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Determination of Hydraulic Properties of Soil as a Porous Medium

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Abstract: Both soil water retention curve and unsaturated hydraulic conductivity data are often necessary for solving unsaturated flow problems. A field experiment was carried out at the Agriculture Research Experimental Area, Tandojam to evaluate appropriate and time efficient methodologies to determine soil hydraulic properties. The soil profile on which experiment was carried out consisted of clay, clay loam and silty clay soil. Three conventional analysis methods such as Instantaneous profile method, Millington and Quirk method, CGA method, and one parameter optimization model MULSTP were applied to calculate unsaturated hydraulic conductivity as a function of soil moisture content [K(θ)] from the field as well as laboratory data. Instantaneous profile method was used as reference against which the alternative methods were compared. The simplified methods (Millington & Quirk and CGA) were found to show satisfactory results with considerably less effort and the VGM parameter optimization method with MULSTP model was found to yield realistic values of hydraulic conductivity. The VGM parameters known through optimization technique by MULSTP model provided extrapolation of unsaturated hydraulic conductivity close to the Millington and Quirky CGA methods. Having been based on continuous function, MULSTP has the advantage that it can be used for computer simulation of salt and water movement in the unsaturated soils.

Keywords: Soil, Hydraulic, Infiltration, Water, Properties

Introduction

Mismanagement of water results in suffering of human civilization in the form of salinity and waterlogging. Pakistan is badly affected by salinity and waterlogging caused by improper use of irrigation water in absence of natural and artificial drainage. The struggle to prevent a disastrous build up of salts in soil and water-logging, made it necessary to install even more costly drainage systems and to use large proportion of limited water supply for leaching salts down the profile. Proper and efficient management of water for optimum crop production requires knowledge of movement of water and solutes into and through soil. The ability of soil in the unsaturated zone to retain and conduct water is a function of its hydraulic properties. The most important properties of soil are saturated and unsaturated conductivity functions and the moisture retention characteristics (Ahuja *et al.*, 1980). Considerable work has been done in the field of soil physics to develop an understanding of parameters governing fluid flow in the vadoze zone. The most obvious way to obtain these parameters is by experimental methods. Calculations of hydraulic properties from soil cores, however, are only estimate of the actual field conditions. Recently, new or modified methods have been developed to measure the hydraulic properties in situ. However, these tend to be difficult, laborious and time consuming (Libardi *et al.*, 1980) Due to the physical and theoretical limitations of measuring soil hydraulic properties in the field, many investigators have sought to derive soil hydraulic properties from very basic relationship known as soil moisture characteristic curve either known in the field or in the laboratory (Mualem 1976). The hydraulic properties derived from such approaches are relatively simple, rapid and inexpensive. Two different approaches are normally used for estimating the unknown hydraulic parameters. These approaches are (i) direct measurements of the limited number of soil water retention and hydraulic conductivity data points followed by fitting a parametric model of hydraulic functions to the experimental data and (ii) estimating the hydraulic parameters from a transient flow experiment by applying some type of inverse procedure (Kool *et al.*, 1987). In this study the first approach was followed because it is rapid and cost effective for evaluating the soil hydraulic parameters from measured field and laboratory soil water retention data. The results achieved through this approach are compared with the unsteady drainage flux method (Instantaneous profile method) based on analysis of soil water content and soil water tension measured in the field by applying the Darcian flow analysis as reference method.

Theory:

Water movement in the unsaturated zone of the soil occurs due to gradients in the hydraulic potential H.

$$H = h + z \qquad (1)$$

Where "h" is the matric potential (L) and "z" is the gravitational potential or height above a reference level (L).

