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AN EVALUATION OF SIX MODELS PERFORMANCE OF THE SOIL-WATER CHARACTERISTIC CURVE USING FIVE DIFFERENT SOIL TYPES

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ABSTRACT
Soil-water characteristic curves (SWCCs) are important in terms of groundwater recharge, agriculture, and soil chemistry. These relationships are also of considerable value in geotechnical and geo environmental engineering. Their measurement, however, is difficult, expensive, and time-consuming. Many empirical models have been developed to describe the SWCC. Statistical assessment of soil-water characteristic curve models found that exponential-based model equations were the most difficult to fit and generally provided the poorest fit to the soil-water characteristic data. In this paper verification was performed with 5 independent data for five different of soil textures. Fitting results were compared with the most widely used models to assess the model's performance. It was proven that the Van Genuchten (1980) model and Durner (1994) provided greater flexibility and a better fit to data on various types of soil.

KEYWORDS: groundwater, recharge, agriculture, soil.

INTRODUCTION

Soil-water characteristic curve (SWCC) or Soil Moisture Retention Curve represents the relationship between the volumetric water content (θ) in pore space and the matric suction (Lal and Shukla, 2004; Malaya and Sreedeep, 2010; Heshmati and Motahari, 2012; Nazari *et al*., 2018). The soil-water characteristic curve is an important soil property to understand and determine water movement in soil, and useful to identify unsaturated soil behavior to provide water to plant and water-holding capacity in different matric suctions. Also, to estimate moisture variables like field capacity, willing point and available water which special variables dependent upon on the soil type. Those variables are useful to calculate required water irrigation water quantity (Sreedeep and Singh, 2005; Gallage and Uchimura, 2010; Shorafa *et al*., 2010; Rao and Singh, 2010; Abbaspour *et al*., 2012). Soil-water characteristic curve (SWCC) indirectly allows for the determination of unsaturated soil properties. There are several methods available to express Soil-water characteristic curve using water content (w) or volumetric water content (θ) or effective saturation (Θ) (Fredlund, 2002; Fredlund *et al*., 2011). We can use water content in mechanical processes, and volumetric water content in agricultural and theoretical processes take into account the soil density and water content. The effective saturation is another term commonly used to indicate the percentage of the voids that are filled with water. The above variables have also been used in a normalized form where the water contents are referenced to residual water content (or to zero water content) (Fredlund, 2002).

Numerous empirical equations have been proposed to simulate the soil-water characteristic curve to describe it based on pores size distribution which can describe soil water content within specific matric sections some of these questions are:

1. Brooks and Corey's Model (1964) (BC model): Brooks and Corey's model is among the earliest equations proposed for the soil-water characteristic curve and remains a popular model where it is in the form of a power-law relationship. The model is given by the following equation:

$$\Theta = \left[\frac{\Psi}{h_b}\right]^{-\lambda} \qquad (1)$$

$\Psi > h_b$

$\Theta = 1 \quad \Psi \leq h$

The equation uses two fitting parameters, namely, $_b$ and λ. Parameter $_b$ is related to the air entry value of the soil. The λ parameter is termed the pore size index and is related to the pore size distribution of the soil. The model is assumed to be constant for suctions less than the air entry value. The soil water characteristic curve is assumed to be an exponential decreasing function at soil suctions greater than the air entry value (Sillers *et al*., 2001). Rooks and Corey model can be written as follows:

$$\theta = \theta_r + (\theta_s - \theta_r)\left[\frac{\Psi}{h_b}\right]^{-\lambda} \qquad (2)$$

The Brooks and Corey model is relatively simple and thus widely used (Song *et al*., 2013); but the model does not provide a continuous mathematical function for the entire soil-water characteristic curve (Sillers *et al*., 2001).

2. Van Genuchten (1980) Model (VG model): The most widely adopted used is the closed form that proposed by Van Genuchten, to describe soil moisture characteristic curve in disturbed and undisturbed soil (Leech *et al*.,

2006), even in organic soils (Naasz *et al.*, 2005) by using this model we can get a high fit between measured and fitted data (Cornelis *et al.*, 2005) also the ability to predict Unsaturated hydraulic conductivity and to calculate Soil water diffusivity. The Van Genuchten model can mathematically be described as follows:

$$\theta = \theta_r + (\theta_s - \theta_r)\,[1 + (\alpha\psi)^n]^{-m} \qquad (3)$$

Where α is related to the inverse of air entry value, the n parameter is related to the pore size distribution of the soil, and the m parameter is related to the asymmetry of the model.

