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Estimating the Saturated Soil Hydraulic Conductivity from Soil Properties

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ABSTRACT : *The saturated soil hydraulic conductivity (K_{sat}) serves as an essential parameter in the design of efficient drainage systems. The measurement reflects the soil's capacity to convey water, influenced by the dimensions and structure of its pores. A multitude of studies has demonstrated a connection between K_{sat} and different soil characteristics; nonetheless, the constraints of the data utilized in formulating these equations necessitate careful consideration. This investigation sought to determine the soil characteristics that affect K_{sat} and to connect these factors with laboratory-measured conductivity (K_{lab}) acquired through a permeameter setup, along with other readily measurable soil properties. Soil samples were gathered from two locations defined by sandy, unstable soils. The samples underwent analysis in the laboratory to ascertain their physical and chemical properties, which encompassed grain size distribution, plastic limit, liquid limit, field hydraulic conductivity, and chemical composition. Statistical analyses were performed on the laboratory results to investigate the relationships related to K_{sat}. In the analysis of the sandy unstable soils, statistical regressions were established, demonstrating significant correlations between K_{sat} and K_{lab}, soil specific gravity, the d_{90} grain size, and the concentration of hydrocarbonate anions.*

KEYWORDS *-Saturated soil hydraulic conductivity, drainage systems*, Physical Properties, Chemical Properties.

I. INTRODUCTION

Egypt is deploying subsurface drainage systems extensively in recently reclaimed areas. Many of these areas possess unstable sandy soil and require appropriate drainage systems. Designing drainage systems necessitates knowledge of soil qualities, including grain size distribution, soil texture and structure, plasticity index, hydraulic conductivity, mineralogy, and chemical composition. The unsaturated hydraulic conductivity, *K*, is the paramount parameter influencing water movement in the unsaturated zone [1]. The hydraulic conductivity (*K*) in unsaturated soils is contingent upon the soil-water content and the pressure head (*h*).

Numerous laboratory and field techniques have evolved over the years to quantify *K* in relation to the pressure head or water content. Van Genuchten et al. [2] categorized these strategies as direct and indirect. He also noted that direct procedures are, nearly universally, challenging to adopt, particularly in field situations. Notwithstanding several enhancements, direct-measurement technology has progressed only little in recent decades. Nonetheless, indirect approaches that estimate hydraulic characteristics from more readily measurable data (such as soil-water retention and particle-size distribution) have garnered very limited focus. Unfortunately, these indirect techniques, known as 'predictive estimating methods', can produce precise estimations of hydraulic soil parameters with considerably less labor and cost. Hydraulic conductivity assessed by estimation approaches may be sufficiently accurate for certain applications [3], [4]. Another significant indirect approach is inverse parameter estimation with analytical models that characterize water retention and hydraulic conductivity [5].

The design and operation of subsurface drainage systems are heavily influenced by the saturated hydraulic conductivity (K_{sat}) of soils, and all equations related to drain spacing utilize this critical parameter [6]–[12]. This parameter influences the economic and technical viability of extensive subsurface drainage initiatives. Consequently, accurately determining K_{sat} is essential for the design or evaluation of drainage projects. Furthermore, assessing K_{sat} in any drainage project presents a significant challenge [9], [13]. The values of K_{sat} exhibit spatial variability, making it challenging to identify a representative value for use in drain spacing calculations [10], [14]–[17].

Determining the saturated hydraulic conductivity of soils can be achieved through correlation methods or hydraulic methods. The hydraulic in-situ methods can be categorized into small-scale and large-scale approaches [10].

The methods for correlating K_{sat} in drainage surveys often rely on the relationships between K_{sat} and various soil properties, such as soil texture, pore-size distribution, grain-size distribution, or soil mapping unit. The benefit of correlation methods lies in the fact that estimating the K-value is frequently more straightforward and faster than obtaining a direct measurement. A potential limitation is that the relationship employed may not be precise, making it susceptible to random errors.

The main goal of this paper is to compare the field hydraulic conductivity of sandy Egyptian soils (K_{sat}) to the hydraulic conductivity measured in the laboratory using the permeameter set-up (K_{lab}) and different soil properties. Moreover, it highlights the soil parameters, which affect the value of the field hydraulic conductivity, and shows the correlation coefficients between the measured K and the most effective soil parameters.

II. MATERIALS AND METHODS

Soil sampling was conducted in two designated areas. The characteristics of these areas include sandy soils that exhibit varying physical and chemical properties. A total of 29 soil samples were gathered from Nobaria, while 14 soil samples were obtained from Sinai. Soil samples that had been disturbed were gathered from the designated areas and locations, and the hydraulic conductivity was assessed at each site utilizing the auger-hole method [18].