According to Darcy's Law, water movement through a one-dimensional unsaturated vertical soil column is mathematically expressed as:

$$q = -k(h)\frac{\partial H}{\partial z} \qquad (2)$$

Where q is the soil water flux density (LT^{-1}), K (h) is the unsaturated hydraulic conductivity (LT^{-1}).

$$q = -k(h)\frac{\partial h}{\partial z} - k(h) \qquad (3)$$

under transient conditions, where the water content changes with time, conservation of matter is accounted for with the equation of continuity.

$$\frac{\partial \theta}{\partial t} = \frac{\partial q}{\partial z} \qquad (4)$$

Where θ is the volumetric water content L^3/L^3 and "t" is the time (T).
Combining equation 3 and equation 4

$$\frac{\partial \theta}{\partial t} = \frac{\partial\left[-k(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} \quad (5)$$

Instantaneous Profile Method: The instantaneous profile method is frequently used to determine the unsaturated hydraulic conductivity (Hillel and Gardner 1970 and Watson 1966). This method is based on free drainage of a plot after wetting. It requires frequent and concurrent measurements of soil water content and soil water suction profiles during drainage conditions. From these measurements instantaneous values of hydraulic head gradients δH/δz and soil water flux q within the profile can be obtained, from which hydraulic conductivity can be calculated.

$$k(\theta) = \frac{\frac{\partial \theta}{\partial t}}{\left[\frac{\partial H(z,t)}{\partial z}\right]_{z=L}} \quad (6)$$

Millington and Quirk Method: When the matching factor is based on the saturated hydraulic conductivity, Both Millington and Quirk and Marshall equations can be written in the following from:

$$k(\theta_i) = k_s\left(\frac{\theta_i}{\theta_s}\right)^p \frac{\sum_{j=1}^{m}\frac{2j+1-2i}{hj^2}}{\sum_{j=1}^{m}\frac{2j-1}{hj^2}} \quad (7)$$

Where k (θ) is the calculated conductivity at water content, k_s is the saturated hydrauiic conductivity, θ_s is the saturated water content, m is the number of water content increments equally divided on the soil moisture characteristic curve (usually between 10 and 20 is adequate) and, i and j are indices. The exponent, p is a constant originally given the value of 4/3 in the Millington and Quirk formulation and 0 for Marshall. A value of 1 has been found to give better results.

Chong method (CGA method): In a uniform soil profiles with a deep ground water table it may be assumed that the hydraulic gradient is nearly equal to one (3H/3z =1) during redistribution following infiltration of a large amount of water. The water content is then function of time only, but not of depth because the profile is uniform.

$$K(\theta)_L = Lba^{\frac{1}{b}}\left[\theta^*\right]^{\frac{b-1}{b}} \quad (8)$$

Thus,this procedure yields K (θ) as a power function of θ* which has often been proposed to represent conductivity as a function of water content (Brooks and Corey 1966).

Parameter Optimization Method: The empirical water retetion curve is given as:
Mualem (1976) gave a theoretical relation between hydraulic conductivity and pore size

$$\frac{\theta-\theta_r}{\theta_s-\theta_r} = \frac{1}{\left[1+(\alpha h)^n\right]^m} \quad (9)$$

Distribution expressed as:

$$K(h) = K_s S_e^{\lambda}\left[\frac{\int_0^s \frac{dx}{h(x)}}{\int_0^l \frac{dx}{h(x)}}\right]^2 \quad (10)$$

Where λ = parameter which determine δK/δh

Se = effective relative saturation

$$= \frac{\theta-\theta_r}{\theta_s-\theta_r}$$

Combining equation (9) and (10) we get

$$K(S_e) = K_s S_e^{\lambda}\left[1-(1-S^{\frac{1}{m}})^m\right]^2 \quad (11)$$

Solving equation (9), (10) and (11), we have

$$K(h) = K_s \frac{\left[\left\{1+(\alpha h)^n\right\}^m - (\alpha h)^{n-1}\right]^2}{\left[1+(\alpha h)^n\right]^{m(\lambda+2)}}$$

Where θ_s is the saturated water content $\left(L^3/L^3\right)$ is the residual soil water content or the non capillary bound water $\left(L^3/L^3\right)$ α is a shape parameter corresponding roughly to the reciprocal of the main air entry value in (L), n is the dimensional parameter, is the parameter which determines δk/δh and m = 1-1/n.