Where n and m parameters in the SWCC equation can have a fixed relationship with:

$$m = 1 - \frac{1}{n} \qquad (4)$$

By substituting (4) into (3), we can write the volumetric water content form of the Van Genuchten model as:

$$\theta = \theta_r + (\theta_s - \theta_r)\,[1 + (\alpha\psi)^n]^{-(1-1/n)} \qquad (4)$$

The Van Genuchten model has a complex form and relies on more fitting parameters than the models discussed above. However, it produces a continuous output in the unsaturated zone and provides a good description of the soil-water characteristic curve under most circumstances (Song *et al.*, 2013).

3. Fredlund and Xing (1994) Model (FX model): an empirical model, to describe soil moisture characteristic curve with high fitting with Sandy and Clay Loam soils.

$$\theta(w) = \frac{\theta_s}{\left[\ln\left[e + \left(\frac{\psi}{a}\right)^n\right]\right]^m} \qquad (5)$$

Where a = ψ_i, a soil parameter dependent on AEV.

4. Durner (1994) (DB model): Durner (1994) developed a multimodal retention function, constructed by a linear superposition of subcurves of the VG model, as shown in the DM model. The basic idea of Durner's method is that the soil water retention curve of soils having a heterogeneous pore structure can be expressed as a superposition of the curves of a homogeneous pore structure. Any homogeneous pore structure model can be used for the base model, for which Durner selected VG mode l.

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r} \left\{ \sum_{i=1}^{k} w_i\,[1 + (\alpha\,|\psi|^{n_i})^{m_i} \right. \qquad \psi=0,\ \psi\geq 0 \quad (6)$$

1

Where k is the number of "subsystems" that form the total pore-size distribution, and wi are weighting factors for the sub curves, ubject to $0 < w_i < 1$ and $\Sigma w_i = 1$. As for the unimodal curve, the parameters of the subcurves (α_i, n_i, m_i) are subject o the conditions $\alpha_i > 0$, $m_i > 0$, $n_i > 1$. We explicitly do not impose the additional constraint mi+1/ni = 1.

5. Kosugi (1996) Model (LN model): OR Lognormal Distribution Model. The last SWCC model considered is based on the model suggested by Kosugi (1996). This model was developed by applying a lognormal distribution law and its parameters are directly related to the soil pore radius distribution. The lognormal distribution model by Kosugi is described as follows:

$$\Theta = Q\left[\frac{\ln\frac{\psi}{h_m}}{\sigma}\right] \qquad (7)$$

Where Q is related to the complementary error function, erfc, and defined as:

$$(x) = \mathrm{erfc}\,\frac{\left(\frac{x}{\sqrt{2}}\right)}{2} \qquad (8)$$

The model uses two fitting parameters, namely, $_m$ and σ. Parameter $_m$ is a capillary pressure head related to the median pore radius and σ is a dimensionless parameter related to the width of the pore radius distribution. By substituting (1) into (7), we can write the volumetric water content form of the lognormal distribution by Kosugi:

$$\theta = \theta_r + (\theta_s - \theta_r)Q\left[\frac{\ln\frac{\psi}{h_m}}{\sigma}\right] \qquad (9)$$

The lognormal distribution model has a more complex form because of the complementary error function present and thus it is difficult to use. The model does, however, have greater flexibility in terms of representing the soil-water characteristic curve in the wet and dry regions for all soil types (Sillers *et al*., 2001).

6. Seki (2007) Model (BL model): Seki (2007) proposed a multimodal pore-size distribution model, combining the ideas of Durner and Kosugi:

$$Se = \sum_{i=1}^{k} Q\,[(\ln\psi/\psi mi)/\sigma i] \qquad (10)$$

Where ($0<w_i<1$, $\Sigma w_i = 1$). The special case of k = 2 can be termed as a bimodal log-normal pore-size distribution.

