농 학 석 사 학 위 논 문

Estimating soil water retention function from its particle-size distribution

입자 분포를 이용한 토양 수분 보유 곡선의 추정

2013 년 8 월

서울대학교 대학원

농생명공학부 응용생명화학전공

이 태 규

A Thesis for the Degree of MASTER OF SCIENCE

Estimating soil water retention function from its particle-size distribution

Advised by Hee-Myong Ro

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Tae-Kyu Lee

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Abstract

Estimating soil water retention function from its particle-size distribution

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The soil water retention function or soil water retention curve (SWRC), which describes how much volumetric water (θ) is held within the soil at a given suction or matric potential (h), is one of the important hydraulic properties for characterizing and modeling water flow and solute transport in soils. SWRC is difficult to measure directly, i.e., the pressure plate extraction method, because the technique is expensive, time-consuming, and laborious process. Instead, SWRC has been predicted from easily obtainable soil properties. From previous studies, however, there were some limitations such as low predicting power and restricted to apply only sandy soil. In this study, SWRC was estimated from particle-size distribution (PSD) based on similarity of distributional shape with SWRC that van Genuchten suggested. Data for conduct study were selected from the UNSODA, which contain more than five data points and saturated water contents (149 datasets were selected; 103 datasets for calibration and 46 datasets for validation).

Verification was conducted additionally with data from previous studies (Ariana silty clay loam and Yolo loam) and experimentally obtained data (Bancheon silty clay, Upyeong silty clay, Chusan clay loam). From calibration dataset, PSD and SWRC were fitted independently and Pearson product moment correlation coefficients (R^2) of each model were shown 0.987 and 0.965, respectively, which means estimation was appropriate based on the van Genuchten model. Shape-related parameters, m, for cumulative PSD and SWRC were shown nonlinear relationship each other. In contrast, any relationship between inflection points of each cumulative PSD and SWRC could not be found. Alternatively, particle-size and reciprocal of matric head were partial linearly related at the point of 43 % of each normalized cumulative distribution. Root mean square of residuals (RMSR) of predicted SWRC were 0.091 to entire verification dataset, which was highest in sandy clay (RMSR=0.241) and lowest in silty clay loam (RMSR=0.016). Estimated water contents were relatively smaller than actual contents, because the inflection point was predicted higher than ideal value. Although particle-size and reciprocal of matric head were asymmetrically related in each soil, the relationship was shown very different among the soil survey data. Further researches need to be conducted to solve under-estimation by verifying the relationship between particle- and pore-size that could cover overall soil.

Key words : particle-size distribution, pedotransfer function, soil water,

van Genuchten model, water retention function

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1. Introduction

The soil water retention function or soil water retention curve (SWRC), which describes how much volumetric water (θ) is held within the soil at a given suction or matric potential (h), is one of the important hydraulic properties for characterizing and modeling water flow and solute transport in soils (Hwang et al., 2011; Tietje and Tapkenhinrichs, 1993; Wösten and van Genuchten, 1988). The shape of SWRC is influenced by pore-size distribution (POD) which is affected by soil texture and structure, but usually described as continuous sigmoid curve as described in Figure 1 (Hillel, 2003; Lal and Shukla, 2004).

Pressure-plate apparatus have been used as a standard technique for determining soil water retention at an imposed matric potential (Cresswell et al., 2008; Richards, 1986). However, direct determination of the SWRC is costly and time consuming process. In addition, many studies on unsaturated region are deal with spatial variety region, so the direct measurement is hard to conduct (Mohammadi and Vanclooster, 2011; Schaap et al., 2001). As the direct measuring has some difficulties, the SWRC has been frequently estimated from easily measurable physical properties, such as particle-size distribution (PSD) to lend a physical basis to the model that estimates the SWRC (Cornelis et al., 2001; Hwang et al., 2011).

Most approaches that have been empirically or theoretically studied from the measured PSD are regression models, lognormal distribution models, or pore-solid fractal (PSF) models (Hwang et al., 2011; Hwang and Choi, 2006; Kosugi, 1994; Perrier et al., 1999; Schaap et al., 1998). However, the applicability of regression models is limited due to their inherent dependence on reliable regression-based

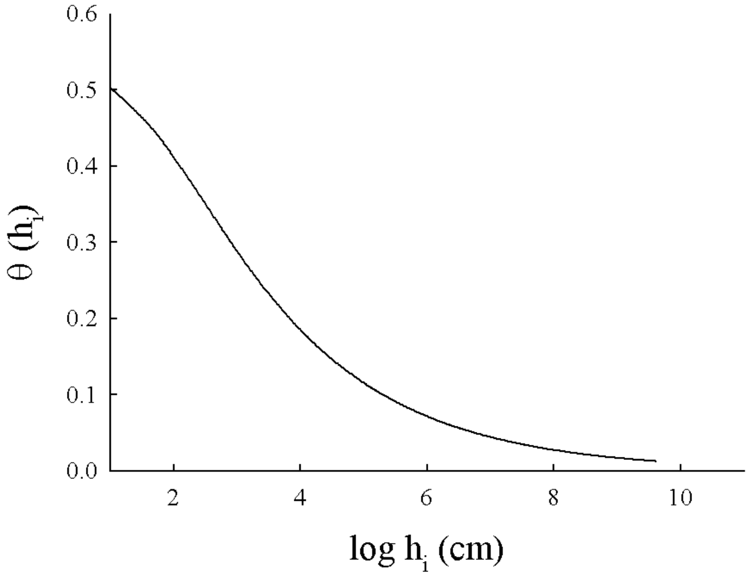


Figure 1. General soil water retention curve

estimates (Tietje and Tapkenhinrichs, 1993).

To overcome such drawback of regression-based model that was formulated based not only on distributional similarity between the SWRC and the PSD, but also symmetrical relationship between the PSD and the POD (Arya and Paris, 1981; Haverkamp and Parlange, 1986). Some approaches adopted an asymmetry between the PSD and the POD, because the pore-size is usually smaller than particle-size. One approach is lognormal distribution model (Hwang and Choi, 2006; Hwang and Powers, 2003; Kosugi, 1996; Rouault and Assouline, 1998). However, this model does not fully reflect the effects of particle packing and shape, and shows relatively low goodness-of-fit (Hwang and Choi, 2006).

Another approach is the PSF model that adopts fractal geometry analysis to the PSD and the POD (Kravchenko and Zhang, 1998). The original PSF models were based on the assumption that both the PSD and the POD follow a power-law function with identical fractal dimensions, assuming that particles and pores should exist at the same size (Bird et al., 2000; Neimark, 1989; Perrier et al., 1999). However, because the original PSF model involves discrepancy at the asymptotic region of near soil saturation, considerable effort has been made to overcome such discrepancy with adopting piecewise approach or asymmetrical relationship between particle- and pore-size. (Hwang et al., 2011; Millán and González-Posada, 2005).

Despite this effort, this drawback is inevitably occurred power-law function like Brooks and Corey (1964) model as well as PSF model (Brooks and Corey 1964; van Genuchten, 1980). Draining water from the POD can be classified into two dimensions; structural pore water flows out above inflection point and textural pore water flows out below inflection point (Dexter, 2004). However, in fractal theory, these two dimensions are not reflected in single power-law function, because the pore arrangement of PSF model is not regarded structural pore or aggregation effect (Hwang et al., 2011). Even if fractal model pretty well fitted at high suction, this weakness makes non-continuous slope of SWRC at low suction and not adaptable to predict hydraulic conductivity (Tietje and Tapkenhinrichs, 1993; van Genuchten, 1980).