Materials and Methods

The study was conducted at Agriculture Research Station, Tandojam. A leveled piece of land of 100m x

90m was selected for the experiment. Three plots of 2m x 2m, 25 m apart, were selected at different locations. These plots (locations) were separated from the surrounding area by the construction of earthen bunds. In the middle of each plot five tensiometers, 20 cm apart were installed at depth of 20 cm, 40 cm, 60 cm, 80 cm, and 100 cm. Before installing, the tensiometers ceramic cups were soaked in the de-aerated water for 24 hours to saturate the cups and leakage test was performed. The tensiometers were filled with distilled water and closed at the top by stopper. For installation of a tensiometer, a hole was dug (bored) to the required depth with a small core sampler of approximately the same diameter as the porous cup. Then the tensiometer was installed by pushing the ceramic cup slightly into the bottom of the hole. The sides surrounding tensiometers were filled with sand to achieve better contact of ceramic cup and soil. The plot was then ponded with water until the soil profile up to 100 cm was fully saturated or when all tensiometers in the plot showed zero or positive matric potential. To prevent evaporation from surface,the soil surface was covered with a plastic sheet. During the depletion of soil moisture, the soil water tension and moisture content for each depth was measured simultaneously at regular intervals. For determining moisture content, soil samples were taken regularly from corresponding depth. In the beginning rapid changes occurred in soil water tensions and corresponding change in soil moisture content. Hence frequent measurements of soil water content and tension were carried out. The data collection on soil moisture and tension continued until the change in soil moisture was negligible.

Results and discussion

Soil Texture and Bulk Density: The table 1 indicates that soil texture and the bulk density of the experimental area at different depths. The soil texture of two locations was almost identical throughout the soil profile in which clay is dominant. Where as the soil texture of third location varied below 40 cm of a soil profile, in which silt was dominant. Typically the soil was classified as clay loam to silty clay.

Table 1: Soil Texture and Bulk Density of the Experimental Plot.

Soil depth (cm)	Location I		Location II		Location III	
	Soil texture	Bulk density (g/cm³)	Soil texture	Bulk density (g/cm³)	Soil texture	Bulk density(g/cm³)
0-20	Clay	1.37	Clay	1.35	Clay loam	1.30
20-40	Clay loam	1.32	Clay loam	1.28	Clay loam	1.29
40-60	Clay loam	1.27	Clay	1.34	Silty clay	1.33
60-80	Silty clay	1.31	Clay loam	1.27	Silty clay	1.30
80-100	Clay loam	1.30	Clay loam	1.28	Silty clay	1.31

Table 2: Chong's Equation Parameters

Depth (cm)	θ = atb		R2
0-20	0.530	-0.070	0..976
20-40	0.518	-0.064	0.959
40-60	0.503	-0.068	0.954
60-80	0.502	-0.066	0.934
80-100	0.482	-0.072	0.923

Table 3: VGM Parameters

Soil depth (cm)	α	η	λ	K_S (Cm/day	θ_S	θ_r
0-20	0.042	1.24	-3.57	0.853	0.4942	0.1381
20-40	0.046	1.29	-2.46	1.053	0.4871	0.1108
40-60	0.044	1.31	-488	1.132	0.4766	0.1034
60-80	0.032	1.27	-6.74	0.996	0.4781	0.1283
80-100	0.035	1.26	-8.06	1.003	.4772	0.1165

