrus-1D, for both soils. The curve plotted for sandy loam and clay soils shows the best fit between the observed and simulated cumulative infiltration data (Figs. 3 and 4).

The fitted and observed cumulative infiltration

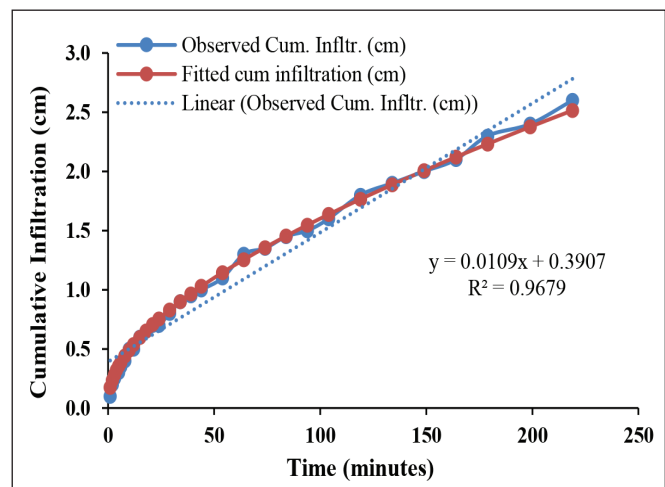
curves for sandy loam soil exhibit a strong correlation, with an  $R^2$  value of 0.9826, while the curve for clay soil also shows a strong correlation, with an  $R^2$  value of 0.9679.

### Unsaturated hydraulic conductivity

A curve plotted between volumetric water content and unsaturated hydraulic conductivity for sandy loam soil and clay soil is shown in Fig. 5 and Fig. 6,



**Fig. 3.** Fitted vs. observed cum. Infiltration curve of sandy loam soil



**Fig. 4.** Fitted vs. observed cum. Infiltration curve of clay soil

respectively. The graph shows a direct relationship between unsaturated hydraulic conductivity ( $K$ ) and volumetric water content ( $\theta_h$ ). However, in clay soils, a

gradual rise in unsaturated hydraulic conductivity was observed as the volumetric water content increased. Conversely, in sandy loam soil, this relationship shows

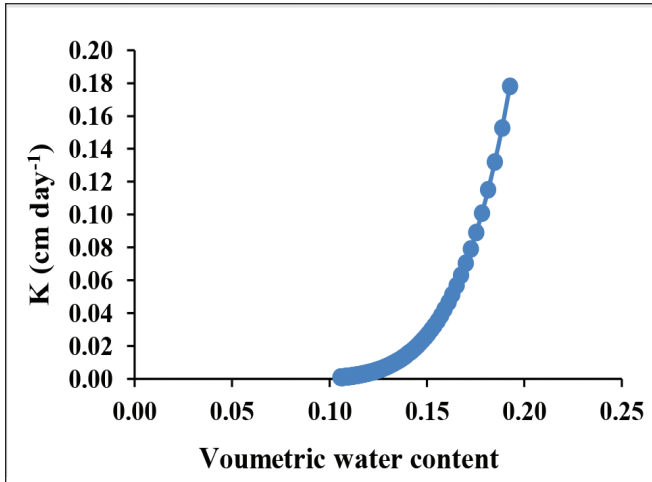


Fig. 5.  $K$  vs.  $\theta_h$  graph of sandy loam soil

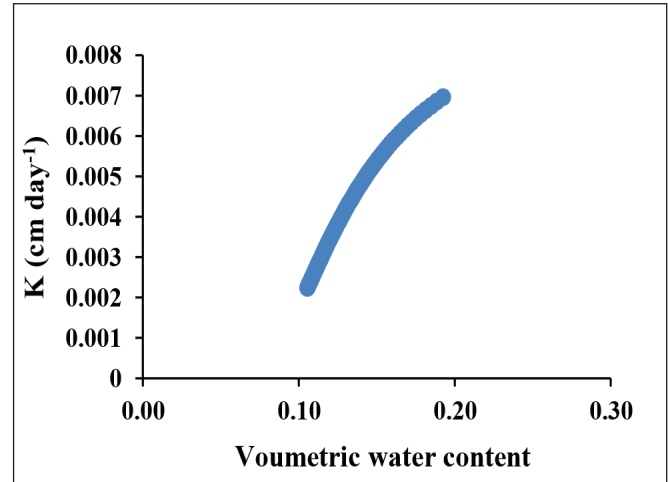


Fig. 6.  $K$  vs.  $\theta_h$  graph of clay soil

a rapid and noticeable increase.

