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Characteristic equations for estimation of unsaturated hydraulic conductivity – a case study

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Abstract
The knowledge of the physics of soil water movements in the unsaturated zone is very important for the studies related to watershed hydrology, irrigation and recharge to groundwater. The design and functioning of subsurface drainage systems also depends to a great extent on unsaturated hydraulic conductivity of the soil. Direct prediction of unsaturated hydraulic conductivity is difficult and it can be indirectly evaluated through the soil moisture characteristic curve. In view of the above, an attempt has been made to derive the characteristic equations for the estimation of unsaturated hydraulic conductivity using a regional data base, for different types of soil of Narsingpur, India. Total soil samples collected from 24 locations are about 120 numbers (5 samples from each location). Extensive field and laboratory measurements have been carried out for each of the soil samples. Soil Textures are determined using the mechanical sieve analysis and hydrometer analysis. Saturated Hydraulic Conductivity is determined using Guelph Permeameter (for In-Situ measurement). The soil moisture characteristic data were obtained through Pressure Plate Apparatus in the laboratory. The unsaturated hydraulic conductivity function has been derived from the Brooks and Corey relationship by non-linear regression analysis. These characteristic equations can be used for estimating the unsaturated hydraulic conductivity of the different soil in the study area.

INTRODUCTION

The prediction of soil water movements in the unsaturated zone is very important phenomena in many branches of science and engineering. These include soil science, agricultural engineering, environmental engineering, watershed and groundwater hydrology. The design and functioning of subsurface drainage systems also depends to a great extent on unsaturated hydraulic conductivity of the soil. Direct prediction of unsaturated hydraulic conductivity is difficult and it can be indirectly evaluated through the soil moisture characteristic curve. It is the functional relationship between the hydraulic conductivity, the moisture content and suction (pressure) head. Characteristic equation is useful in the studies related to ground water modelling and particularly in subsurface flow modelling in unsaturated zone. The main difficulty in the Richards equation to actual field situations is the estimation of the parameters of the soil characteristic curves. Physical properties of soil constitute the basic data to carry out the studies related to the above problems. For example, prediction of runoff and infiltration following precipitation, the subsequent distribution of infiltrated water by drainage depends upon the reliability and adequacy of the physical properties of soil. In subsurface drainage design the textural analysis of the soil is an important parameter which governs the movement of the water in subsurface soil. Soil texture is a characteristic, which has a general relationship with hydraulic conductivity and water retention. For the management of water in irrigation command area the wilting point, field capacity and available moisture are very important parameters, which can be determined from the characteristic curve. Soil moisture characteristic curves are useful to understand the amount of water that is available to plants, the water that can be taken up by the soil before percolation starts, and the amount of water that must be used for irrigation (Micheal, 1986). Therefore, the basic data must provide the knowledge of soil texture, saturated hydraulic conductivity and the soil characteristics of the area under consideration. Convenient and reliable techniques for estimating these properties are necessary. Therefore, suitable techniques for the estimation of unsaturated hydraulic conductivity are required based on national and regional data base. For this purpose, the characteristic equations have been derived to estimate the unsaturated hydraulic conductivity.

In this paper, an attempt has been made to derive the characteristic equations to estimate the unsaturated hydraulic conductivity for different types of soil in a Narsingpur study area. The present study area is the doab between Barurewa river, Umar river and Bargi left bank canal, which falls in Narsingpur district of Madhya Pradesh, India. Narsingpur is about 100 kms away from Jabalpur. River Sher is passing through the middle of the study area. This is a part of the command area of Bargi irrigation project of Narmada River.

GENERAL DESCRIPTION OF THE STUDY AREA

The study area, comes under the command area of Bargi Irrigation Project, which is a multipurpose project constructed on river Narmada. The area selected for the present study is the doab of river Barurewa, Umar and left bank canal of Bargi Irrigation Project. This area is bounded by river Barurewa in west, river Umer in the east and north, and Bargi Left Bank Canal in the South as shown in Figure 1. This is one of the most fertile and densely populated part of Narsinghpur.