MATERIALS AND METHODS

Five different-texture soil samples were taken from fields and all sample of disturbed soil were taken from the Ap horizon (0-30 cm). Sandy Loam (SL), Loam (L), Sandy Clay Loam (SCL), and Clay (C) samples were air dried up, ground and sifted with a sieve of 2 mm diameter sieve's holes. Table (1) shown some soil physical properties.

TABLE 1. shown some soil physical properties

Property	Soil samples				
	Sandy Loam	Loam	Sandy Clay Loam	Silt Loam	Clay
Sand (%)	71.20	38.78	65.20	20.49	7.50
Silt (%)	12.40	35.64	11.10	60.66	35.30
Clay (%)	16.40	25.88	23.70	18.85	57.20
Bulk Density	1.55	1.52	1.45	1.38	1.21
K_S	1.083	2.560	2.241	1.260	0.252

The relation between volumetric water content θ and matric section ψ were estimated for the soil samples. A Tempe cells have been used to measure the moisture content at matric section between 1-1000 cm, and a pressure plate apparatus in the range -2500 to -15000 cm. soil moisture were calculated according to Soil Lab (2003) No. 415 (Tuller and Or, 2003).

Six models used to describe the relation between θ and ψ: Brooks and Corey's Model (1964) (BC model), Van Genuchten (1980) Model (VG model), Fredlund and Xing (1994) Model (FX model), Durner (1994) (DB model), Kosugi (1996) Model (LN model), and Seki (2007) Model (BL model) using "SWRC Fit," to performs nonlinear fitting of soil water 5 retention SWCCs. Parameters of the SWCC models showed in table (2).

TABLE 2. Parameters of the SWCC models

Models	Parameters
BC	h_b, λ
VG	α, n, m
FX	a, m, n
DB	w_1, α_1, n_1, α_2, n_2
LN	h_m, σ
BL	w_1, h_{m1}, σ_1, h_{m2}, σ_2

Quantitative statistical parameters were calculated and analysis of residual errors, and differences between measured and predicted values to evaluate the accuracy of predicted results and reliability of fitted results by using 6 hydraulic models (Homaee *et al*., 2002; Mohamed and Sahli, 2006; Khodaverdiloo and Homaee, 2011; Obiero *et al*., 2013, Naji, 2014, de Almeida *et al*., 2015):

Classic Coefficient of Determination (R_2):

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(\theta_i^m - \theta_i^f\right)^2}{\sum_{i=1}^{n}\left(\theta_i^m - \bar{\theta}^m\right)^2} \qquad (11)$$

- Root Mean Squared Error of θ ($RMSE_\theta$): RMSE value shows how much the fitting overestimates or underestimate the measurements.

$$RMSE_\theta = \sqrt{\frac{\sum_{i=1}^{n}\left(\theta_i^f - \theta_i^m\right)^2}{n}} \qquad (12)$$

- Mean Absolute Error (MAE): MAE small values which indicated a high significant fitting between measured and fitted values.

$$MAE = \frac{\sum_{i=1}^{n}\left|\theta_i^f - \theta_i^m\right|}{n} \qquad (13)$$

- Coefficient of Determination (CD): coefficient of determination (CD) gives the ratio between the scatter of the fitted values and of the measurements.

$$CD = \frac{\sum_{i=1}^{n}\left(\theta_i^m - \bar{\theta}^m\right)^2}{\sum_{i=1}^{n}\left(\theta_i^f - \bar{\theta}^m\right)^2} \qquad (14)$$

Modeling Efficiency (EF): EF value compares the fitted values to the averaged measured values, negative EF values indicate that the averaged measured values give a better estimate than the fitted values.

$$EF = \frac{\sum_{i=1}^{n}\left(\theta_i^m - \bar{\theta}^{om}\right)^2 - \sum_{i=1}^{n}\left(\theta_i^f - \theta_i^m\right)^2}{\sum_{i=1}^{n}\left(\theta_i^m - \bar{\theta}^m\right)^2} \qquad (15)$$

Coefficient of Residual Mass (CRM): RM is a measure of the tendency of the model to overestimate or underestimate the measurements.

$$CRM = \frac{\sum_{i=1}^{n}\theta_i^m - \sum_{i=1}^{n}\theta_i^f}{\sum_{i=1}^{n}\theta_i^m} \qquad (16)$$

 Error Ratio (ε):

$$\varepsilon = \frac{\theta^f}{\theta^m} \qquad (17)$$

- Geometric Mean of Error Ratio (GMER): GMER values were less than 1 indicates that the corresponding model overestimates fitted data.

$$\mathrm{GMER} = \exp\left(\frac{1}{n}\sum_{i=1}^{n}\ln(\varepsilon_i)\right) \tag{18}$$

- Geometric Standard Deviation of Error Ratio (GSDER): GSDER indicates deviation values of fitted values from measured values.