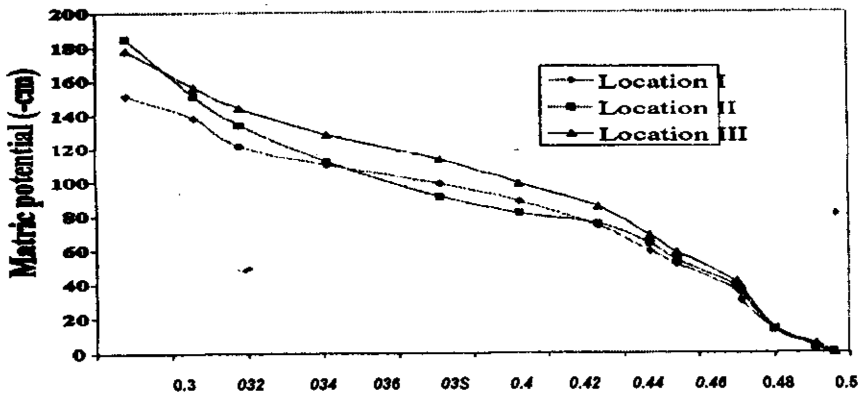

Fig. 1: Moisture Content Release Cure for all Three Locations at Depth 20 cm

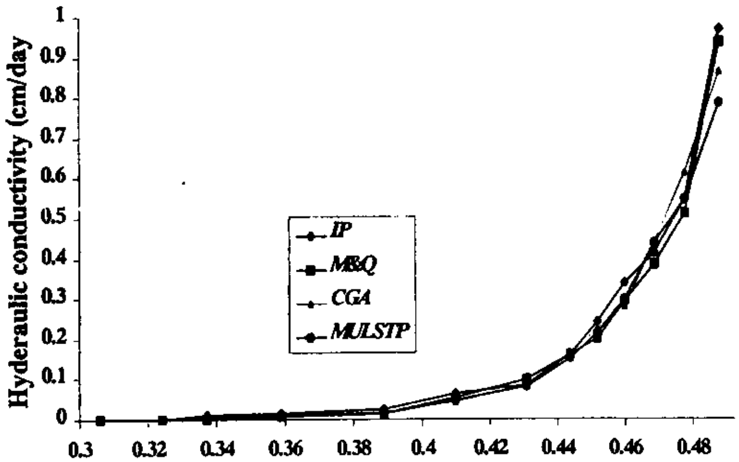

Fig. 2: Moisture Content and Hydraulic Conductivity of IP, M&Q, CGA and MULSTP

Bulk density of soil profiles of all the locations was in the range of 1.25 g/cm^3 to 1.38 g/cm^3 with an average bulk density of 1.31 g/cm^3. The higher value of bulk density of a soil may be due to the presence of clay contents, which are liable to compaction by field operations, or due to drying and wetting process

Water Retention: It was observed from the field that as the matric potential increases; the corresponding moisture content decreases (Fig. 1). The curves of sites II and I were almost identical, since soil at depth 0-20 cm was clay with slight difference in bulk density. Where as, the curve at site III showed slight shift in water retention due to difference in soil texture. It can be further observed that the curve at site III showed sharp decrease in moisture content as compared to water retention curves for sites II and I. This may be because of the difference in soil types. It may be noted that clay soil has the characteristics to retain more water at lower matric potentials than the coarse textured soils.

The moisture release curves of all the sites for specific depths from laboratory data indicated that the difference between the curves was almost negligible.

Parameters used for calculation of unsaturated hydraulic Conductivity:

(a) Chong's Equation Parameter: Table 2 shows the best fitted parameters and corresponding goodness of fit values at soil depths of 20, 40, 60, 80 and 100 cm for three locations. The values of parameters a and b for clay, clay loam and silty clay were near the values calculated by Moghal *et al.* (1990).

This method is simple because it assumes unit hydraulic gradient throughout the profile. Once the parameters a and b for any soil texture are known, the unsaturated hydraulic conductivity of soil can be calculated using only moisture content data.

(b) VGM Parameters: VGM parameters fitted with MULSTP model are given in table 3. It is however interesting to compare with parameters determined for same textural group by other authors. Wosten and Whisler (1972) fitted Van Genuchten-Mualem (VGM) parameters to measure θ(h) and K (θ) data for standard soils of Netherlands using the line fitting program RETC.

By fixing residual moisture content θ_r at zero, they found n values varying from 1.12 for clay to 1.32 for clay loam. Similar values were determined for clay and clay loam soils in this study by MULSTP model. This confirms our results to that of Wzten and Whisler (1972). The α values of Wasten and Whisler (1972) are between 0.028 for clay loam to 0.051 for clay, which also correspond well with the values shown in table 3 determined for all the sites at different depths. Although the parameters determined in this study have same resemblance to parametric values of other authors. Simple comparisons do not contribute to understanding of the soil hydraulic properties. Fitting procedures are often not comparable and the VGM parameters are all interrelated. Individual VGM model alone do not have distinct meaning, they only describe a certain soil water retention and hydraulic conductivity relation when they are in their specific relation with each other. The physical parameters θ_r, θ_s and K_s have a physical meaning and have direct influence on other parameters. Consequently each set of parameters has to be considered individually. The only valid comparison of the VGM parameters is with K, calculated with instantaneous profile method and with the measured soil water retention.