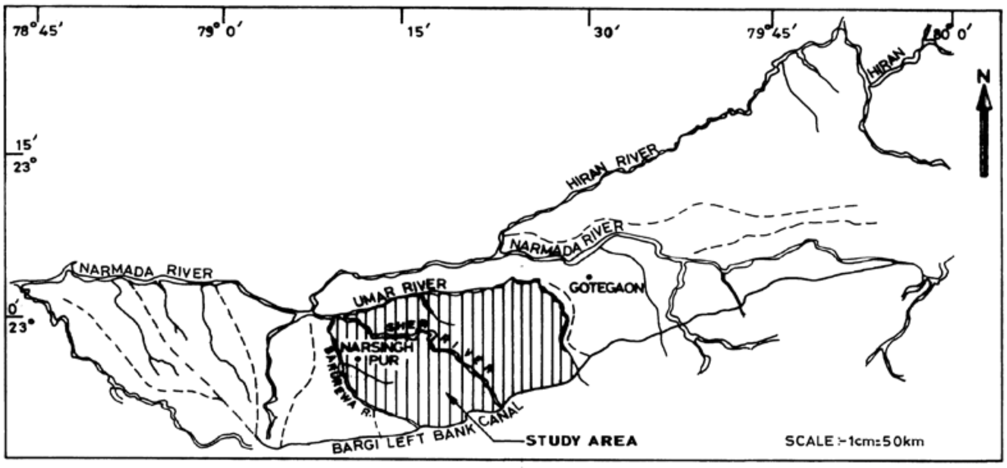

Figure 1. Map of study area showing Bargi left bank canal project.

The study area lies between longitudes E79^o 9' to E79^{o}32' and latitudes N 22^{o}53' to N 23^{o}03'. The general topography of the area appears to be flat except in the vicinity of the rivers, where deep gullies and ravines have formed giving rise to undulating to rolling topography. As such the entire area is a broad plain of low relief and local differences in elevation is small. The general slope of the area is towards north and northwest. The landscape of the command area is such that most of the surplus rain water drains through rivers and streams. The natural drainage follows the general slope of the land. The study area enjoys a sub-tropical climate. The annual rainfall of Narsinghpur district varies from 563.3 mm to 1893.6 mm, with average annual rainfall of 1162 mm. Most of it precipitate during monsoon season i.e. end of June to end of September. The summer temperature goes as high as 45^{o}C. The extremes of cold and heat are experienced during winter and summer respectively. Soils of the area are alluvial in nature. The thickness of alluvium increases towards north. Soil of whole of the Bargi Project in Jabalpur and Narsingpur district have been derived from trap rock but with regard to soils only Deccan trap is important one which has given rise to Characteristic colour and properties to the soils of the area. Deccan trap is the great formation of horizontally bedded basaltic lavas that occupies a large portion of the western part of India. Kankars have been observed at a depth of 80 cm to 150 cm. In some places, soils have been formed from sand stone parent material in which lot of textural variation is found. It varies from silty loam to clay and soil crust is deep having fair amount of gravel or kankar (Soni and Srivastava 1996; Singh et al. 1997). The study area is mostly agricultural area having no forest. Forest lies beyond the Bargi canal in the south. The main crops grown in the area are Soyabean, Gram, Arhar, Masoor, Moong, Jwar, Wheat and Sugar Cane. Rice is also cultivated in some of the low-lying areas.

METHODOLOGY

Soil characteristic curves, also called moisture retention curves, are the plots of moisture content versus suction head. It shows the amount of moisture in a given soil holds at various tensions. The moisture characteristic curve of a soil can generally be determined by equilibrating a soil sample at a succession of known tension value and each time by determining the amount of moisture. The graph is plotted between the tension and corresponding soil moisture value to obtain the soil moisture characteristic curve. Different soil type gives different characteristic curves.