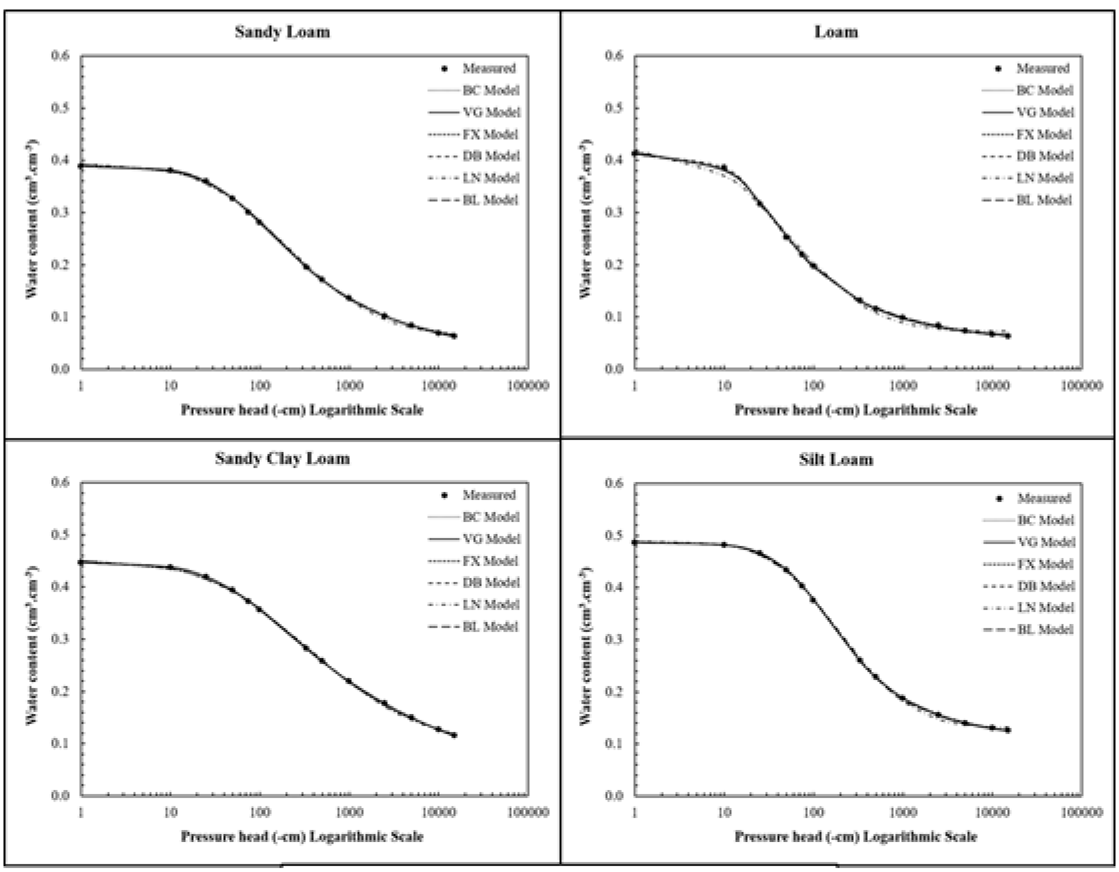
$$\mathrm{GSDER} = \exp\left[\left(\frac{1}{n-1}\sum_{i=1}^{n}[\ln(\varepsilon_i) - \ln(\mathrm{GMER})]^2\right)^{1/2}\right] \tag{19}$$

Where θ^m measured volumetric water content ($cm^3.cm^{-3}$), θ^f fitted volumetric water content ($cm^3.cm^{-3}$), and n numbers of data.