In this study, as a part of effort to overcome the limitation, the SWRC model was selected that fully reflects two dimensions of POD irrespectively to texture. Then the SWRC was predicted from cumulative particle-size distribution (cPSD) using van Genuchten (1980) suggested SWRC model based on distributional similarity. Since van Genuchten model is empirical SWRC model, parameters and its physical meaning were derived from PSD. Using measured PSD data from UNSODA, cPSD model was constructed and parameters for SWRC were predicted from cPSD model. The performance was validated using UNSODA, literature data, and experimental data of Korean soils, and the limitations were discussed using various soil textures.

2. Theory

Among the models for predicting the SWRC from the PSD, the asymmetry-based PSF model was found to fit the SWRC fairly well irrespective of soil texture (Hwang et al., 2011). The concept of this model is based on self-similarity between particle-and pore-size distributions that are asymmetrically interrelated. Since this model was theoretically formulated, the physical meaning of the interrelationship can easily derive. Nonetheless, as mentioned above, the asymmetry-based PSF model described that water drainage rapidly decrease at air-entry value, which abrupt (non-derivative) slope change (Brady and Weil, 1999; Kosugi, 1994). Although PSF model fitted well and suggested physical meaning, this major drawback was unacceptable concept. Therefore, there have to examine relationship between particle- and pore-size in new ways.

The most widely used empirical model to predict soil water retention curve is the van Genuchten (vG) model (1980):

$$S_e = [1 + (\alpha h)^{n_h}]^{-m_h} \tag{1}$$

Where h is matric suction (cm), S_e is the normalized volumetric water content, defined as $\frac{\theta-\theta_r}{\theta_s-\theta_r}$, θ is the volumetric water content, θ_s is the saturated water content, θ_r is residual water content, α is a scaling parameter that is inversely proportional to mean pore diameter, and n_h and m_h ($=1-n_h^{-1}$) are functional shape-related parameters (Chiu et al., 2012; Kosugi, 1994; Leij et al., 2005; Mualem, 1976; Schaap and Bouten, 1996; van Genuchten, 1980). Saturated water contents were chosen from the UNSODA and the residual waters were set to zero (Groenevelt and Grant, 2004; Kosugi, 1994; Vanapalli et al., 1998). Curve-fitting parameters for the van Genuchten model represent pore-size distribution of the soil (Schaap and Bouten, 1996).

Kosugi (1994) addressed a concept of inflection point (h_c) to fit the van Genuchten model by differentiating equation 1 twice with respect to h (Kosugi, 1994). This inflection point, however, actually is corresponded to air-entry value (Dexter and Bird, 2001). The inflection point of sigmoidal curve is derived by differentiating equation 1 twice with respect to log h (Dexter and Bird, 2001). The inflection point is

$$h_c = \frac{1}{\alpha}\left(\frac{1}{m_h}\right)^{\frac{1}{n_h}} \quad (2)$$

Substituting equation 2 to α of equation 1, then

$$S_e = [1 + \frac{1}{m_h}\left(\frac{h}{h_c}\right)^{n_h}]^{-m_h} \quad (3)$$

From Kosugi (1994), the van Genuchten model was modified to include air-entry value (VK model). However, the air-entry value was estimated very low in this study (data not shown), it was neglected and equation 3 was used.

In many studies, cPSD models were constructed based on shape similarity with SWRC (Arya and Paris, 1981; Fredlund et al., 2002; Haverkamp and Parlange, 1986). From this approach, the cPSD model was constructed, which is,

$$F_e = [1 + (\alpha p)^{n_p}]^{-m_p} \tag{4}$$

where p is particle-size (cm). From previously suggested by Haverkamp and Parlange (1986), the model was fitted well at coarse texture soil, but it was not good at find texture soil. To overcome this point, the residual term was added. Because the PSD has colloidal fraction, which is not clearly defined the range, is expressed as residual fraction. Consequently, F_e is normalized cPSD fraction, defined as $\frac{F-F_r}{1-F_r}$, and F_r indicates residual fraction.

The other parameters, α, n_p, and m_p are same meaning as parameters of SWRC. Mualem's assumption is also adopted cPSD model, so $m_p = 1 - \frac{1}{n_p}$. In the same manner, cPSD model was differentiated by log p twice, then

$$F_e = [1 + \frac{1}{m_p}\left(\frac{p_c}{p}\right)^{n_p}]^{-m_p} \tag{5}$$

where p_c is inflection point.

3. Materials and methods

3-1. Soil database

The dataset to estimate SWRC was obtained from the Unsaturated Soil Hydraulic Property Database (UNSODA) (Nemes et al., 2001). From 790 datasets, it was selected that containing more than or equal to six point of PSD fraction and drying process of θ-h set each, and saturated water contents. Then the repeated datasets were discarded and finally 149 datasets (103 datasets for calibration and 46 datasets for verification) were selected and it was described in Table 1.

3-2. Calibration procedure

SWRC and cPSD were fitted to experimental data by equation 3 and 5, respectively, to estimate parameters F_r, m_p and p_c for cPSD and m_h and h_c for SWRC using iterative non-linear regression procedure (Wraith and Or, 1998). Saturated water contents was used experimental data and residual water contents was neglected to zero. The goodness-of-fit was examined by square of Pearson product moment correlation coefficient (R^2) and statistically significance was examined by t-test.

The parameter m_h for SWRC was calibrated with m_p for PSD by non-linear regression (Leatherbarrow, 1990).

To fine relationship between p and h, equation 3 and 5 was rearranged. From equation 3,

Table 1. Selected soil datasets from UNSODA.

Texture	Number of soils	Calibration dataset		Verification dataset	
		Number of soils	UNSODA code	Number of soils	UNSODA code
Clay	5	4	2340, 2360, 4680, 4681	1	2362
Silty clay	2	1	2350	1	3030
Sandy clay	2	1	1134	1	1135
Clay loam	4	3	1123, 3031, 3033	1	3032
Silty clay loam	2	1	3212	1	2463
Sandy clay loam	13	8	1092, 1102, 1103, 1113, 1115, 1117, 1132, 3202	15	1104, 1116, 1122, 1133, 2341
Loam	13	8	2321, 2530, 3190, 3191, 3194, 3195, 4710	5	2320, 2531, 3192, 3193, 3221
Silt loam	19	14	2351, 2491, 2493, 3210, 3211, 3220, 3222, 3223, 3224, 3250, 3260, 3261, 3262, 3263, 4040	5	2464, 3213, 3225, 3252, 3264
Sandy loam	14	10	1091, 1101, 1112, 1121, 1130, 1131, 2111, 3200, 3201, 3203	4	1120, 2532, 3180, 3205
Silt	1	1	3214	0	
Loamy sand	24	17	1010, 1011, 1013, 1015, 1051, 1062, 1090, 1111, 2102, 2104, 2110, 3130, 3150, 3152, 3170, 3204, 4011	7	1012, 1143, 2103, 2105, 3131, 3151, 4010
Sand	50	35	1014, 1020, 1050, 1052, 1053, 1060, 1061, 1063, 1070, 1072, 1073, 1074, 1100, 1140, 1141, 1461, 1462, 1464, 1465, 1466, 2100, 2310, 2342, 3080, 3132, 3141, 3172, 3173, 3175, 3206, 4442, 4650, 4660, 4661, 4720	15	1021, 1022, 1023, 1024, 1054, 1071, 1075, 1142, 1463, 1467, 3070, 3162, 3181, 4444, 4651
Total	149	103		46	