Pressure plate apparatus is a standard method for obtaining the soil characteristic curves. It consists of a pressure chamber in which a saturated soil sample (either disturbed or undisturbed) is placed on a porous ceramic plate through which the soil solution passes but no soil particle or air can pass easily. The soil solution, which passes through membrane is in contact with atmospheric pressure. As soon as the air pressure inside the chambers are raised above the atmospheric pressure it takes excess water from the soil and flow out of the chamber through the membrane outlet. Soil water will flow out from the soil sample until the metric potential of the soil is same as the applied air pressure. This is the point of equilibrium at which the applied pressure is same as the tension in the soil. The air pressure is then, released and the moisture content of the soil is determined gravimetrically for that particular pressure. The same procedure is repeated at various pressures and corresponding values of moisture content are obtained. The pair of suction pressure and moisture content data so obtained are used to construct the soil moisture characteristic curves. The characteristic equations can be derived by the regression analysis of all the data.

A soil water matrix potential of about -1/3 bars has been found to correspond to the field capacity, where as a soil water matrix potential of about -15 bars has been found to correspond to wilting point (Henry, 1984). The water present in the soil between field capacity and wilting point is known as available water. It is generally considered to be matrix potential in the range of -0.3 to -15.0 bars.

PROCEDURE

The study area, as shown in Figure 1, was selected for the estimation of characteristic equations. There are 24 locations from where 120 soil samples at different depths have been collected (5 samples from each locations). Figure 2 shows the locations of the soil sampling sites. These sites were tentatively chosen in such a way that different types of soils found in the area were covered and the sites were easily approachable and were well distributed all over the study area. Collected soil samples have been used for the analysis of grain size distribution and soil characteristic curve. Measurement of field saturated hydraulic conductivity were also carried out at all sites by Guelph Permeameter.

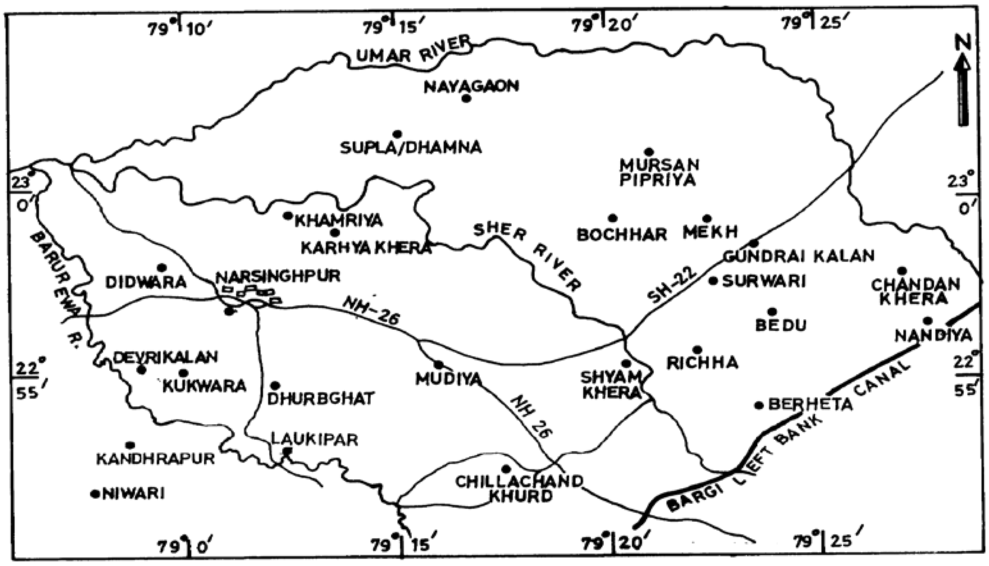

Figure 2. Location of soil sampling sites.