RESULTS AND DISCUSSION

Fig. (1) showed relationships between θ and ψ for measured and fitted SWCCs for five different soil types by using six fitting models, BC, VG, FX, DB, LN, and BL respectively. Results revealed there are differences between measured and fitted Fig. (2) represented 1:1 correlation between measured and fitted of SWCC for six fitting models which showed a good correlation between the measured and fitted data, through high correlation coefficients for all soil samples.

Table (3) showed fitting parameters for five different soil types by using six fitting models. Table (3) showed that saturated water continent values were the lowest by using BC models for all soil types. The classic coefficient of determination (R^2) [Eq. 11] values were higher VG, DB, and BL models respectively. R^2 lowest values concurring to BC model for all soil types. Root Mean Squared Error of θ ($RMSE_\theta$) [Eq. 12] RMSE values showed how much the fitting overestimates or underestimate the measurements. $RMSE_\theta$ results gave very small values which indicated a high significant fitting between measured and fitted values for all soil samples by using six fitting models, BC, VG, FX, DB, LN, and BL respectively (table 3). $RMSE_\theta$ showed the differences between measured and fitted values for all soil matric range SWCCs fitting models are very small and statistically insignificant, the smaller (closer to 0) the RMSE value was, the better the model was (Homaee *et al*., 2002; Mohamed and Sahli, 2006; Khodaverdiloo and Homaee, 2011; Obiero *et al*., 2013, Naji, 2014, de Almeida *et al*., 2015). According to $RMSE_\theta$ and MAE [Eq. 13] showed that VG and DB models were better performance from the other models for all soil types and BG model was the less (table 3).