Fig. 7 and Fig. 8 shows the graph plotted between unsaturated hydraulic conductivity ( $K$ ) and pressure head ( $h$ ). There are distinct differences in how pressure head relates to unsaturated hydraulic conductivity in sandy loam and clay soils. In clay soil, a steady increase in hydraulic conductivity with pressure head was observed. Meanwhile, in sandy loam soil, there was an

initial slow rise in conductivity followed by a sudden, more pronounced increase.

The average saturated hydraulic conductivity ( $K_s$ ) for the sandy loam soil under study was found as  $0.028 \text{ cm day}^{-1}$  and for the clay soil, it was  $0.0043 \text{ cm day}^{-1}$ . The average unsaturated hydraulic conductivity of sandy loam soil was found as  $0.018 \text{ cm day}^{-1}$ , and for clay soil, it was  $0.0039 \text{ cm day}^{-1}$ . These results are

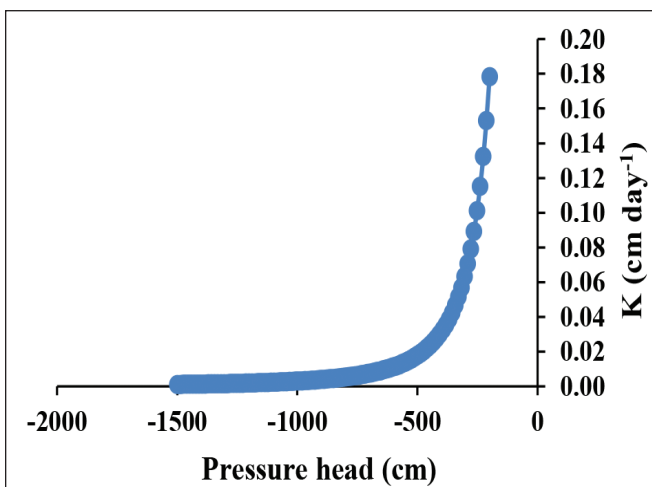


Fig. 7.  $K$  vs.  $h$  graph of sandy loam soil

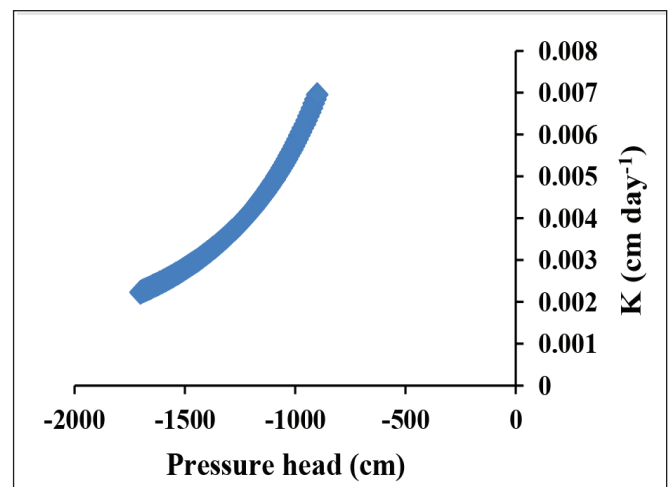


Fig. 8.  $K$  vs.  $h$  graph of clay soil

consistent with established findings in the literature, which indicate that sandy soils typically exhibit higher hydraulic conductivity due to their larger pore sizes and lower bulk density, while clay soils have smaller pores that restrict water movement (Hillel, 1998).

Fig. 9 and Fig. 10 depicts the variation of unsaturated hydraulic conductivity with depth from the ground surface. Generally, the  $K$  value increases with an increase in depth. For sandy loam soil, it shows a rapid increase compared to clay.

Fig. 11 shows a comparison of the unsaturated

hydraulic conductivity of sandy loam and clay soil. The unsaturated hydraulic conductivity decreases with an increase in pressure head for both sandy loam and clay soil. The curve is flatter for clay soil and steeper for sandy loam soil. Both soils have almost the same value of unsaturated hydraulic conductivity at higher-pressure heads. For the same pressure head, unsaturated hydraulic conductivity is higher for sandy loam soil.