GRAIN SIZE DISTRIBUTION AND SATURATED HYDRAULIC CONDUCTIVITY

Sand, silt and clay are the primary particles of soil, which form its textures. Particles of size larger than 2.0 mm are graded as gravel. Soil is divided in two groups i.e. coarse grain soil (particle size > 0.075 mm) and fine grain soil (particle size < 0.075 mm). Coarse grain size analysis has been carried out by mechanical sieve analysis and fine grain size analysis has been carried out by the hydrometer analysis. Both the results (coarse grain and fine grain) were blended to determine the percentage of clay, silt, sand and gravel. Table 1 shows the grain size distribution at the surface for all the locations. Results of grain size distribution for different depth are not presented here because there is little variation along depth. The major soils found in the study area are clay and silty clay, but at some place small patches of silty loam, clay loam and silty clay loam are also found (Soni and Srivastava 1996; Singh et al. 1997).

Saturated hydraulic conductivity was measured in the field by using the Guelph Permeameter at all the sites (Refold and Elicit, 1985) and at 20 to 40 cm depth. Wide variations were observed in the saturated hydraulic conductivity at different locations.

Table 1. Textural Classification of Soil.

Sl. No	Location	Gravel %	Sand %	Silt %	Clay %	Soil Texture	K_s (m/d)
1	Didwara	2.2	7.7	12.6	77.5	Clay	0.07158
2	Devrikalan	5.2	11.3	13.5	70.0	Clay	0.003625
3	Kukwara	4.2	5.6	11.0	79.0	Clay	0.001987
4	Dhurbghat	1.1	2.6	11.3	85.0	Clay	0.04950
5	Kandhrapur	2.1	11.7	10.7	75.5	Clay	0.20270
6	Niwari	7.0	17.5	9.5	66.0	Clay	0.07300
7	Laukipar	0.1	36.3	14.6	49.0	Clay	1.11500
8	Chillychand Khurd	2.6	34.7	10.7	52.0	Clay	0.03700
9	Shyam Khera	0.1	5.4	11.5	83.0	Clay	0.00885
10	Mudiya	0.8	2.8	14.9	81.5	Clay	0.09050
11	Karhiya Khera	5.3	6.5	12.2	76.0	Clay	0.20100
12	Khamriya	2.6	34.7	10.7	52.0	Clay	0.96336
13	Dhamana	0.0	0.9	31.7	67.4	Clay	0.01180
14	Nayagaun	1.0	2.7	41.9	54.4	Silty Clay	0.02380
15	Mushran Piparia	0.0	3.1	46.7	50.2	Silty Clay	0.53734
16.	Bochhar	1.6	5.4	68.7	24.3	Silty Loam	0.20450
17	Mekh	0.9	7.8	44.4	46.9	Silty Clay	0.34270
18	Gudraikala	0.5	2.8	35.2	61.5	Clay	0.13480
19	Surwari	0.0	1.1	46.3	52.6	Silty Clay	0.01200
20	Bedu	0.5	3.2	43.9	52.4	Silty Clay	0.02830
21	Richha	0.0	4.0	91.0	5.0	Silt	0.15600
22	Barheta	1.2	12.2	26.9	59.7	Clay	0.00117
23	Nandia	0.6	21.7	46.3	31.4	Clay loam	0.02400
24	Chandan Khera	0.3	2.9	63.1	33.7	Silty Clay loam	0.02400

Soil Characteristic Curve

Soil samples were prepared after drying, light hammering and passing through 2.0 mm sieve. The passing soils from 2.0 mm sieve were used for determining soil characteristic curve by applying 0.10, 0.33, 1.00, 3.00, 5.00, 10.00, 15.00 bars pressure and by measuring the corresponding moisture content for each pressure. Pressure plate apparatus (Soil Moisture Corporation Co. USA) was used to determine the moisture retention behavior of the soil samples. Each of these samples, were tested against 0.10, 0.33 and 1.0 bar, by one bar pressure plate. Where as 3 bar, by 3 bar plate and 5 bar, by 5 bar plate as well as 10 bar and 15 bar with 15 bar pressure plate and following procedures were followed in the experiment.

