Saturated hydraulic conductivity values of some forest soils of Ghana determined by a simple method

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SUMMARY

A simple falling-head method is presented for the laboratory determination of saturated hydraulic conductivity of some forest soils of Ghana. Using the procedure, it was found that saturated hydraulic conductivity was positively and negatively correlated with sand content and clay content, respectively, both at $P = 0.05$ level. Further, the statistical functional relationships between saturated hydraulic conductivity and sand content and clay content were best described by an exponential function, respectively.

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RÉSUMÉ

BONSU, M. & MASOPEH, B. A. : *Les valeurs de la conductivité hydraulique saturée de quelques sols forestiers du Ghana déterminées par une méthode simple.* Une méthode simple de chutes de tête est présentée pour la détermination de laboratoire de la conductivité hydraulique saturée de quelques sols forestiers du Ghana. Utilisant la procédure il était découvert que la conductivité hydraulique saturée était positivement et negativement corrélée respectivement avec le contenu de sable et le contenu d' argile, tous deux au niveau de $P=0.05$. Davantage, les relations fonctionelles statistiques entre la conductivité hydraulique saturée et le contenu de sable ainsi que le contenu d' argile étaient respectivement mieux décrites par une fonction exponentielle.

Introduction

Hydraulic conductivity which is the measure of the ability of soil to transmit water is an important soil hydraulic property because the use of soil for many agricultural and nonagricultural purposes requires information on hydraulic conductivity. Soil aeration, drainage, and plant growth are influenced by hydraulic conductivity. A knowledge of saturated hydraulic conductivity is needed in the design of drainage and irrigation systems, canals and reservoirs, landfills and septic systems (Bouwer & Jackson, 1974).

Saturated hydraulic conductivity is also important in modelling infiltration which is used in predicting erosion and runoff of a watershed (Mein & Larson, 1973). Furthermore, saturated hydraulic conductivity may be used in the study of spatial variability of soils (Ahuja & Nielson, 1984; Bonsu & Laryea, 1989).

Since soil pore spaces are determined by the texture and density of packing of the soil particles, saturated hydraulic conductivity has been related to soil structure as well as soil texture. Nelson & Baver (1940), Bonsu & Lal (1982) and Ahuja & Neilson (1984) obtained highly significant positive correlations between saturated hydraulic conductivity and soil macroporosity.

Also, several studies have shown significant negative correlations between saturated hydraulic conductivity and clay content (Talsma & Flint, 1958; Zein El Abedine, Abdalla & Moustafa, 1967; Varallyay, 1974; Gumbs, 1974; Bonsu & Lal, 1982; Bonsu & Laryea, 1989), and positive correlations with sand content (Aronovici, 1946; Gumbs, 1974; Bonsu & Lal, 1982; Bonsu & Laryea, 1989). In spite of these significant correlations between saturated hydraulic conductivity and soil texture, few attempts have been made to predict saturated hydraulic conductivity from texture (Bonsu & Laryea, 1989; Bonsu, 1992).

Wherever possible, field methods for saturated hydraulic conductivity determination are preferred to laboratory methods, since laboratory methods are sometimes unreliable due to the problem of sample disturbance during the process of sampling. However, the procedures used in field methods are often time-consuming and tedious. Laboratory methods based on using undisturbed cores are, therefore, often used and data obtained are quite reliable for most practical applications (Bonsu & Lal, 1982; Bonsu & Laryea, 1989).

Information on saturated hydraulic conductivity of soils of Africa south of the Sahara is not only scanty but also undocumented. This lack of information may be attributed, in part, to lack of knowledge of very simple methods for the determination of this important soil hydraulic property. Even though a fairly simple method employing Mariott bottle arrangement can be used to determine saturated hydraulic conductivity with the constant head technique, the objective of this work is to describe an inexpensive and simpler falling head method for the determination of saturated hydraulic conductivity on some forest soils of Ghana. Furthermore, the efficacy of the method would be tested by relating saturated hydraulic conductivity data to the texture of the soils.

