Selecting the Best Soil Particle-Size Distribution Model for Korean Soils

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요 약

입도분포는 토양의 수리특성을 추정하는 데 많이 사용되고 있다. 본 연구는 다양한 가정조건을 가진 9개의 입도분포모형을 가지고 한국토양을 대상으로 어떤 모형이 가장 잘 입도분포를 모사하는지를 조사하였다. 4개의 추정변수를 가진 Fredlund모형, 로지스틱성장곡선, 그리고 Weibull분포가 다른 모형에 비해 PSD를 잘 모사하였다. 특히 추정변수가 없는 로지스틱성장곡선 함수가 좋은 모사를 나타낸 것이 흥미로웠다.

주제어 : 입도분포, 한국토양, 토양수리특성

Abstract

Particle-size distributions (PSDs) are widely used for the estimation of soil hydraulic properties. The objective of this study was to select the best model among the nine PSD models with different underlying assumptions, by using a variety of Korean soils. The Fredlund model with four parameters, the logistic growth curve, and Weibull distribution model showed the highest performance compared to the other models with the majority of soils studied. It was interesting to find that the logistic growth function with no fitting parameters showed a great fitting performance.

Keywords : particle-size distribution, Korean soils, soil hydraulic properties

Ⅰ. INTRODUCTION

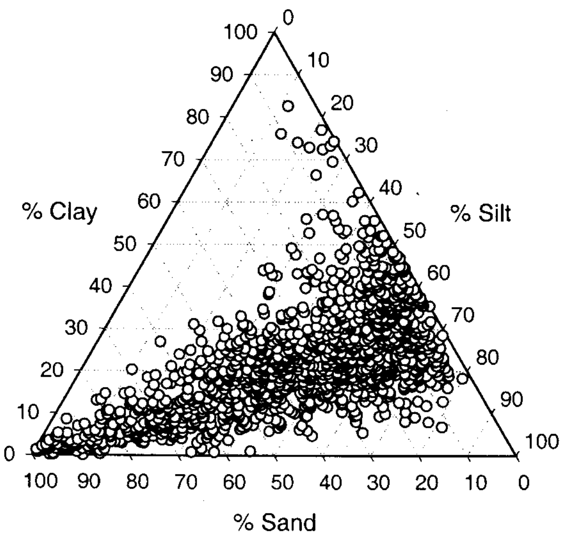
Numerical simulation of transient water flow and contaminant transport in soils offers a powerful and indispensable tool for studying hydrological processes and water-limited ecosystem. Recent advances in the power and accessibility of numerical models have led to the realization that the widespread use of such models in broad-scale land management applications is primarily constrained by the limited availability of the requisite soil hydraulic properties. In particular, direct measurement of the soil hydraulic properties for local- or regional-scale land management can be time-consuming, expensive, and technically demanding. In consequence, traditional soil surveys usually contain scant information on hydraulic properties but often have easily measured particle-size distribution (PSD) data that reflect the spatial variability of soil texture. So, the PSD of a soil has been frequently used as a basis for estimating soil hydraulic properties (Arya and Paris, 1981; Haverkamp and Parlange, 1986; Hwang and Powers, 2003). To describe more completely a sparse experimental PSD data, various parametric PSD models have been proposed (Haverkamp and Parlange, 1986; Buchan et al., 1993; Smettem and Gregory, 1996; Fredlund et al., 2000; Skaggs et al., 2001; Hwang and Powers, 2003). However, little consistency exists among the selection of the PSD models for estimating soil hydraulic properties. Haverkamp and Parlange (1986) and Smettem and Gregory (1996) adopted the van Genuchten (1980) function. Zhuang et al. (2001) adopted two functional relationships, i.e. the van Genuchten (1980) function for sand and loamy sand soils and a logarithm function for other textures, to generate detailed PSD. Schuh et al. (1988) adopted a b-spline interpolation procedure.

Only a few comparative studies of PSD models have been conducted in soil science (e.g. Buchan et al., 1993; Hwang et al., 2002). A limited number of PSD models were compared in Buchan et al. (1993) and Hwang et al. (2002). Buchan et al. (1993) analyzed 71 PSD data sets collected from two regions of New Zealand. Their comparison was limited to the lognormal models. Hwang et al. (2002) compared the capability of seven PSD models to fit experimental PSD data. Seven models used in their work have three different underlying assumptions for the PSD, i.e., lognormal distribution, Gompertz curve (a special case of the more general logistic curve), and the water retention curve developed by Fredlund and Xing (1994). They found that the Fredlund et al. (2000) model showed the best fitting ability.

Besides seven models studied in Hwang et al. (2002), there have been diverse PSD models with different underlying assumption, which have been used in soil literatures. This work is an extension of that of Hwang et al. (2002). The objectives of this work are to test diverse PSD models that have not yet been studied intensively and to determine which model best represents Korean soil PSDs.

II. RESEARCH METHODS

The Korean soil physical database contains data from 1,387 soil layers representing about 378 soil profiles. The data have been published by the Rural Development Administration (1971, 1975, 1977a, 1977b, 1980) of South Korea and are available in Microsoft Excel worksheet file format. Textural composition of the Korean soils is similar to the UNSODA database (Fig. 1; Leij et al., 1999) and that of the Netherlands (Nemes et al., 1999). Detailed description of the database is provided by Hwang et al. (2002).