$$\mathrm{h} = h_c[m_h(S_e{}^{-\frac{1}{m_h}} - 1)]^{\frac{1}{n_h}} \quad (6)$$

and from equation 5,

$$\mathrm{p} = p_c[m_p(F_e{}^{-\frac{1}{m_p}} - 1)]^{-\frac{1}{n_p}} \quad (7)$$

Because SWRC used in this study is drying process, opposite direction of cumulative function. To make cumulative form, SWRC plot was flipped in the y-axis. However, the relationship between p and h^{-1} was not detected among entire range (data not shown), instead, it was almost linearly related in middle range of distribution nearby median (equivalent point to cumulative fraction at 50 % of cPSD and SWRC each; S_e and F_e are equal to 0.5). So p and h^{-1} in middle range was calibrated by linear regression (Leatherbarrow, 1990). The proportion is denoted as *k*, then from (7) and (8),

$$h_k{}^{-1} = h_c{}^{-1}[m_h(k^{-\frac{1}{m_h}} - 1)]^{-\frac{1}{n_h}} \quad (8)$$

$$\mathrm{p}_k = p_c[m_p(k^{-\frac{1}{m_p}} - 1)]^{-\frac{1}{n_p}} \quad (9)$$

Assuming the two independent values are linearly related at same proportion (*k*), then the equation 9 and 10 are combined described below

$$h_c{}^{-1}[m_h(k^{-\frac{1}{m_h}} - 1)]^{-\frac{1}{n_h}} = \mathrm{a} \times p_c[m_p(k^{-\frac{1}{m_p}} - 1)]^{-\frac{1}{n_p}} \quad (10)$$

where a is coefficient to fitting.

The hierarchy of the parameters (F_r, m_p and p_c for PSD and m_h and h_c for SWRC) were tested by Duncan's multiple range test at 95 % confidence level using SAS 9.3 software (SAS Institute Inc., USA).

3-3. Verification procedure

The verification procedure is same process as the goal of this study. From experimentally obtained PSD data, F_r, m_p and p_c for cPSD was estimated using iterative non-linear regression procedure (Wraith and Or, 1998). With equation 6 and 11, the SWRC model was estimated.

The goodness-of-fit was checked by R^2, root mean squared residual (RMSR), and Akaike's information criterion (AIC; Akaike, 1998).

$$\mathrm{RMSR} = \sqrt{\frac{\sum_{i=1}^{N}\{\theta p(h_i) - \theta(h_i)\}^2}{N}} \tag{11}$$

$$\mathrm{AIC} = \mathrm{N}\log\left[\sum_{i=1}^{N}\{\theta p(h_i) - \theta(h_i)\}^2\right] + 2p \tag{12}$$

where $\theta_p(h_i)$ means predicted water contents from PSD, N is total number of data points, and p is the number of parameters.

Additionally, PSD and water retention data from literature and experimentally measured data were fitted with current method. Ariana silty clay loam and Yolo loam were fitted to verify SWRC prediction (Bird et al., 2000; LaRue et al., 1968). These soils have been used frequently in many studies (Bird et al., 2000; Davidson et al., 1969; LaRue et al., 1968; Lima et al., 1990; Rieu and Sposito 1991).

Experimentally, soil samples were obtained from Pear research station of Rural

Development Administration located Naju, Korea (35°01’27.70’’N, 126°44’53.50’’ E), and Bio Venture Valley of Seoul national University located Suwon, Korea (37°15’57.86’’ N, 126°59’17.57’’ E), and Seoul National University Forest located Gwangyang (35°01’56.41’’ N, 127°36’23.88’’ E), Korea. PSD was analyzed using dry-wet sieving/pipette method (Day, 1986). Particle-size was fractionized with 2, 53, 106, 180, 250, 1000, and 2000 μm. Water retention at given suction was obtained by pressure plate extraction (Richards, 1986). Water contents were obtained at 4, 10, 33, 50, 100, 300, 400, and 700 kPa. The saturated water contents were regarded same with porosity, as particle density with 2.65 Mg m^{-3}.

4. Results

4-1. Calibration results

The calibration results of cPSD and SWRC model were described in the Table 2. As described in table, the goodness-of-fit was high among the entire texture. t-test value of sand were smallest among the texture, because of discrepancy between predicted and measure water contents at the highly dried region. Inflection point of cPSD, p_c, was highest in sand and lowest in silty clay loam, but the variation was also relatively wide especially sand. The model's shape-related parameter, m_p, was high in silt and sand and lowest in clay loam. The values of the other textures were generally increased with coarse fraction increased. The results was contrary to residual fraction, F_r were highest in silty clay and sandy clay and lowest in sand. The inflection points of SWRC, h_c, were very broadly both among entire texture and among data in a texture. It was extremely high in sandy clay and lowest in silt. Like p_c, h_c had also very large variations, there were no significantly different except sandy clay and clay. Additionally, it seems hard to generalize because of low sample number. The examples of fitting results of calibration datasets were shown in Figure 2. In clay, water contents were very high and dried very slowly. In contrast, water dried rapidly at the sand.

Table 2. Calibrated results for cumulative particle-size distribution and soil water retention curve.

Texture	Cumulative PSD					SWRC			
	p_c (cm)	m_p	F_r	R^2	$Pr > \|t\|$[†]	h_c (cm)	m_h	R^2	$Pr > \|t\|$
Clay	0.007b[‡]	0.282fg	0.301b	0.992	0.985	1166.368b	0.091bc	0.995	0.951
	(0.008)[§]	(0.091)	(0.159)	(0.012)	(0.012)	(1058.239)	(0.040)	(0.004)	(0.052)
Silty clay	0.003b	0.575abcd	0.435a	0.999	0.974	191.740c	0.046c	0.966	0.974
	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Sandy clay	0.024ab	0.508cde	0.411a	0.998	0.986	4897.149a	0.105bc	0.942	0.978
	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Clay loam	0.013ab	0.211g	0.081d	0.967	0.963	369.167c	0.090bc	0.986	0.970
	(0.012)	(0.115)	(0.140)	(0.031)	(0.027)	(473.996)	(0.107)	(0.010)	(0.039)
Silty clay loam	0.002b	0.506cde	0.220bc	1.000	0.994	60.069c	0.121bc	0.989	0.997
	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Sandy clay loam	0.026ab	0.569abcd	0.272b	0.996	0.980	104.778c	0.093bc	0.965	0.979
	(0.008)	(0.079)	(0.041)	(0.002)	(0.009)	(190.265)	(0.098)	(0.021)	(0.029)
Loam	0.008b	0.393ef	0.080d	0.999	0.990	69.026c	0.173bc	0.985	0.985
	(0.001)	(0.099)	(0.062)	(0.000)	(0.008)	(48.913)	(0.091)	(0.011)	(0.025)
Silt loam	0.003b	0.441de	0.058d	0.994	0.980	106.799c	0.145bc	0.974	0.994
	(0.001)	(0.083)	(0.062)	(0.008)	(0.021)	(132.685)	(0.135)	(0.040)	(0.010)
Sandy loam	0.019ab	0.553bcd	0.136cd	0.996	0.982	93.798c	0.174bc	0.964	0.969
	(0.009)	(0.077)	(0.050)	(0.003)	(0.010)	(128.767)	(0.157)	(0.030)	(0.040)
Silt	0.002b	0.718a	0.110d	1.000	0.986	14.940c	0.083bc	0.978	0.996
	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Loamy sand	0.023ab	0.627abc	0.075d	0.998	0.990	43.851c	0.317ab	0.971	0.955
	(0.010)	(0.058)	(0.024)	(0.001)	(0.005)	(25.195)	(0.075)	(0.016)	(0.027)
Sand	0.035a	0.709ab	0.039d	0.999	0.993	33.045c	0.474a	0.957	0.905
	(0.018)	(0.073)	(0.024)	(0.002)	(0.006)	(17.685)	(0.048)	(0.044)	(0.075)
Total	0.021	0.573	0.099	0.996	0.987	162.139	0.280	0.968	0.950
	(0.017)	(0.156)	(0.102)	(0.008)	(0.013)	(561.072)	(0.120)	(0.034)	(0.060)

[†]Probability (P-value).