Materials and methods

Soils used for the study

Two forest soils, one from Aiyinasi in the Western Region of Ghana and the other from Twifo Praso in the Central Region of Ghana, were used for the study. The soils from Aiyinasi are Ferralsols. These are located in the high rainfall zone where the annual rainfall may exceed 2000 mm. The *p*H of the top soils varies from 3.7 to 5.4. The Twifo Praso soils are Acrisols and are at the moment being used for the production of oil palm. The soils are located in the semi-deciduous rainforest zone with a mean annual rainfall of 1500 mm. In these Acrisols, the *p*H tends to decrease with depth due to the acid nature of the parent material. However, the *p*H of topsoil varies between 5.2 and 6.9.

Collection of soil cores

At Aiyinasi, undisturbed soil cores were collected from a virgin luxuriant forest, a secondary forest, and a cultivated cassava field. At Twifo Praso, undisturbed soil cores were collected from a secondary forest. All the soil cores were collected in the top soil (0 - 10 cm).

To obtain an undisturbed soil core, a metal cylinder in the form of an open can 13 cm long and 10 cm diameter was carefully worked into the soil by carving the soil outside the cylinder. The two ends of the metal cans were open. The cylinder was bevelled at the bottom end so as to facilitate the cutting of the soil to fit snugly inside the cylinder. The bottom end of the core was covered with a nylon cloth mesh and secured in place with the help of a rubber band to restrain the core from falling out. A soil depth of 8 cm was maintained in the cylinder, leaving a free space of 5 cm above the soil surface to be used as water head during the determination of the saturated hydraulic conductivity. In all, 15 samples were taken from Aiyinasi, five from virgin forest, five from secondary forest, five from cultivated cassava field, whilst nine samples were taken from Twifo Praso.

Determination of saturated hydraulic conductivity

A modified falling head permeameter system was used for the saturated hydraulic conductivity determination. The set-up of the system is illustrated in Fig. 1. The core samples were saturated overnight by placing them in a basin of water. A rectangular metal container perforated at the bottom was filled with gravel. The perforated container with gravel was placed over a laboratory sink. The saturated sample was placed on the gravel and then connected to a water manometer using a flexible tubing (Fig. 1). The surface of the sample was partly covered with a filter paper and water was gently added to the top of the filter paper

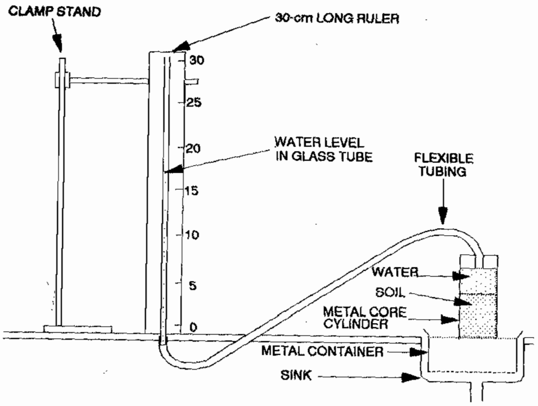

Fig. 1. A sketch of the falling-head permeameter system used for the determination of the saturated hydraulic conductivity

in order to minimize sample dispersion during addition of water.

Water was siphoned from the surface of the sample through the flexible tubing so as to get rid of any air entrapped in the flexible tubing. The flexible tubing was then connected to the manometer whilst water was still flowing out of the tubing. In this way, air was completely removed from the manometer system. Water was again added to the surface of the sample to the required mark. The initial hydraulic head H_0 was noted from the manometer (Fig. 1), and the fall of the hydraulic head H_t as a function of time t was recorded as water moved through the soil into the gravel and finally out through the sink. The function of the gravel was to provide free drainage at the bottom so that water would flow out at zero pressure potential.