First of all, the pressure plates were saturated and prepared soil samples were placed on plate in three separate rings and soaked with water for complete saturation.

Saturated plate containing soil samples were placed in pressure chambers and applied desired pressure till it reached equilibrium.

Samples were taken out from the pressure chambers after reaching equilibrium and weighed on the high precision microbalance to record the moist weight of the samples.

These weighed samples placed in the oven at 105^{o} C-110^{o} C till weight became constant on drying. The dry weight was recorded by weighing and soil moisture by weight was determined from the moist and dry weight of the sample.

Soil moisture measurement for all soil samples of 24 sites and at all depth were carried out and results are presented in Table 2. Based on the results obtained for moisture contents at different suction head, the characteristic equations are obtained by using the non-linear regression analysis for each soil type.

RESULTS AND DISCUSSION

Soil characteristic curve may be represented by means of relatively simple parametric expression. The problem of characterizing the soil hydraulic properties then reduces to estimating parameters of the appropriate constitutive model. The results of moisture content and suction head (θ - ψ) can be fitted to the desired soil moisture characteristic model. Once the soil moisture characteristic function is estimated the unsaturated hydraulic conductivity relationship $K(\theta)$ - θ can be evaluated if the saturated hydraulic conductivity, K_s is known. A number of different functional relationships have been used to describe the relationships between K, θ and ψ. The most common relationships are Brooks – Corey and van Genuchten model. In this study, Brooks – Corey model has been used for its simplicity (Rawls and Brakensick 1988).

Brooks – Corey relations

Soil moisture retention:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi_b}{\psi}\right)^{\lambda} \quad (1)$$

Hydraulic conductivity :

$$\frac{K(\theta)}{K_s} = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{3-2/\lambda} \quad (2)$$

in which, $K(\theta)$ and θ are the hydraulic conductivity (cm/hr) and moisture content of the soil; θ_r = residual moisture content; θ_s = saturated moisture content; ψ_b = bubbling pressure (cm); K_s = saturated hydraulic conductivity (cm/hr) and λ = constant (pore size index).

Table 2. Soil Moisture Characteristic Data for all the Soil Samples.

Sl No	Location	Pressure in Ist row is in Bar and in 2nd row is in cm						
		0.1	0.33	1	3	5	10	15
		101.98	336.53	1019.8	3059	5099	10198	15297
1	Didwara	38.01	35.80	29.43	24.63	21.97	21.09	16.87
2	Devrikalan	40.20	32.72	27.49	23.04	21.13	19.46	16.73
3	Kukwara	48.34	40.78	32.89	26.24	25.82	24.16	19.68
4	Dhurbghat	46.17	40.34	35.20	29.25	25.40	23.39	21.83
5	Kandhrapur	37.88	28.97	26.08	24.15	20.90	19.67	16.21
6	Niwari	35.68	32.88	23.23	21.14	18.34	16.74	14.42
7	Laukipar	32.36	25.43	18.66	16.42	14.35	12.89	11.59
8	Chillychand Khurd	39.07	38.01	32.02	29.43	24.63	22.09	21.09
9	Shyam Khera	45.91	42.22	38.02	33.60	29.83	27.07	21.71
10	Mudiya	38.06	37.01	30.81	27.06	23.42	21.73	20.56
11	Karhiya Khera	45.05	38.27	33.34	26.69	25.96	24.68	19.47
12	Khamriya	26.55	24.99	20.52	15.23	13.53	12.57	10.30
13	Dhamana	36.59	34.88	33.37	31.36	30.52	29.57	29.19
14	Nayagaun	33.48	29.79	28.78	27.51	26.68	25.76	25.38
15	Mushran Piparia	25.77	23.19	21.47	19.97	19.32	18.33	18.19
16	Bochhar	29.41	26.33	23.91	21.87	21.02	19.53	19.42
17	Mekh	33.69	31.90	30.60	28.74	27.97	26.62	26.40
18	Gudraikala	32.37	30.57	29.06	27.34	26.54	25.76	25.41
19	Surwari	35.00	33.72	32.44	30.57	29.67	29.21	28.99
20	Bedu	29.37	28.41	27.53	26.17	25.74	25.38	25.18
21	Richha	40.11	38.49	33.96	26.90	24.52	23.29	22.98
22	Barheta	36.51	34.95	33.73	31.74	30.97	30.04	29.75
23	Nandia	31.82	30.78	30.00	28.49	27.86	26.66	26.52
24	Chandan Khera	33.85	33.01	32.04	29.83	28.77	27.16	26.94