The soil samples that were collected underwent analysis in the laboratory to ascertain their physical and chemical properties. The permeameter setup was employed to evaluate the laboratory hydraulic conductivity (K_{lab}) in accordance with Darcy’s law. The laboratory conducted an analysis of the collected soil samples and determined to categorize them into two groups according to their chemical composition. The initial group comprises samples from Nobaria, whereas the subsequent group consists of samples from Sinai. All samples consisted of sandy soils, yet they exhibited varying physical and chemical properties. The clay content of the soil ranges from 0.00% to 37.4%, while the hydraulic conductivity measured in the field (K_{aug}) spans from 0.07 m/day to 6.06 m/day. Soil samples obtained from the Sinai region exhibit a higher concentration of salts compared to those gathered from the Nobaria region.

The clay content in the Nobaria samples was observed to range from 0.10% to 27.00%, while the Sinai samples exhibited a variation from 0.00% to 37.4%. The d90 of the samples ranges from 0.12 mm to 4.37 mm for Nobaria samples and from 0.12 mm to 0.34 mm for Sinai samples. The hydraulic conductivity measured in sample locations in Nobariaarae ranged from 0.07 m/day to 6.06 m/day, while in Sinai samples, it ranged from 0.35 m/day to 1.39 m/day [7]. The electric conductivities EC(s) of Nobaria samples are observed to be below 4.0 dS/m, likely attributable to their elevated salinity levels. The electric conductivities EC(s) of Sinai samples exceed 37.0 dS/m, and the sodium absorption ratios are greater than 15.0, indicating that the soil is alkaline. The laboratory determined the hydraulic conductivity using the permeameter setup and the disturbed soil samples collected from the two areas. The results of the laboratory analysis of the soil samples are summarized in Tables 1, 2, 3, and 4.

III. RESULTS ANALYSIS

Correlation coefficients between field hydraulic conductivity (K_{aug}) and several soil characteristics were computed. K_{aug} of Nobaria samples exhibits strong association coefficients with K_{lab}, the plastic limit of the soil (PL), soil pH, chloride ions (Cl), hydrocarbonate anions (HCO_3), soil (Sp), and calcium carbonate content ($CaCO_3$). Soil Sp can be excluded from the components used to estimate K_{aug} due to its strong correlation with $CaCO_3$. Likewise, the plastic limit (PL) and soil pH can be disregarded because they are substantially linked with $CaCO_3$ and HCO_3, respectively. K_{field} is regarded as a function of K_{lab}, HCO_3, Cl, and $CaCO_3$.

Analysis of Sinai samples revealed that K_{aug} has strong correlation coefficients with K_{lab}, the clay/silt ratio, the d_{90} of soil grains, the liquid limit (LL), chloride ions (Cl), and calcium carbonate content ($CaCO_3$) of the soil. Figs. (1) and (2) illustrate the correlation coefficients for both regions. The internal correlation among the soil metrics was assessed to eliminate the dependent variables. The table indicates that d_{90} of the soil grains can be excluded from the components used to estimate K_{field} due to its strong correlation with Cl, and $CaCO_3$ can also be excluded because of its significant correlation with the LL. Consequently, K_{field} is regarded as a function of the clay/silt ratio, liquid limit (LL), and clay content (Cl). Regression equations were developed from the previous data and this yield to the following:

For saline soils similar to Nobaria soil (Multiple R = 0.94):

$$K_{field} = 30.14 + F(K_{lab}) + F(HCO_3) + F(Cl) + F(CaCo_3) \quad (1)$$

Where:

$$F(K_{lab}) = 0.035\,K_{lab} + \;\; 0.0004\,K_{lab}^2 \quad (2)$$

$$F(HCo_3) = -14.9\,HCo_3 + \;\; 1.88\,{HCo_3}^2 \quad (3)$$

$$F(Cl) = -0.58\,Cl + \;\; 0.04\,Cl^2 \quad (4)$$

$$F(CaCo_3) = 0.06\,CaCo_3 + 0.00096\,{CaCo_3}^2 \quad (5)$$

Where, the K_{lab} is the hydraulic conductivity measured in the laboratory in m/day, the $HCO_3$is the hydro carbonate anions in the soil sample in meq/l, Cl is the the chloride ions in the soil sample in meq/l and the $CaCO_3$ is the calcium carbonate content in the soil sample in meq/l.

For saline soils similar to Sinai soil: (Multiple R = 0.63):

$$K_{field} = 0.781 + F(K_{lab}) + F(LL) + F(Cl) + F({}^{clay}/_{silt})\,ratio \quad (6)$$

$$F(K_{lab}) = 0.017\,K_{lab} + \;\; 0.00018\,K_{lab}^2 \quad (7)$$

Table 1 Summary of Physical Properties of the soil samples (Nobaria area).