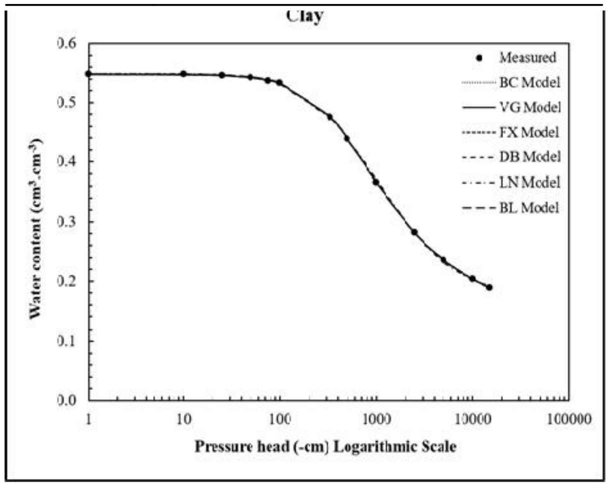


FIGURE 1. The SWCCs fitting models for five soil types

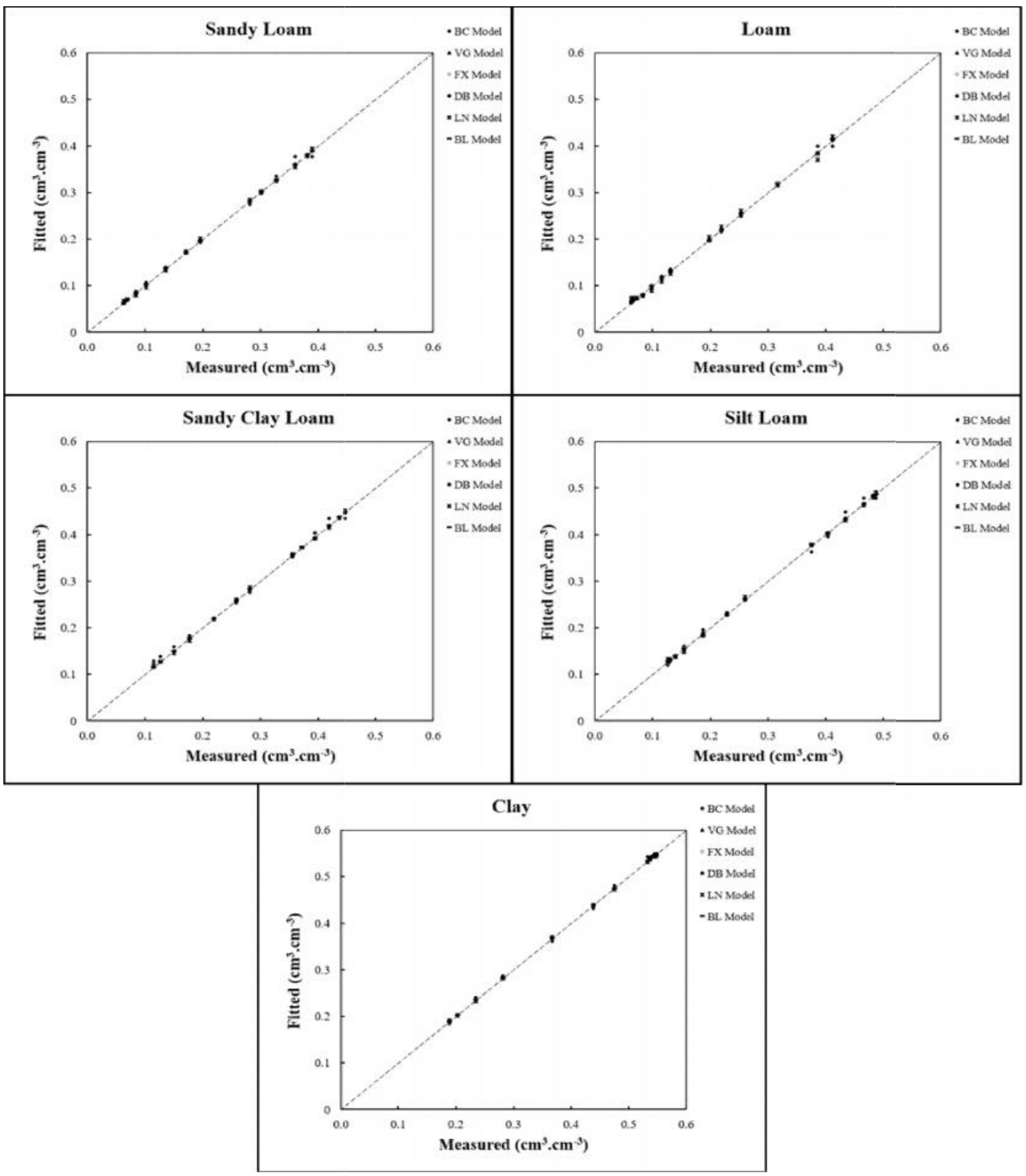


FIGURE 2. Correlation between measured and fitted of SWCC for six fitting models

TABLE 3. Parameters of the SWCC fitting models and calculated quantitative statistical parameters