The soil moisture measurement for soil samples were carried out at seven pressures (0.1, 0.33, 1.0, 3.0, 5.0, 10.0, 15.0 bar) are presented in Table 2. The value of field capacity varies from 23% to 42.2 % and wilting point varies from 10.3 % to 29.75 % respectively. The parameters of soil characteristic equations were obtained through non-linear regression analysis for all the samples. The saturated moisture content was assumed to be equal to porosity. Table 3 presents the Brooks – Corey retention parameters for all soil samples. In view of wide variations found in the saturated hydraulic conductivity of all sites, the parameters were determined for each site. In the modelling studies of unsaturated flow, different soil moisture characteristic can be assigned for different soils. Therefore, for different soils different characteristic equations have been derived. Residual moisture, θ_r, saturated moisture content, θ_s and bubbling pressure, ψ_b for different soils have been taken from Chow et al. 1988. Saturated hydraulic conductivity for the clay and silty clay has been taken as the mean value based on all the data for the clay and silty clay respectively. Final values of all the parameters of the characteristic equations after regression analysis for different soils have been presented in Table 4. The constant λ has been obtained by regression analysis, which is used in the another characteristic equation for unsaturated hydraulic conductivity. The unsaturated hydraulic conductivity can be calculated from equation 2. The coefficients of correlation for different types of soil have also been presented in Table 4. Its value lies between 0.966 to 0.989, which indicates good correlation.

Table 3. Characteristic Parameters for Brookes and Corey.

Sl No	Name of the Site	Type of Soil	θ_r	θ_s	K_s (cm/hr)	ψ_b (cm)	λ	r
1	Didwara	Clay	0.09	0.475	0.29825	31.6	0.204	0.996
2	Devrikalan	Clay	0.09	0.475	0.01510	31.6	0.221	0.998
3	Kukwara	Clay	0.09	0.475	0.00828	31.6	0.153	0.986
4	Dhrubghat	Clay	0.09	0.475	0.20625	31.6	0.144	0.991
5	Kandhrapur	Clay	0.09	0.475	0.84458	31.6	0.240	0.997
6	Niwari	Clay	0.09	0.475	0.30417	31.6	0.262	0.995
7	Laukipar	Clay	0.09	0.475	4.64583	31.6	0.388	0.999
8	Chillachand Khurd	Clay	0.09	0.475	0.15417	31.6	0.165	0.996
9	Shyam Khera	Clay	0.09	0.475	0.03687	31.6	0.116	0.991
10	Mudiya	Clay	0.09	0.475	0.37708	31.6	0.180	0.997
11	Karhiya Khera	Clay	0.09	0.475	0.83750	31.6	0.156	0.993
12	Khamriya	Clay	0.09	0.475	4.01400	31.6	0.433	0.980
13	Dhamana	Clay	0.09	0.475	0.04917	31.6	0.121	0.990
14	Nayagaun	Silty Clay	0.056	0.479	0.09917	29.2	0.149	0.982
15	Mushran Piparia	Silty Clay	0.056	0.479	2.23892	29.2	0.265	0.944
16	Bochhar	Silty Loam	0.015	0.501	0.85208	16.7	0.177	0.976
17	Mekh	Silty Clay	0.056	0.479	1.42792	29.2	0.134	0.985
18	Gudraikala	Clay	0.09	0.475	0.56167	31.6	0.173	0.982
19	Surwari	Silty Clay	0.056	0.479	0.05000	29.2	0.115	0.988
20	Bedu	Silty Clay	0.056	0.479	0.11790	29.2	0.164	0.963
21	Richha	Silty Clay	0.056	0.479	0.12917	29.2	0.138	0.997
22	Barheta	Clay	0.09	0.475	0.00487	31.6	0.117	0.993
23	Nandia	Clay Loam	0.155	0.464	0.10000	20.9	0.190	0.989
24	Chandan Khera	Silty Clay Loam	0.039	0.471	0.08330	27.3	0.114	0.989