	K_{aug} (M/d)	K_{lab} (M/d)	Sand %	Silt %	Clay %	d_{90} (mm)	LL %	PL %	PI %
Max	6.06	93.41	93.3	40.8	27.0	4.37	50.6	21.3	32.2
Min	0.07	1.90	37.2	2.2	0.1	0.12	19.3	12.2	1.7
Avg	1.05	17.76	67.7	17.4	14.9	1.35	27.9	17.1	11.0
STD	1.45	19.83	15.9	9.5	8.5	1.54	6.9	2.8	6.8

Table 2 Summary of Chemical Properties of the soil samples (Nobaria area).

	pH	EC at 25C° d/m	Ca	Mg	Na	K	HCO_3	SO_4	Cl	Soil Sp %	Soil SAR	Soil ESP %	$CaCO_3$ %
			meq/L										
Max	8.1	3.4	17.0	11.9	20	0.7	4.6	34.7	11.4	74.0	8.8	11.7	54.9
Min	7.1	0.5	1.1	1.1	2.3	0.2	2.3	0.2	1.7	18.0	1.6	2.4	1.9
Avg	7.5	1.6	4.9	4.2	7.4	0.3	3.8	8.6	4.6	40.6	3.5	5.0	29.3
STD	0.3	0.9	3.4	3.3	4.5	0.1	0.6	7.8	2.9	15.2	1.7	2.2	16.6

Table 3 Summary of Physical Properties of the soil samples (Sinai area)

	K_{aug} (M/d)	K_{lab} (M/d)	Sand %	Silt %	Clay %	d_{90} (mm)	LL %	PL %	PI %
Max	1.4	87.9	88.0	19.3	37.4	0.3	24.5	16.5	8.0
Min	0.4	0.1	43.8	2.9	0.0	0.1	1.0	1.0	1.0
Avg	1.0	23.5	75.9	11.0	13.1	0.2	5.1	3.1	1.7
STD	0.4	24.5	11.7	6.0	11.3	0.1	8.4	5.3	1.9

Table 4 Summary of Chemical Properties of the Soil Samples (Sinai area).

	pH	EC at 25C° d/m	Ca	Mg	Na	K	HCO_3	SO_4	Cl	Soil Sp %	Soil SAR	Soil ESP %	$CaCO_3$ %
			meq/L										
Max	7.5	122	260	543	1980	26	7.0	949	2058	43	197	74.7	13.1
Min	7.3	37	26	9	305	6	5.5	29	208	20	40	37.3	1.6
Avg	7.4	75	97	178	1033	15	6.2	212	975	31	91	54.2	3.7
STD	0.1	29	75	130	634	9	0.5	242	645	9	49	12.1	2.8

$$F(LL) = -0.13\,LL + 0.009\,LL^2 \qquad (8)$$

$$F(Cl) = 0.00045\,Cl + 2.7 \times 10^{-7} Cl^2 \qquad (9)$$

$$F(clay/silt) = 0.049\,(clay/silt) - 0.019\,(clay/silt)^2 \qquad (10)$$

The K_{lab} is the hydraulic conductivity measured in the laboratory in m/day, the *LL* is the liquid limit in the soil sample, the *clay/silt* is the ratio of clay to silt in the soil sample and Clis the the chloride ions in the soil sample in meq/l.

For the two developed regression equations, the root mean square error (*RMSE*), mean absolute error (*MAE)*, and mean absolute percentage error (*MAPE)* for K_{field} (equation (1)) were 0.41 m/day, 0.289 m/day, and 23.21%, respectively, compared to values of 0.54 m/day, 0.365 m/day, and 30.32%, respectively, for K_{field} (equation (6)).