**Soil moisture characteristics curve**

In addition to the final estimates of optimized parameters, the Hydrus-1D model also predicts the soil

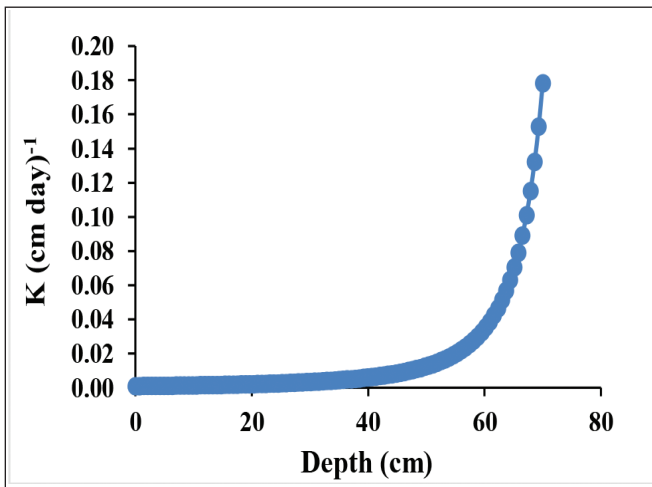


Fig. 9.  $K$  vs. Depth graph of sandy loam soil

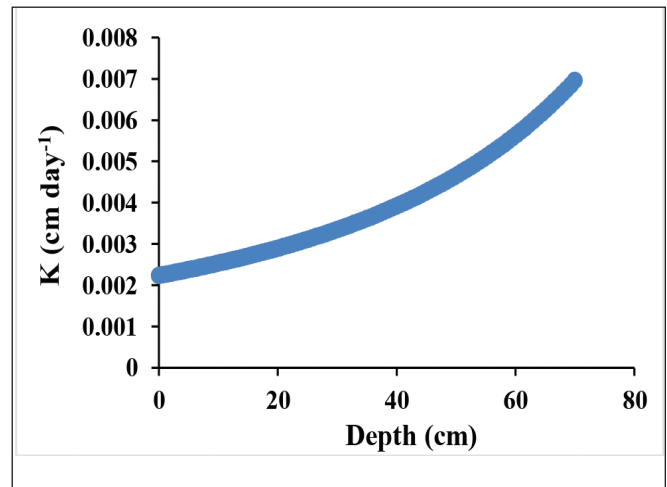


Fig. 10.  $K$  vs. Depth graph of clay soil

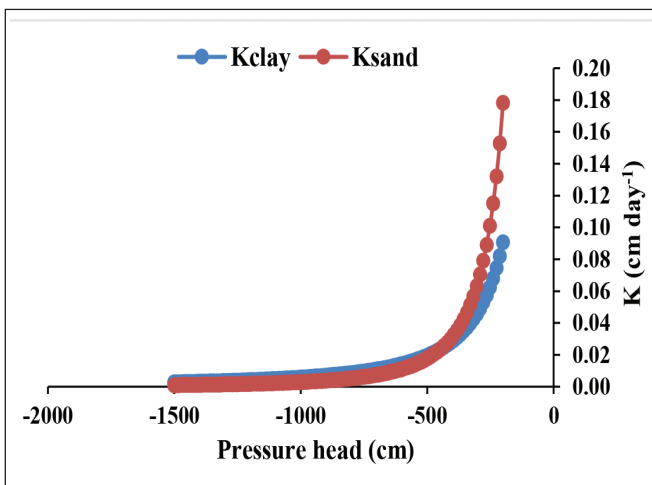
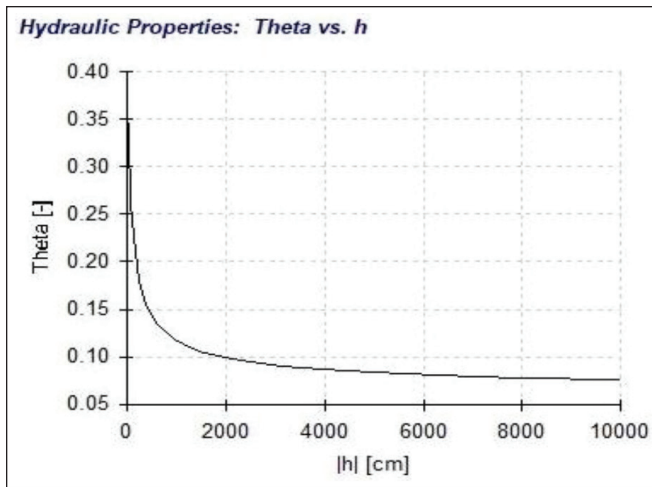