Calculation of saturated hydraulic conductivity

The saturated hydraulic conductivity was calculated by the standard falling head equation (Baver, Gardner & Gardner, 1972) as:

$$K_s = (AL)/(at)\ \text{In}\,(H_0/H_t) \qquad (1)$$

where A is the surface area of the cylinder, L is the length of the sample, and 'a' is the surface area of the soil. In this method, since A = a, equation (1) becomes

$$K_s = (L/t)\ \text{In}\ (H_0/H_t)$$
(2)

Rearranging equation 2, we have

$$\text{In}\,(H_0/H_t) = K_s t/L \qquad (3)$$

The theory indicates that a plot of In (H_0/H_t) as a function of time t gives a straight line with zero intercept, and a slope equal to K_s/L. If this slope is designated b, then

$$b = K_s/L \qquad (4)$$

$$\text{and } K_s = bL \qquad (5)$$

A sample plot of In (H_0/H_t) against t is presented in Fig. 2. The plot gave a straight line but the intercept deviated slightly from zero. This deviation could be attributed partly to the various experimental errors.

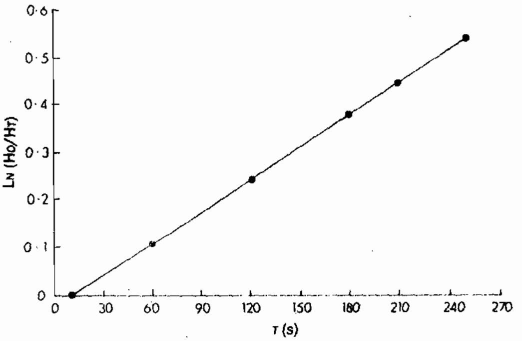

Fig. 2. A sample graph for the plot of $\ln(H_0/H_t)$ against time (t)

Determination of texture

The texture of the soils was determined on air-dried soil separates that were passed through a 2-mm sieve. The samples were pre-treated with hydrogen peroxide to digest the organic carbon and then dispersed in sodium hexametaphosphate solution. The hydrometer method (Day, 1965) was used in the particle size analysis.

Results and discussion

The particle size distribution and the saturated hydraulic conductivity values of the samples studied are presented in Table 1. At Aiyinasi, the K_s values of the uncultivated forest soils were higher

TABLE 1

Saturated Hydraulic Conductivity (K_s), Sand Content (S), Clay Content (C) and Silt Content (Si) of Aiyinasi Virgin Forest Soils (AF), Secondary Forest (ASF), Cultivated Soils (ASC) and Twifo Praso Secondary Forest Soils (TSF)

Sample	*(10^{-4} K_s/ms-1) MS*	*Sand (2-0.02 mm) (per cent)*	*Silt (0.02-0.002 mm) (per cent)*	*Clay (<0.002 mm) (per cent)*	*Textural class*
AF1	1.56	79.4	3.4	18.2	SL
AF2	5.05	79.3	5.3	15.4	SL
AF3	3.59	82.4	2.4	15.2	SL
AF4	1.63	79.3	5.0	15.8	SL
AF5	1.10	79.8	2.0	18.2	SL
ASF1	8.40	72.0	5.8	22.2	SCL
ASF2	2.20	73.1	5.4	21.4	SCL
ASF3	2.60	75.3	3.3	21.4	SCL
ASF4	2.07	74.0	3.3	22.7	SCL
ASF5	2.05	71.1	5.4	23.4	SCL
ASC1	0.91	71.3	5.3	23.4	SCL
ASC2	0.75	77.3	3.3	19.4	SCL
ASC3	0.89	71.1	5.4	23.4	SCL
ASC4	1.77	74.0	5.3	20.7	SCL
ASC5	1.45	70.4	8.2	21.4	SCL
TSF1	0.47	63.3	13.3	23.4	SCL
TSF2	0.83	65.3	7.3	27.4	SCL
TSF3	0.74	71.3	3.3	25.4	SCL
TSF4	0.24	74.0	3.3	22.7	SCL
TSF5	0.31	72.4	5.4	22.2	SCL
TSF6	0.42	72.4	5.4	22.2	SCL
TSF7	0.86	70.4	5.4	24.2	SCL
TSF8	0.63	67.1	7.4	25.4	SCL
TSF9	0.45	68.4	6.2	25.4	SCL

SL = sandy loam
SCL = sandy clay loam

than the cultivated soils. The average K_s value of the virgin forest soils was 2.3 times higher than that of the cultivated soils, whilst the average K_s value of the secondary forest soils was 3 times higher than the cultivated soils. The texture of the secondary forest soils and the cultivated soils at Aiyinasi are identical (sandy clay loam). The lower K_s values of the cultivated soils could, therefore, be ascribed to soil structure deterioration due to cultivation.