[‡]Means in the same column with different letters represent result of Duncan's multiple range test (p<0.05).

[§]The values in parentheses indicate standard deviations (n=the number of datasets of each texture).

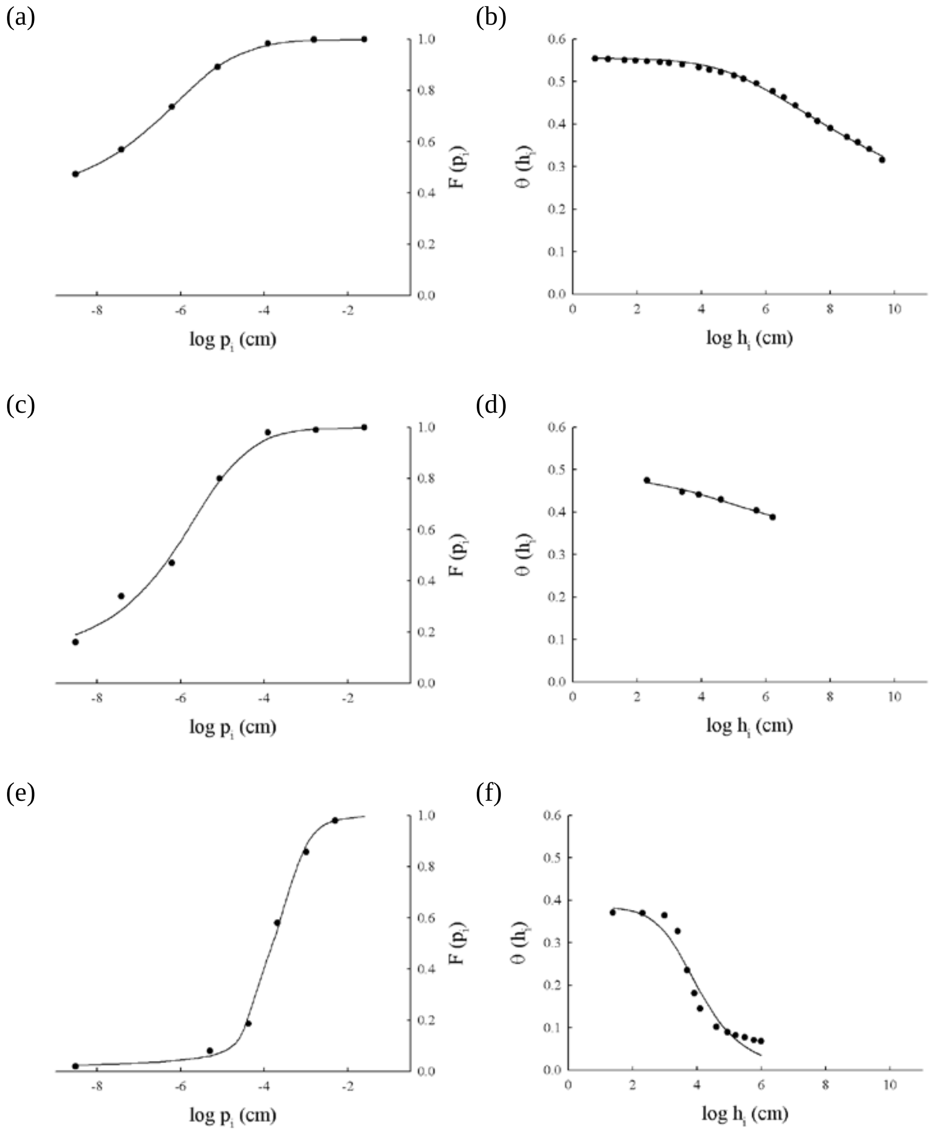


Figure 2. Examples of measured (closed circle) and empirically fitted curve (solid line) of cumulative particle-size distribution (cPSD) model and soil water retention curve (SWRC) model of calibration datasets. (a) cPSD for clay (UNSODA code 4680), (b) SWRC for clay (UNSODA code 4680), (c) cPSD for silt loam (UNSODA code 2351), (d) SWRC for silt loam (UNSODA code 2351), (e) cPSD for sand (UNSODA code 1140) and (f) SWRC for sand (UNSODA code 1140).

4-2. Relationship between parameters for cPSD and for SWRC

The relationship between shape-related parameters, m_p for PSD and m_h for SWRC were found by regression (Figure 3). These two parameters were shown non-linear relationship. At low value of m_p, clayey soil, small pores were dominant and relatively homogenized size. The soil water then gradually dried, so the rate is relatively little changed and m_h was shown also lower value. Meanwhile, in sandy or silty soil, pores are larger than clayey soil so the drying rate is more rapid and m_h increased.

The relationship between inflection point for PSD, p_c, and for SWRC, h_c, were hard to find. The PSD was very steep, while distribution of SWRC was broader than PSD. The cumulative percent until inflection point was 56.8 % for cPSD and 68.6 % for SWRC. The slope change was occurred in distinct region, which make no direct correlation found. Instead, the point with same proportion was regressed to find relationship. If any relationship existed, i.e., symmetry or asymmetry, the trend had to be found all of the range (Arya and Paris, 1981; Haverkamp and Parlange, 1986; Hwang and Powers, 2003; Rouault and Assouline, 1998). At low and high cumulative fraction, particle-size and inversely proportional to matric suction had no relation. In the middle range, it was almost linearly related. The maximum correlation was found and a point that about 43 % of cumulative percent was shown maximum linear relation (Figure 4). Sand and loamy sand was shown high this tendency, while clayey soil was almost no correlation. The regression results of parameters were described in Table 3.

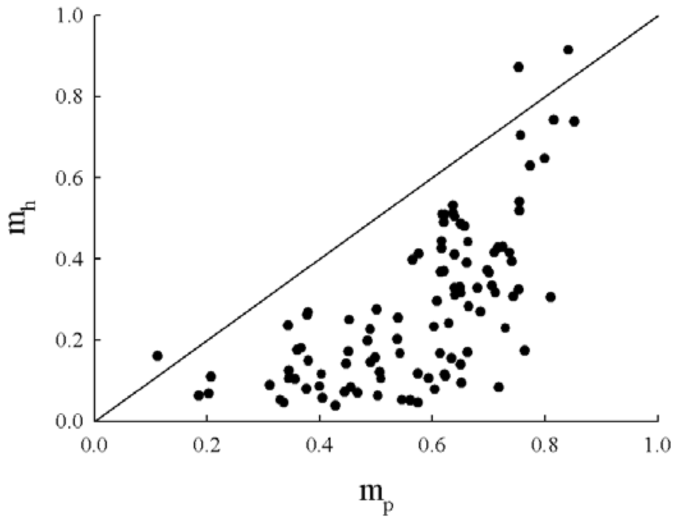


Figure 3. Regression result of shape-related parameter m_p for particle-size distribution and m_h for water retention curve (R^2=0.54).