Table 4. **Characteristics Parameters for different type of soil in the study area**.

Sl. No	Type of soil	θ_r	θ_s	K_s (cm/hr)	ψ_b (cm)	λ	r
1	Clay	0.090	0.475	0.8824	31.6	0.191	0.966
2	Silty Clay	0.056	0.479	0.6772	29.2	0.153	0.966
3	Clay Loam	0.155	0.464	0.1000	20.9	0.19	0.989
4	Silty Loam	0.015	0.501	0.8520	16.7	0.177	0.976
5	Silty Clay Loam	0.039	0.471	0.0833	27.3	0.114	0.989

The derived characteristic equations for different types of soil using Brookes and Corey equation are given below:

For Clay:

$$\theta(\psi) = 0.09 + 0.385\left(\frac{31.6}{\psi}\right)^{0.191} \tag{3}$$

$$K(\theta) = 0.8824\left(\frac{\theta - 0.09}{0.385}\right)^{-7.471} \tag{4}$$

For Silty Clay:

$$\theta(\psi) = 0.056 + 0.423\left(\frac{29.2}{\psi}\right)^{0.153} \tag{5}$$

$$K(\theta) = 0.6772\left(\frac{\theta - 0.056}{0.423}\right)^{-10.072} \tag{6}$$

For Clay Loam:

$$\theta(\psi) = 0.155 + 0.309\left(\frac{20.9}{\psi}\right)^{0.19} \tag{7}$$

$$K(\theta) = 0.1\left(\frac{\theta - 0.155}{0.309}\right)^{-7.526} \tag{8}$$

For Silty Loam :

$$\theta(\psi) = 0.015 + 0.486\left(\frac{16.7}{\psi}\right)^{0.177} \tag{9}$$

$$K(\theta) = 0.852\left(\frac{\theta - 0.015}{0.486}\right)^{-8.299} \tag{10}$$

For Silty Clay Loam:

$$\theta(\psi) = 0.039 + 0.432\left(\frac{27.3}{\psi}\right)^{0.114} \tag{11}$$

$$K(\theta.) = 0.0833\left(\frac{\theta - 0.039}{0.432}\right)^{-14.544} \tag{12}$$

Equations 3 to 12 are the derived characteristic equations, which can be used to estimate the unsaturated hydraulic conductivity.

CONCLUSIONS

Field and laboratory based soil investigations were carried out for the chracteristic equations for the soil of Narsingpur district, India. Grain size analysis and saturated hydraulic conductivity have been obtained in the laboratory and field respectively. It is found that there are two major type of soils i.e. clay and silty clay. Besides this, small patches of clay loam, silty loam and silty clay loam are also found in the study area. The soil moisture characteristic relation has been determined based on the data of moisture content and corresponding suction head for all the soils. The parameters of the characteristic equations for Brooks and Corey relationship have been obtained by nonlinear regression analysis of the above data. The unsaturated hydraulic conductivity function has been derived using Brooks and Corey relationship. Resulting characteristic equations can be used for estimating the unsaturated hydraulic conductivity of the soils in Narsingpur district.

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