Soil type	Model	θ_s	θ_r	P_1	P_2	P_3	P_4	P_5	R^2	$RMSE_\theta$	MAE	CD	EF	CRM	GMER	GSDER	$\varepsilon_{avarege}$
Sandy Loam	**BC**	0.377	0.063	3.357E+01	2.929E-01				0.99657	7.00E-03	5.91E-03	1.014768928	1.46E-02	-2.92E-03	1.0084776	1.0272544	1.0088141
	VG	0.390	0.063	1.893E-02	1.404E+00	2.876E-01			0.99999	3.41E-04	3.14E-04	0.999995633	-4.37E-06	-2.03E-05	1.0000305	1.0027505	1.0000340
	FX	0.393	0.066	8.504E+01	1.066E+00	1.037E+00			0.99967	2.17E-03	2.19E-03	1.005425947	5.40E-03	-1.55E-03	1.0047575	1.0165610	1.0048834
	DB	0.389	0.063	6.732E-02	3.715E-02	2.082E+00	1.574E-02	1.409E+00	0.99999	2.08E-04	1.40E-04	0.999961892	-3.81E-05	7.70E-07	1.0000080	1.0026769	1.0000113
	LN	0.394	0.069	2.196E+02	1.847E+00				0.99893	3.90E-03	3.59E-03	1.001042501	1.04E-03	-6.85E-06	1.0012344	1.0378716	1.0018762
	BL	0.389	0.063	5.412E-01	1.053E+02	1.295E+00	1.084E+03	2.019E+00	0.99999	2.94E-04	2.43E-04	0.999973999	-2.60E-05	-1.49E-05	1.0000210	1.0028674	1.0000248
Loam	**BC**	0.399	0.062	1.407E+01	4.338E-01				0.99770	5.68E-03	4.07E-03	1.002306753	2.30E-03	-4.23E-06	0.9994932	1.0228508	0.9997294
	VG	0.415	0.065	5.019E-02	1.564E+00	3.605E-01			0.99962	2.30E-03	1.80E-03	1.000378336	3.78E-04	3.95E-05	1.0007075	1.0183176	1.0008599
	FX	0.414	0.063	2.207E+01	8.360E-01	1.460E+00			0.99970	2.05E-03	1.61E-03	1.001294316	1.29E-03	-4.69E-04	1.0014413	1.0086236	1.0014753
	DB	0.412	0.064	3.837E-01	5.774E-02	2.252E+00	2.539E-02	1.496E+00	0.99995	8.63E-04	6.68E-04	1.000106082	1.06E-04	-1.59E-05	1.0001289	1.0104729	1.0001788
	LN	0.420	0.073	5.806E+01	1.696E+00				0.99561	7.85E-03	7.08E-03	1.004388773	4.37E-03	-7.87E-06	1.0029068	1.0713306	1.0051290
	BL	0.414	0.064	6.425E-01	3.616E+01	1.098E+00	3.648E+02	1.942E+00	0.99975	1.87E-03	1.62E-03	1.000258614	2.59E-04	4.74E-06	1.0000986	1.0131783	1.0001776
Sandy Clay Loam	**BC**	0.434	0.128	3.491E+01	2.017E-01				0.99439	8.83E-03	1.04E-02	1.063132429	5.94E-02	-9.87E-03	1.0212344	1.0437216	1.0221063
	VG	0.447	0.115	1.935E-02	1.239E+00	1.928E-01			0.99999	4.13E-04	3.69E-04	1.001349546	1.35E-03	-1.85E-04	1.0004461	1.0017361	1.0004475
	FX	0.451	0.119	115.87	0.94882	8.358E-01			0.99950	2.63E-03	2.46E-03	1.001846765	1.84E-03	-1.57E-04	1.0008267	1.0133797	1.0009085
	DB	0.447	0.115	9.394E-02	3.735E-02	1.577E+00	1.478E-02	1.234E+00	0.99998	4.64E-04	4.15E-04	1.000085976	8.60E-05	-5.65E-05	1.0001141	1.0017829	1.0001155
	LN	0.451	0.120	3.798E+02	2.188E+00				0.99913	3.48E-03	2.98E-03	1.000901154	9.00E-04	-3.44E-06	1.0003430	1.0194627	1.0005149
	BL	0.447	0.115	5.692E-01	1.470E+02	1.561E+00	4.036E+03	1.981E+00	0.99998	5.22E-04	4.10E-04	1.000001017	1.02E-06	1.22E-05	0.9999861	1.0017234	0.9999874
Silt Loam	**BC**	0.478	0.119	4.058E+01	3.774E-01				0.99658	8.19E-03	7.07E-03	1.003456726	1.00E+00	1.00E+00	0.9998182	1.0310643	1.0002497
	VG	0.487	0.126	1.279E-02	1.620E+00	3.826E-01			0.99999	2.74E-04	2.34E-04	0.999949512	1.00E+00	1.00E+00	0.9999750	1.0009995	0.9999755
	FX	0.488	0.125	8.875E+01	9.791E-01	1.408E+00			0.99995	9.59E-04	8.22E-04	1.000036477	1.00E+00	1.00E+00	1.0000078	1.0049229	1.0000190
	DB	0.487	0.126	4.572E-02	2.824E-02	1.601E+00	1.223E-02	1.627E+00	0.99999	2.36E-04	1.57E-04	0.999946486	1.00E+00	1.00E+00	0.9999912	1.0007683	0.9999915
	LN	0.490	0.132	2.067E+02	1.472E+00				0.99912	4.15E-03	3.68E-03	1.00085528	1.00E+00	1.00E+00	1.0002588	1.0249899	1.0005402
	BL	0.487	0.128	9.474E-01	1.877E+02	1.356E+00	5.085E+03	3.961E-01	0.99980	1.99E-03	2.21E-03	1.005567255	1.01E+00	1.01E+00	0.9983601	1.0094703	0.9984010
Clay	**BC**	0.543	0.184	2.085E+02	2.725E-01				0.99844	5.47E-03	4.94E-03	1.001537578	1.54E-03	3.83E-06	0.9999770	1.0155245	1.0000866
	VG	0.548	0.189	2.433E-03	1.554E+00	3.565E-01			0.99999	4.36E-04	3.50E-04	1.000049325	4.93E-05	2.26E-06	0.9999933	1.0011938	0.9999939
	FX	0.549	0.189	3.985E+02	6.462E-01	1.434E+00			0.99998	5.75E-04	4.99E-04	1.0000293	2.93E-05	-3.83E-06	1.0000085	1.0016775	1.0000098
	DB	0.548	0.189	4.423E-02	6.713E-03	1.807E+00	2.233E-03	1.571E+00	0.99999	3.68E-04	3.02E-04	0.9999727	-2.73E-05	4.16E-06	0.9999911	1.0008384	0.9999915
	LN	0.549	0.192	1.065E+03	1.425E+00				0.99980	1.95E-03	1.45E-03	1.000169353	1.69E-04	-4.99E-06	1.0000378	1.0074813	1.0000635
	BL	0.547	0.189	8.965E-01	9.004E+02	1.281E+00	1.070E+04	7.366E-01	0.99998	6.62E-04	5.46E-04	1.000018075	1.81E-05	5.29E-06	0.9999929	1.0015727	0.9999940