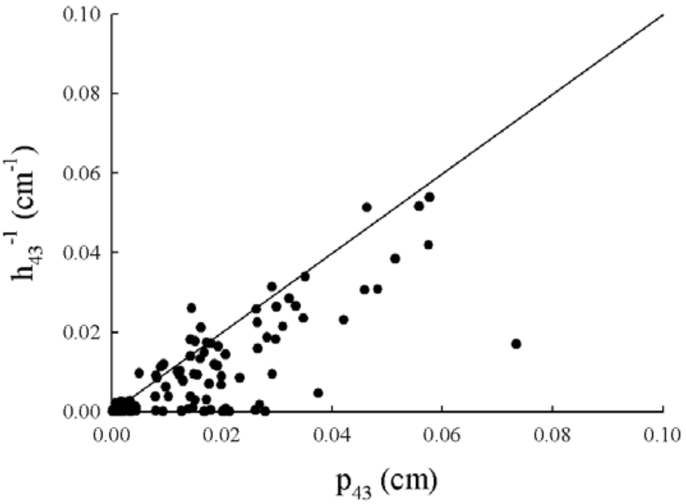


Figure 4. Regression result of relationship between particle size and matric suction (R^2=0.61).

Table 3. Regression results of parameters and its goodness-of-fit.

Object parameter	Regression equation
m_h	$m_h = 1.988{m_p}^2 - 1.251m_p + 0.297$
h_c	$h_c = 1.605{p_c}^{-1}[m_h(0.43^{-\frac{1}{m_h}} - 1)]^{-\frac{1}{n_h}}[m_p(0.43^{-\frac{1}{m_p}} - 1)]^{\frac{1}{n_p}}$

4-3. Validation of SWRC using UNSODA

From PSD data and regression equation described in Table 3, SWRCs were predicted and compared with experimental data. The results of constructed cPSD model are described in Table 4. From UNSODA, the selected dataset satisfied constraint (including over five data points of PSD and SWRC each and saturated water contents) contain one silt soil, so the verification could not be done for silt soil. The results were slightly lower than calibration dataset, but it was also fitted quit well. From fitting results described in Table 4 and predicted parameter using equation described in Table 3, SWRC were validated with observed data (Table 5.) and the examples were illustrated in Figure 5. The results show that both clay and sand soil were fitted quit well, but sandy clay, sandy clay loam, and sandy loam soils were shown worst result among the texture. These textures contain high sand contents, and low clay and silt contents (maximally 41 % and 30 %, respectively). The inflection points were calculated too low suction, so water contents of these soils were highly under-estimated entire drying process. Various particle-sizes with high sand containing soil make pore-sizes quite different to prediction.

Table 4. Fitting results of cumulative particle-size distribution for verification dataset.

Texture	Cumulative PSD				
	p_c (cm)	m_p	F_r	R^2	$Pr > \|t\|$[†]
Clay	0.000 (-)[‡]	0.192 (-)	0.000 (-)	0.998 (-)	0.980 (-)
Silty clay	0.000 (-)	0.380 (-)	0.171 (-)	0.999 (-)	0.982 (-)
Sandy clay	0.027 (-)	0.513 (-)	0.413 (-)	0.997 (-)	0.997 (-)
Clay loam	0.039 (-)	0.121 (-)	0.000 (-)	0.926 (-)	0.981 (-)
Silty clay loam	0.002 (-)	0.253 (-)	0.000 (-)	0.983 (-)	0.931 (-)
Sandy clay loam	0.022 (0.009)	0.521 (0.109)	0.294 (0.022)	0.994 (0.006)	0.981 (0.010)
Loam	0.007 (0.001)	0.326 (0.021)	0.043 (0.040)	0.997 (0.003)	0.984 (0.005)
Silt loam	0.002 (0.000)	0.460 (0.142)	0.042 (0.094)	0.993 (0.012)	0.966 (0.049)
Sandy loam	0.016 (0.003)	0.490 (0.102)	0.124 (0.073)	0.996 (0.003)	0.982 (0.009)
Silt	- (-)	- (-)	- (-)	- (-)	- (-)
Loamy sand	0.020 (0.004)	0.635 (0.029)	0.080 (0.023)	0.998 (0.001)	0.991 (0.006)
Sand	0.045 (0.023)	0.722 (0.082)	0.055 (0.036)	0.995 (0.007)	0.994 (0.005)
Total	0.024 (0.022)	0.549 (0.182)	0.095 (0.102)	0.994 (0.012)	0.985 (0.020)

[†]Probability (P-value).

[‡]The values in parenthesis indicate standard deviations (n=the number of datasets of each texture).

Table 5. Verification results of soil water retention curve.

Texture	SWRC		
	R^{2}[†]	RMSR[‡]	AIC[‡]
Clay	0.909 (-)[§]	0.091	-24.969
Silty clay	0.970 (-)	0.118	-15.678
Sandy clay	0.326 (-)	0.241	1.952
Clay loam	0.981 (-)	0.034	-47.086
Silty clay loam	0.988 (-)	0.016	-45.577
Sandy clay loam	0.704 (0.273)	0.160	18.569
Loam	0.909 (0.072)	0.087	-43.026
Silt loam	0.967 (0.015)	0.076	-58.055
Sandy loam	0.852 (0.095)	0.109	-19.861
Silt	-	-	-
Loamy sand	0.953 (0.031)	0.042	-143.778
Sand	0.940 (0.045)	0.054	-93.776
Total	0.897 (0.149)	0.091	850.436

[†]Average values within textural group.
[‡]Calculated within textural group.
[§]The values in parenthesis indicate standard deviations (n=the number of datasets of each texture).