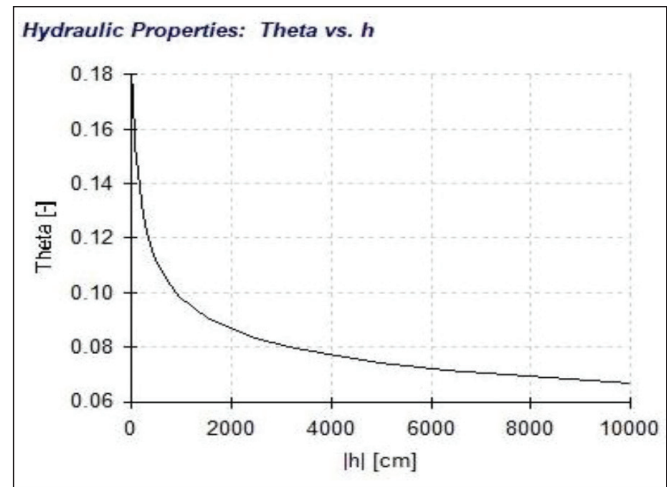
Fig. 11. Comparison of unsaturated hydraulic conductivity of sandy loam and clay soils

moisture characteristic curve for the different types of soil. Fig. 12 and Fig. 13 show the predicted soil moisture characteristic curves for sandy loam and clay soil, respectively.

In the unsaturated zone, larger pores drain more readily than smaller ones. Therefore, the hydraulic conductivity is much less under unsaturated than saturated conditions because of water moving through smaller pores or as films along the walls of larger pores. Kotlar (2018) conducted research using inverse modelling to ascertain soil hydraulic properties, yielding outcomes akin to the findings of this study.



**Fig. 12.** Model predicted soil moisture characteristic curve of sandy loam



**Fig. 13.** Model predicted soil moisture characteristic curve of clay soil

### CONCLUSION

Prediction of water movement in unsaturated porous media is important in many branches of science and engineering, such as fluid mechanics, environmental engineering, soil mechanics, agricultural engineering and others. The present study investigated the infiltration characteristics of the soil for obtaining the van Genuchten soil hydraulic parameters to determine and compare the unsaturated hydraulic conductivity of different soils using Hydrus-1D. The experiment was conducted in two sites of the KCAET campus in Tavanur has sandy loam soil and clay soil with bulk densities of  $1.69 \text{ Mg m}^{-3}$  and  $1.47 \text{ Mg m}^{-3}$ , respectively. The infiltration rate of sandy loam soil is greater than clay soil. The unsaturated hydraulic conductivity of sandy loam soil was observed to vary between  $0.001 \text{ cm day}^{-1}$  and  $0.178 \text{ cm day}^{-1}$ , corresponding to a moisture content range of 0.105 to 0.193. For clay soil, the unsaturated hydraulic conductivity ranged from  $0.002 \text{ cm day}^{-1}$  to  $0.007 \text{ cm day}^{-1}$ , with a moisture content between 0.106 and 0.193. The results effectively illustrated a direct relationship between moisture content and unsaturated hydraulic conductivity. The variation of  $K$  value with pressure head, soil domain depth and volumetric water content for both soils was studied and found that clay soil shows a slow and steady variation in all the cases when compared to sandy loam. Understanding the relationship between moisture content and unsaturated hydraulic

conductivity is crucial for optimizing irrigation practices, ensuring water is used efficiently and avoiding both over- and under-irrigation. These results can assist farmers and land managers in effectively managing soil moisture levels, enhancing crop growth, and minimizing water waste.

### CONFLICTS OF INTEREST

The authors do not report any conflicting interests.

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