The average K_s value of the virgin forest soils at Aiyinasi with sandy loam texture should be expected to be higher than that of the secondary forest soils with sandy clay loam texture, if texture is the dominant factor controlling K_s. However, the average K_s value of the secondary forest soils was 1.3 times higher than that of the virgin forest soils. This discrepancy is uncertain to explain but could be due to the problem of spatial variability between samples. The K_s values of Twifo Praso secondary forest soils were lower than those of Aiyinasi by the one order of magnitude. Since the soils of Twifo Praso are located in a climatic environment different from those of Aiyinasi, the two soils are, therefore, not physically, chemically and biologically related, even though the texture is identical to Aiyinasi cultivated and secondary forest soils.

The relationships between K_s and sand content and clay content were sought statistically using correlations and regressions. It was observed that the statistical relationships between K_s and sand content as well as clay content were best described by exponential functions.

The semi-logarithmic plots between K_s and sand content and clay content are presented in Fig. 3 and Fig. 4 respectively. The statistical exponential function relating K_s and sand content (S) was described as $K_s = 3.2 \times 10^{-7} e^{0.085S}$. The positive correlation coefficient between K_s and sand content was significant at 5 per cent probability level ($r = 0.434$*). The statistical exponential function between K_s and clay content (C) was described as $K_s = 2.0 \times 10^{-3} e^{-0.13C}$. The nega-

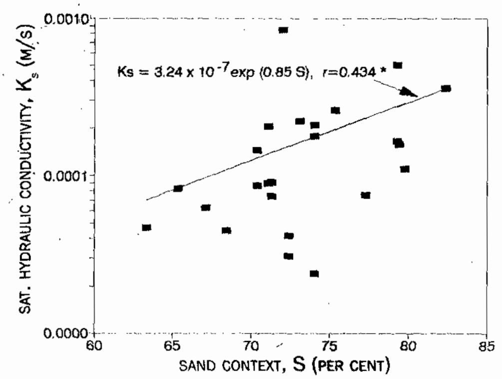

Fig. 3. A semi-logarithmic plot between saturated hydraulic conductivity and sand content

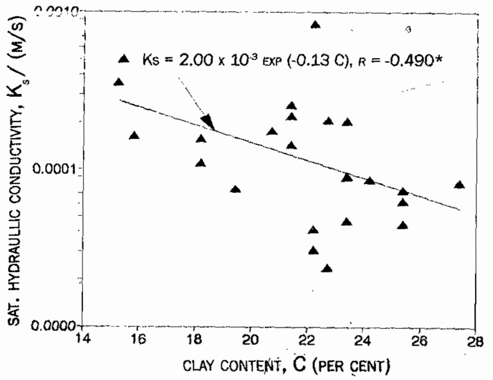

Fig. 4. A semi-logarithmic plot between saturated hydraulic conductivity and clay content

tive correlation coefficient between K_s and clay content was significant at 5 per cent probability level ($r = -0.49$). Similar exponential relationships between K_s and sand content and clay content were reported by Bonsu & Laryea (1989) for some Alfisols in the semi-arid tropics in India. Similar exponential K_s-clay content relationship was reported by Puckett, Dane & Hajek (1985). Also, similar positive and negative correlations between K_s and sand content and clay content respectively have been reported for tropical soils by Gumbs (1974), Bonsu & Lal (1982) and Bonsu & Laryea (1989).

One major limitation precluding prediction of K_s from texture has been spatial variability in K_s values (Bonsu & Laryea, 1989). Besides, prediction of K_s from texture *per se* has not always been very successful (Bonsu, 1992). Deviations associated with prediction of K_s from texture tend to increase as the soil texture becomes finer (Bonsu, 1992).

Conclusion

This simple procedure for the determination of K_s may serve as an inexpensive method for K_s determination in most laboratories in tropical Africa, where foreign exchange is always a constraint to the importation of laboratory equipment. With this simple procedure, routine saturated hydraulic conductivity measurements can be made.

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