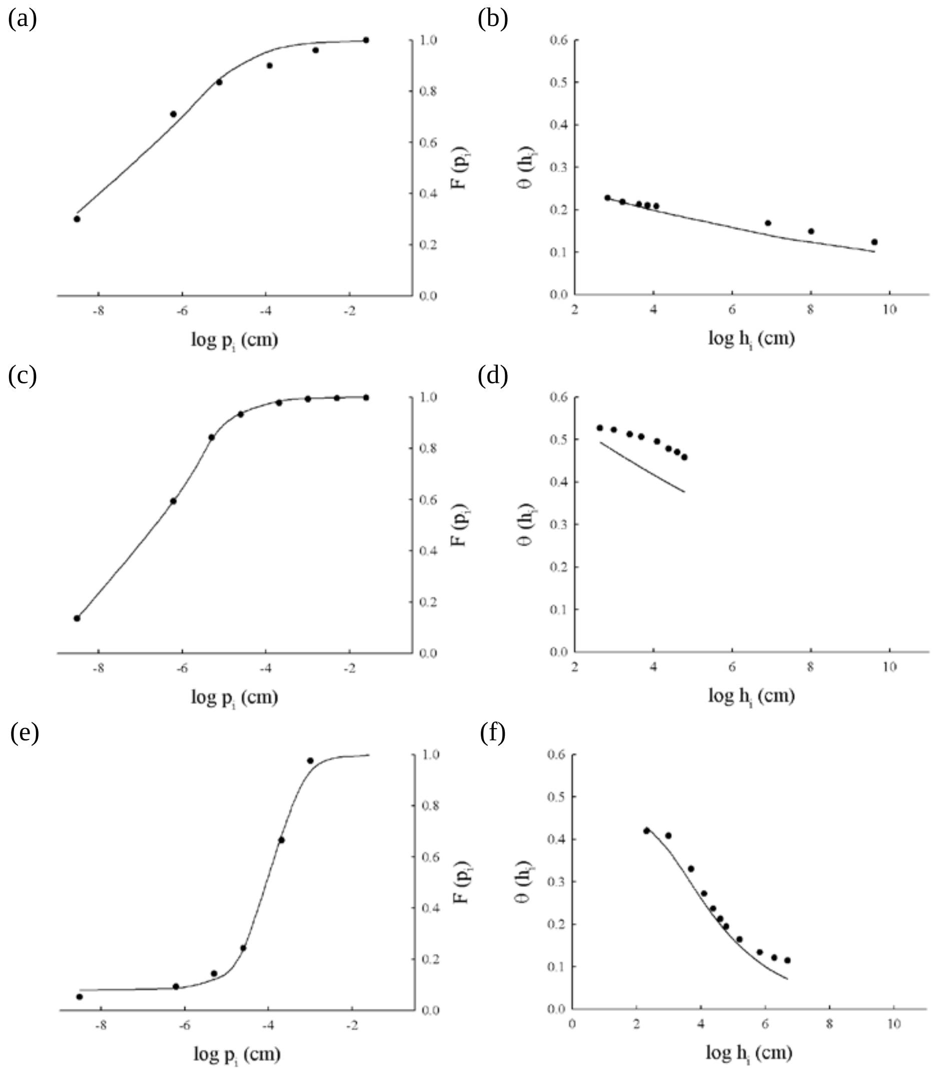


Figure 5. Examples of measured (closed circle) and predicted curve (solid line) of cumulative particle-size distribution (cPSD) model and soil water retention curve (SWRC) model of the UNSODA verification datasets. (a) cPSD for silty clay loam (UNSODA code 2463), (b) SWRC for silty clay loam (UNSODA code 2463), (c) cPSD for silt loam (UNSODA code 3213), (d) SWRC for silt loam (UNSODA code 3213), (e) cPSD for sand (UNSODA code 3151) and (f) SWRC for sand (UNSODA code 3151).

4-4. Validation of SWRC using literature and experiment data

Calibration and Verification was taken using UNSODA, the further verification was taken data from literature (Bird et al., 2000; LaRue et al., 1968). Both UNSODA and literature did not contain Korean soil, it was hard to conclude whether this result is applicable in Korean soil or not. So some Korean soils were tested to possibility. Some characteristics of Korean soil which were used in this study are described in Table 6. In the case of Gwangyang, the bulk density (D_b) was 0.92 Mg m^{-3} actually, to test the effect of D_b, it was also obtained with D_b adjusted to 0.73 Mg m^{-3}. Though collected soils were originally used cultivating or forest, soils were collected slightly deeper depth, so the organic matter contents were low.

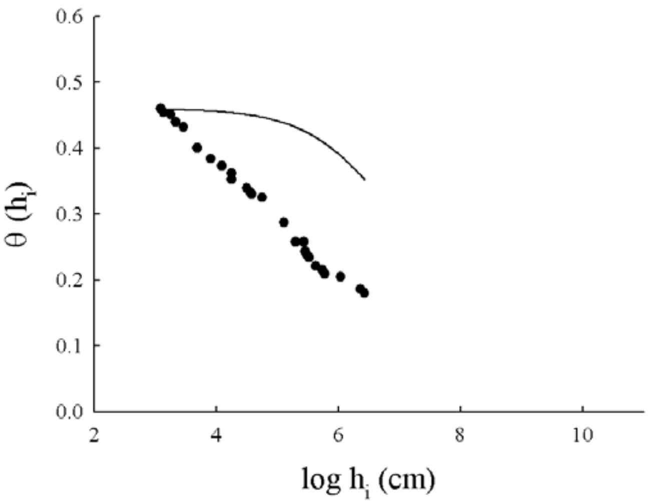
The fitting results of Ariana silty loam and Yolo loam were illustrated in Figure 6. Neither soils were not fitted well, because of too high suction of predicted inflection points. The inflection points were over-estimated, so the predicted water contents were higher than actual contents.

The fitting results of Korean Soil, Naju and and Suwon soil were under estimated, whereas Gwangyang soils were over-estimated both D_b (Figure 7). In the case of Gwangyang soil, the fitting results were better at high D_b than low D_b. The prediction did not regard effect of D_b. the shape of curves was quite well predicted, but as the literature data (Ariana silty clay loam and Yolo loam), the inflection points were wrongly predicted.

Table 6. Characteristics of soil collected from Naju, Suwon, and Gwangyang, Korea.

	Naju	Suwon	Gwangyang	
Soil Series	Bancheon	Upyeong	Chusan	
Land-use type	Pear orchard	Miscanthus cultivating field	Pine forest	
Collected soil depth (cm)	20-30	15-30	10-20	
Organic matter (%)	5.792	3.447	5.248	
Bulk density (D_b, Mg m^{-3})	1.390	1.385	0.92	0.73
Particle-size distribution (PSD)				
Size (cm)	Cumulative fraction			
0.0002	0.457	0.478	0.294	
0.0053	0.960	0.989	0.665	
0.0106	0.963	0.964	0.699	
0.0180	0.967	0.968	0.761	
0.0250	0.973	0.971	0.788	
0.1000	0.994	0.992	0.950	
0.2000	1	1	1	
Water retention				
Pressure (kPa)	Water contents (m^3 m^{-3})			
4	0.537	0.525	0.330	0.271
10	0.462	0.445	0.297	0.244
33	0.410	0.381	0.249	0.206
50	0.376	0.366	0.237	0.197
100	0.356	0.337	0.218	0.175
300	0.304	0.286	0.184	0.134
400	0.293	0.268	0.169	0.126
700	0.282	0.272	0.167	0.114

(a)



(b)

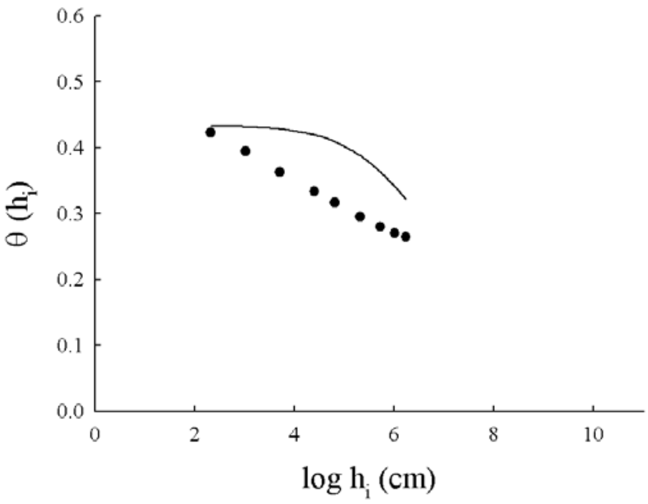


Figure 6. Fitting results of SWRC for (a) Ariana silty clay loam (RMSR=0.136) and (b) Yolo loam (RMSR=0.067). Closed circles indicate measured data and solid lines indicate estimated curve.