Fitting of VGM parameters with MULSTP has the advantage that it yields data which can be used directly in different simulation models like SWATRE or WORN and it facilitates extrapolation from the measured data and interpolation between measured data.

Unsaturated Hydraulic Conductivity: Comparison of methods shows that there is very slight difference in computation of unsaturated hydraulic conductivity function between the methods and that the difference is not significant.

Site I showed maximum hydraulic conductivity at 100-cm soil depth. Where as sites II and III showed maximum hydraulic conductivity at 100 and 80-cm soil depths respectively. Minimum hydraulic conductivity values were found at depths 40, 40 and 60-cm for sites I, II and III respectively. The top 20-cm layer has shown quite variable results of hydraulic conductivity at specific moisture contents. This may be due to considerable effect of cultivation over the number of years, which alter the basic properties of soil. The results of site I are comparable to site III but the results of site II are slightly different. This may be due to variation in soil texture throughout the soil profile. The soil profile of sites I and III contain silt at greater depths where as site II contains clay content.

The low level of soil moisture content, have marked effect on hydraulic conductivity, as compared with high level moisture content. As the moisture content drops from 45 percent to 35 percent, the hydraulic conductivity reduces more than 100 times.

Comparison of instantaneous profile method with other methods.

Because the relation between hydraulic conductivity (K) and soil water content (θ) is known to be less sensitive to hysteresis than between K and soil water tension, therefore K (θ) relation is often regarded as a more valuable function.

The linear correlation coefficient was used to express closeness of evaluated methods to that of Instantaneous Profile method. The R^2 values were computed to assess the magnitude of correlation. It was found that R^2 values for all methods were high, varying from 0.89 to 0.99, which indicates good relative agreement between all evaluated methods. From fig. 2 it is clear that all the evaluated methods express good correspondence with Instantaneous profile method. It is interesting to note that the Millington and Quirk method has shown very close agreement with Instantaneous Profile method followed by CGA method. The least correlation was obtained by MULSTP model.

Conclusions

1 As the moisture content decreases, the unsaturated hydraulic conductivity also decreases.
2. Water retention values can be determined from concurrent water content and soil water tension measurements. This yield a set of discrete water retention points for different locations at various depths.
3. A continuous function of water retention can be obtained by fitting the Van Genuchten Mualem parameters to the observed data with the model MULSTP.
4. VGM (Van Genuchten Mualem) parameters fitted with MULSTP described both soil water retention and hydraulic conductivity functions including extrapolation sufficiently accurate for the use in computer simulation applications.
5. The simplified methods (Millington & Quirk and CGA) correspond well with the classical field method (Instantaneous profile method) followed by MULSTP model. MULSTP describes K (h) and K (θ) as a continuous function and has the advantage over the other methods in that it can be used in simulation models of soil and water movement.
6. Comparison of all the methods with instantaneous profile method show very high correlation coefficient varying from 0.89 to 0.99.
7. VGM parameters and the CGA equation parameters were in close agreement with other authors such as Wosten and Whisler (1972) and Mualem (1976).
8. At low level soil moisture content the effect on unsaturated hydraulic conductivity was markedly high. For 5% change in moisture content the change in unsaturated hydraulic conductivity was found more than 100 times.

Suggestions

1. To see the validity of applied methods of calculating unsaturated hydraulic conductivity, further studies be carried out to determine unsaturated hydraulic conductivity of different soil textures.
2. To save time and effort, it is suggested that the moisture content of the soil should be determined by Neutron probe rather than by gravimetric method.
3. Optimization of VGM parameters with SFIT and RETC models should also be studied.
4. It is suggested to use different type of soils and profiles to determine VGM parameters under varying conditions and locations. The parameters once known can be used confidently in computer simulation studies such as SWATRE, SWAP, SWARRB, DRAINMOD and other simulation soil water models.

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