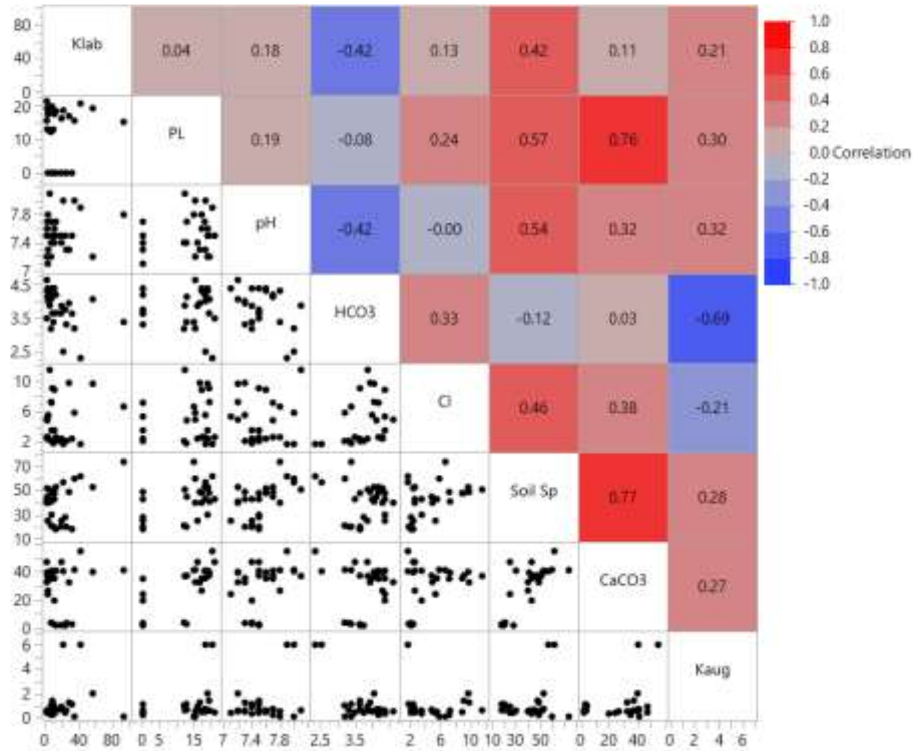

Fig. 1 Correlation Coefficients between K_{sat} and soil parameters “Nobaria”.

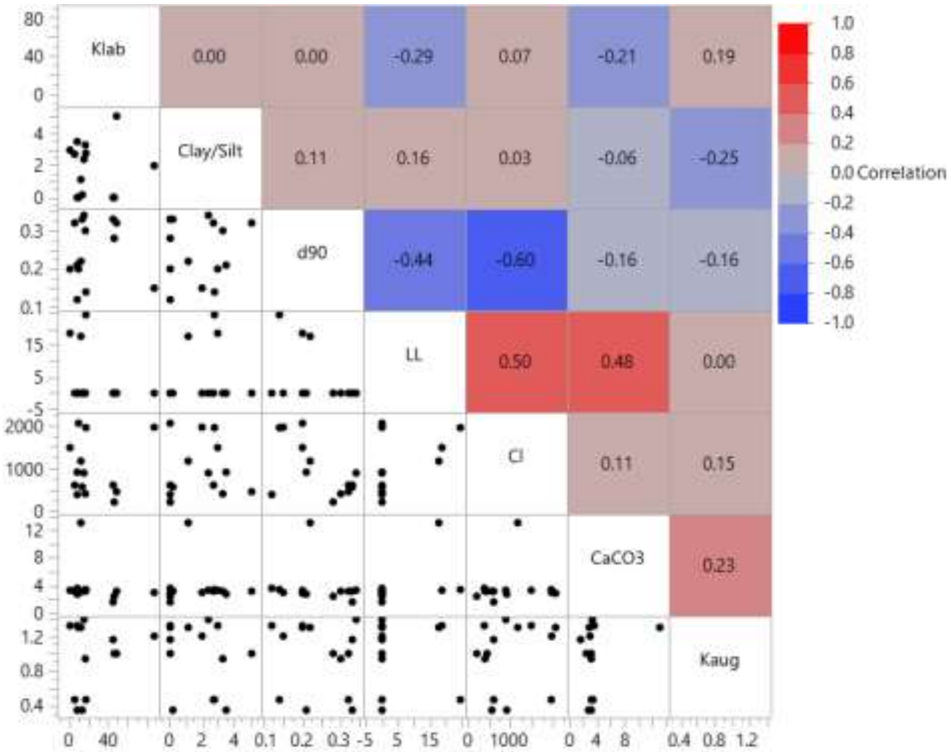

Fig. 2 Correlation Coefficients between K_{sat} and soil parameters “Sinai”.

IV. Conclusion

A conclusion section must be included and should indicate clearly the advantages, limitations, and possible applications of the paper. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

Correlation approaches can estimate saturated field hydraulic conductivity from readily observable soil characteristics. Two distinct study regions characterized by sandy, unstable soils were selected based on their physical and chemical features. First, identify the soil type (saline or alkaline) to ascertain the appropriate correlation equations. Considering K_{lab} as a primary soil parameter, statistical regressions were conducted to estimate K_{field} using multiple regressions in Microsoft Excel. The K_{field} for saline soils, such as those resembling Nobaria soil, exhibited a strong correlation with chloride ions (Cl), hydrocarbonate anions (HCO3), soil pH (Sp), and calcium carbonate concentration ($CaCO_3$) (equation 1). In alkaline soils, akin to Sinai soil, K_{field} exhibited a strong correlation with the clay/silt ratio, the liquid limit of the soil (LL), and chloride ions (Cl) (equation 10). Equations (1) and (10) are advantageous for estimating K_{field} when field hydraulic conductivity is unmeasurable, providing a cost-effective method for rapid K_{field} determination.

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