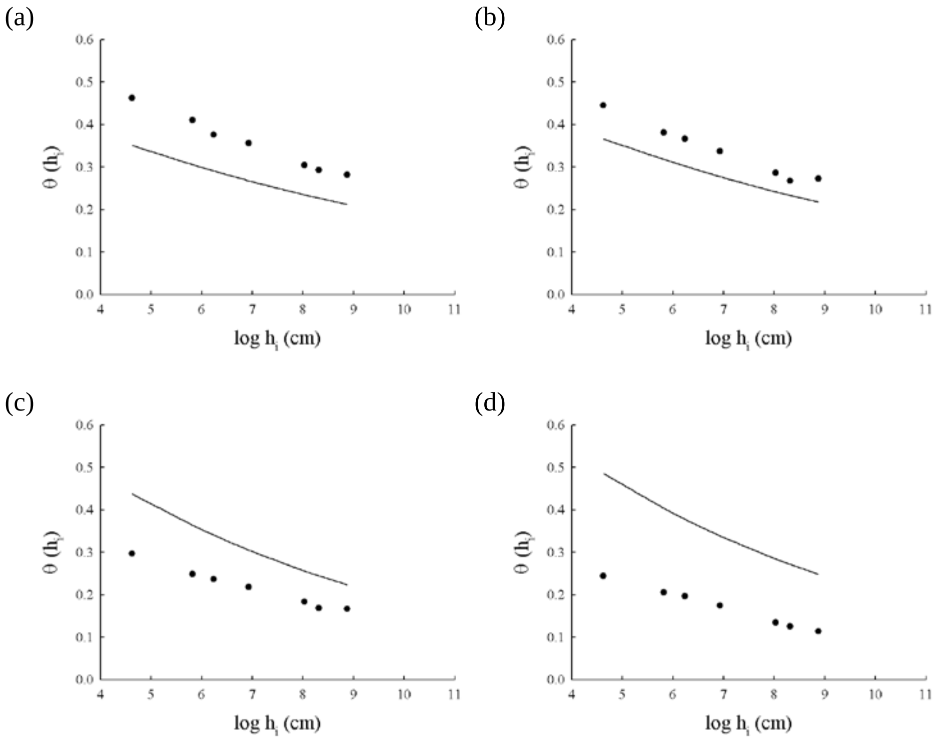


Figure 7. Fitting results of SWRC for (a) Bancheon silty clay (Naju, RMSR=0.081) (b) Upyeong silty clay (Suwon, RMSR=0.055) (c) Chusan clay loam (Gwangyang, D_b=0.92 Mg m^{-3}, RMSR=0.091) and (d) Chusan clay loam (Gwangyang, D_b=0.73 Mg m^{-3}, RMSR=0.166). Closed circles indicate measured data and solid lines indicate estimated curve.

5. Discussions

The cPSD model suggested in this study was suitable for almost every soil data used. The most important term was residual fraction (F_r). As mentioned above, previously suggested model was suitable for sandy soil (Haverkamp and Parlange, 1986; Schaap and Bouten, 1996). This model was limited to express high clay-contained soil. In the dry-wet sieving/pipette method, the clay particles are remained as colloidal fraction of the soil suspension and it takes too long to precipitate (Brady and Weil, 1999; Day, 1986). It makes hard to separate fractions more precisely. The suggested model in current study, which contains F_r, reflected fine-size particle unless it could not separate more precisely. Residual fractions were almost same with clay fractions. As clay fraction increased, the F_r also increased. It makes the curvature of cPSD model moderately, so the m_p also low in clayey soil.

On the other hands, the meaning of residual water contents is not clear, it was treated many ways (Groenevelt and Grant, 2004; Kosugi, 1994; Mohammadi and Meskini-Vishkaee, 2013; Vanapalli et al., 1998). One of the concepts explained that residual water contents are water contents resided as film coated solid phase (Nimmo, 1991). However, any concept describing residual contents have not been demonstrated experimentally (Nimmo, 1991).

Between the clayey soil and sandy soil, the changes of m_h were not linear with changes of m_p. In the SEM images, the clay packing highly affected the porosity (Fiès and Bruand, 1998). The compaction consequently reduce large pore, the capillary water is hard to drying out (Richard et al., 2001). The heterogeneous mixture of particles hold more water than if particles were homogeneously arranged.

At near saturation, the capillary water was held in large number of pores, which was made by various sizes of particles, so the effect of suction was complicated. Meanwhile, at high suction, particle fraction was mixed with colloids that also make the effect distort. In the middle of range, the pore-size distribution was relatively homogenized, so the effect of particle-size was easy to detect than at high or low suction.

From verification of SWRC using the UNSODA, Ariana silty loam, Yolo loam, and Korean soils, the inflection point was most error-occurring parameter. The physical meaning of the 43 % of cumulative distributions was hard to characterize. This middle region, about half of the pores were filled with water, the others were filled with air. At the same time, the fine solid particles affected capillary effects. However, this point was various among the soils, the point was located under inflection point in sandy soil, where it was located very dried region in the clay. Because of this variation, the normalized relationship between particle-size and matric head among the soil texture was hard to conclude. Alternatively, the relationship between particle-size (p) and inverse of suction (h^{-1}) in individual code was plotted within the range from 5 % to 95 % of cumulative percent of each model (cPSD and SWRC) at 5 % intervals. As illustrated examples in Figure 8, p and h^{-1} were shown in exponential relationship, as previously suggested (Hwang and Powers, 2003; Rouault and Assouline, 1998). However, the trends were various among the soils, even within the textural class (clays were described as examples in (a) and (b) of Figure 8). It was hard to find generalized relationship between p and h^{-1}, so the inflection point was estimated difficulty and inaccurately. It is also