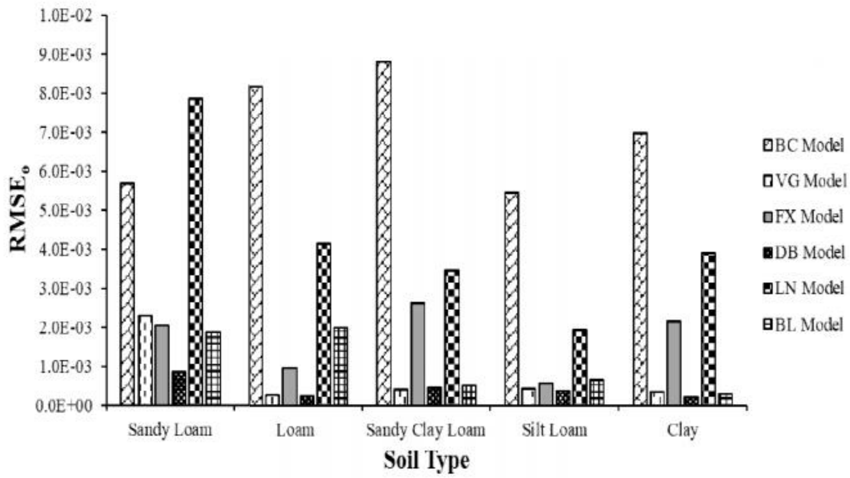


FIGURE 3. RMSE$_\theta$ of the SWCC fitting models

Other quantitative statistical parameters were calculated and analysis of residual errors, differences between measured and fitted values, the results showed in the table (3). The coefficient of determination (CD) [Eq. 14] gives the ratio between the scatter of the fitted values and of the measurements. CD results showed significant values (less 1 and higher than 1) indicated a high significant fitting between measured and fitted values for all soil samples by using six fitting models. Modeling efficiency (EF) [Eq. 15] value compares the predicted values to the averaged measured values. EF gave negative values for all soil samples, negative EF values indicate that the averaged measured values give a better estimate than the fitted values, and positive EF values indicate that the averaged fitted values give a better estimate than the values measured (Khodaverdiloo and Homaee, 2011; Naji, 2014), while Coefficient of residual mass (CRM) [Eq. 16] is a measure of the tendency of the model to overestimate or underestimate the measurements. The negative CRM showed a tendency to overestimate whereas the positive CRM indicate a tendency to underestimate. Error ratio (ε) [Eq. 17] results showed some ε parameter values were less than 1 which indicated the fitted values underestimated, while the values higher than 1 indicated fitted values overestimated. The geometric mean of error ratio (GMER) [Eq. 18] values were less than 1 indicates that the corresponding model overestimates fitted data, in other hand the values higher than 1 indicates that the corresponding model underestimate fitted data. Geometric standard deviation of error ratio (GSDER) [Eq. 19] indicates deviation values of predicted values from measured values, all GSDER values were greater than 1 indicates that the corresponding model overestimates fitted data, table (3).

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