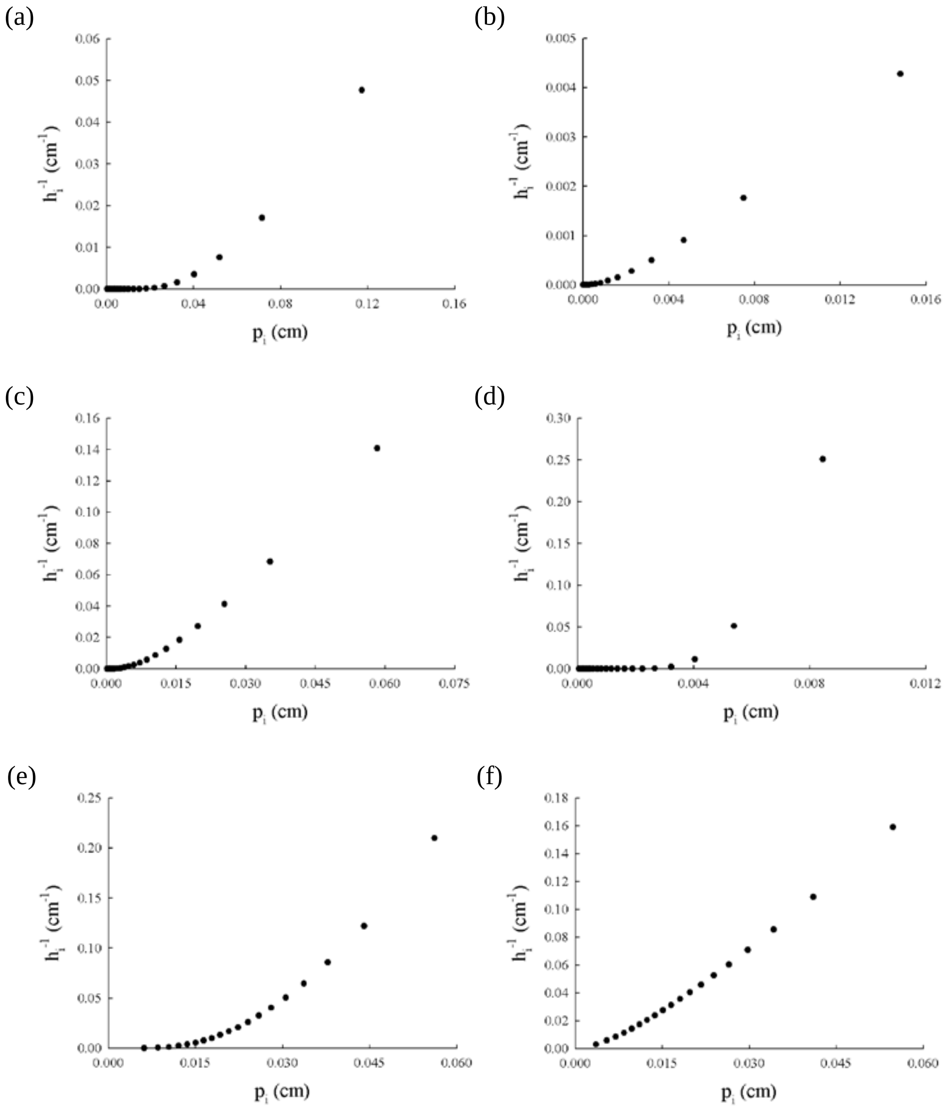


Figure 8. Non-linear relationship between particle-size and matric suction for (a) clay (UNSODA code 2340), (b) clay (UNSODA code 4681), (c) loam (UNSODA code 3190), (d) silt loam (UNSODA code 2493), (e) loamy sand (UNSODA code 3130) and (f) sand (UNSODA code 4720).

caused by fundamental drawback that any universally applicable theory describing matric suction versus water contents exist (Hillel, 2003). It is likely to be carried out clarifying pore-size distributions experimentally such as mercury intrusion or SEM technique (Klock et al., 1969; Fiès and Bruand, 1998). In addition, the entire verification datasets were used with ignoring whether the soil samples were disturbed or undisturbed, the soil structure effects were not considered. It could also affect the mistaken prediction. In drying process of water retention, the water flows out is mainly occurred by structural pore until drying reached inflection point (Dexter, 2004). From selected calibration datasets of the UNSODA, almost 90 % of datasets were undisturbed soil. That means predicting process for matric head from particle-size was actually included structural effect. In the case of laboratory measured Korean soil, however, the samples were used with disturbed condition, so the predicting inflection point of SWRC by equation described in Table 3 was error-prone estimation.

6. Conclusions

SWRC of van Genuchten (1980) suggested model was estimated by van Genuchten-like cPSD model suggested current study. The parameters containing similar concept were regressed to find any relationship, and the shape related parameter (m_h) and inflection point (h_c) of SWRC were estimated by that of cPSD model (m_p and p_c each). The estimation was carried out using UNSODA and the performance was checked by UNSODA, Ariana silty clay loam, Yolo loam, and Korean soils (collected from Naju, Suwon, and Gwangyang, Korea).

The results were shown that the shape related parameters were under nonlinear relation and the particle-size and pore-size were partial linearly related. However, the individually fitted results of particle-size and inversely proportion to matric suction showed the nonlinear and soil-dependent relationship. Though the shape of SWRC was predicted well, because the inflection point was predicted inaccurately, SWRC was slightly differed from experimentally observed data. Besides, as mentioned Wösten et al. (2001), model construction has to use reliable and large quantity of data (Wösten et al., 2001). Because of lack of soil data, especially silt, it was hard to generalize to all of the soil. In addition, the relationship between particle- and pore-size distributions and residual water contents should be identified experimentally first. Further studies need to conduct to find the limitation of current study.

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8. 국문초록

토양수분보유곡선은 특정 수두 조건에서의 토양이 보유하는 물의 함량을 나타내는 토양의 물리적 특성이다. 토양수분보유곡선은 토양 수분추출기 (pressure plate extractor)를 이용하여 직접 측정할 수 있으나 비용과 시간, 노동력을 많이 필요로 하여 측정에 어려움이 있어 그 대안으로 보다 쉽게 얻을 수 있는 토양 정보로부터 토양수분보유곡선을 간접적으로 추정하려는 연구가 진행되었다. 하지만 기존 연구에서 비교적 낮은 예측력을 보이거나 모래 토양 (sandy soil)을 대상으로 하는 등 단점들이 존재하여 본 연구에서는 이를 보완해 예측력을 높이고자 새로운 입자분포모델을 세우고 이를 이용해 토양수분보유곡선을 추정하였다. 본 연구에서는 입자의 분포가 van Genuchten (1980)이 제시한 토양수분보유곡선의 분포와 비슷하다는 가정 하에 새로운 누적 입자분포 모델을 제시하고, 제시된 모델과 토양수분보유곡선의 매개 변수 (parameter)간의 관계식을 도출하였다. 이를 위해 UNSODA의 데이터 중 6 개 이상의 측정값 (data point)과 포화수분함량 (saturated water contents)를 포함하는 149 개를 선정하여 (분포를 추정하기 위한 103 개의 데이터와 수분보유곡선 검정을 위한 46 개의 데이터) 연구를 진행하였으며, 이를 기존 연구의 데이터 (Ariana silty clay loam, Yolo loam)와 실험값 (Bancheon silty clay, Upyeong silty clay, Chusan clay loam)을 이용하여 추가적으로 검정하였다. 그 결과 입자분포와 수분보유곡선을 추정한 결과 R^2이 각각 0.987과

0.965로 나타나 입자분포와 수분함량을 묘사하는데 적합한 모델인 것을 확인하였다. 각 분포의 형태를 결정하는 매개 변수 (m) 간에는 비선형적 (nonlinear)인 관계가 있었다. 하지만 두 분포의 변곡점 (inflection point) 간에 직접적인 관계는 찾을 수 없었고 각 누적분포의 43 %에 해당하는 지점 간에 국소적인 선형관계가 가장 높았다. 이를 토대로 토양수분보유곡선을 추정한 결과 검정 데이터 전체를 대상으로 오차 (Root mean square of residuals, RMSR)가 0.091 였는데 사질식토 (Sandy clay)에서 0.241로 가장 높았고 미사질식양토 (Silty clay loam)에서 0.016으로 가장 낮아 기존 연구보다 비교적 높은 예측력을 보이는 것으로 확인할 수 있었다. 하지만 추정값은 측정값보다 다소 낮게 예측되는 경향성이 나타났는데, 이는 변곡점에서의 수두가 실제보다 높게 예측된 결과로 보인다. 개별 토양별로 입자의 크기와 수리수두의 관계를 분석한 결과, 비선형적인 관계가 있었으나 그 차이가 토양간에 매우 크게 나타나 일반화하기 어려웠으며 이로 인해 변곡점을 추정하는데 오차가 발생한 것으로 생각된다. 이 관계를 더 명확히해야 추정의 정확성을 높일 수 있을 것으로 보인다.

주요어 : 토양입자분포, 토양특성식, 토양 수분, van Genuchten 모델,

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