<Figure 1> Textural composition of the Korean soil data set

Herein, in addition to the Fredlund model which showed the best performance in the work of Hwang et al. (2002), eight PSD models with different number of fitting parameter were tested. Nine PSD models used in this work are listed in Table 1. The Skaggs (S-1 and S-2) models are based on the assumption that the soil PSD follows the logarithmic growth function. The S-2 model has two fitting parameters, but the S-1 model has no fitting parameter because they are calculated from three fractions (i.e., clay, silt, and fine plus very fine sand fractions). Fractal model with two parameters (FR, Kravchenko and Zhang, 1998) assumes that the PSD of a soil has fractal characteristic. Logarithm, exponential, log-exponential, and Weibull models assume that the PSD follows the corresponding function. The van Genuchten model is derived from the van Genuchten (1980) function representing water retention characteristics. This approach is based mainly on the similarity between shapes of the PSD and water retention curves.

<Table 1> Particle-size distribution models tested in this study

Name	Model*	Parameters
Skaggs-1 (S-1, Skaggs et al., 2001)	$F(r)=\{1+(1/cl-1)\exp[-u(r-1)^c]\}^{-1}$ where $c=-0.609\ln(v/w)$, $u=-v^{2.94}/w^{1.94}$, $v=\ln\left(\frac{(cl+si)^{-1}-1}{cl^{-1}-1}\right)$, $w=\ln\left(\frac{(cl+si+fvfs)^{-1}-1}{cl^{-1}-1}\right)$	None (cl, clay fraction; $fvfs$, fine plus very fine sand fraction; si, silt fraction)
Fractal (FR, Kravchenko and Zhang, 1998)	$F(r)=\exp\left\{\ln c+\left(\frac{3D^2-13D+14}{D^2-5D+4}+1\right)\ln r\right\}$	c, D
Logarithm (L, Zhuang et al., 2001)	$F(d)=a\ln d+b$	a, b
Exponential (E, Giménez et al., 2001)	$F(d)=cd^{-\beta}$	c, β
Log-exponential (LE, Kolev et al., 1996)	$F(d)=A\exp(B\log d)$	A, B
Van Genuchten (VG, Haverkamp and Parlange, 1986)	$F(d)=[1+(d_g/d)^n]^{-m}$, where $m=1-1/n$	dg, n
Skaggs-2 (S-2, Skaggs et al., 2001)	$F(r)=\{1+(1/F(r_0)-1)\exp[-uR^c]\}^{-1}$ where $R=(r-r_0)/r_0$	u, c ($r_o=1$ µm, $F(r_o)$: clay fraction)
Weibull (W, Modified from Assouline et al. (1998))	$F(d)=c+(1-c)\{1-\exp(-aD^b)\}$ where $D=(d-d_{min})/(d_{max}-d_{min})$	a, b, c ($d_{max}=2$ mm, $d_{min}=0.002$ mm)
Fredlund (F, Fredlund et al., 2000)	$F(d)=\frac{1}{\left\{\ln\left[\exp(1)+\left(\frac{a}{d}\right)^n\right]\right\}^m}\left\{1-\left[\frac{\ln\left(1+\frac{d_f}{d}\right)}{\ln\left(1+\frac{d_f}{d_m}\right)}\right]^7\right\}$	a, n, m, df ($d_m=0.0001$ mm)

*d : particle diameter in mm, r : particle radius in mm.

The coefficient of determination (r^2) was used as a relative measure of the goodness-of-fit of the predicted PSD data points to the observed ones for each soil. The higher r^2 value of a model indicates its greater fitting ability. An additional statistic, Akaike's information criterion (AIC; Akaike, 1973) was used to compare the quality of model fits while taking into account for the variable number of parameters in the models. The AIC was defined by

$$AIC = N\ln\left(\sum_{i=0}^{N}(P_i - \overline{P_i})^2\right) + 2p \qquad (1)$$

where N is the number of PSD data points in each soil, P_i and $\overline{P_i}$ denote observed and predicted cumulative mass fractions, respectively, and p is the number of model parameters. A smaller AIC value indicates better performance.

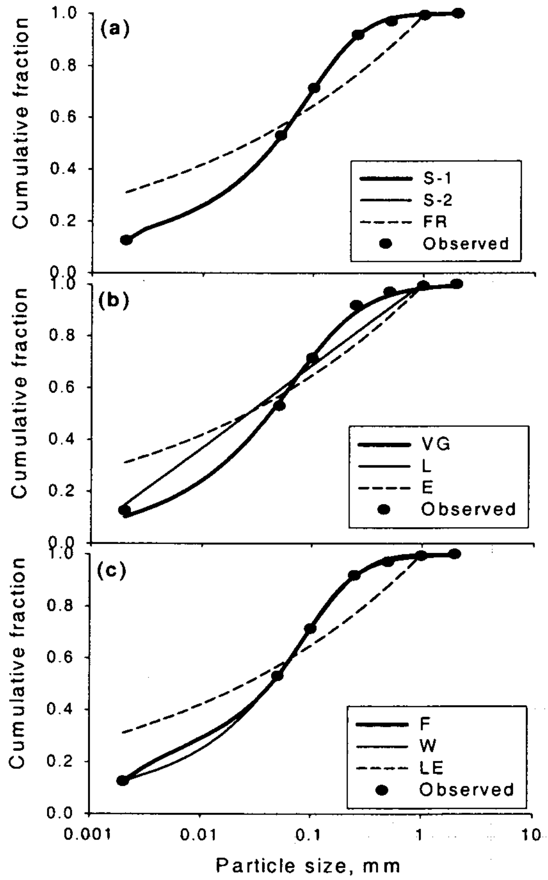
All models were fit to experimental PSD data using an iterative nonlinear regression procedure, which finds the values of the fitting parameters that give the 'best fit' between the model and the data. This procedure was done using the SOLVER routine of Microsoft Excel software.

Ⅲ. RESULTS AND DISCUSSION

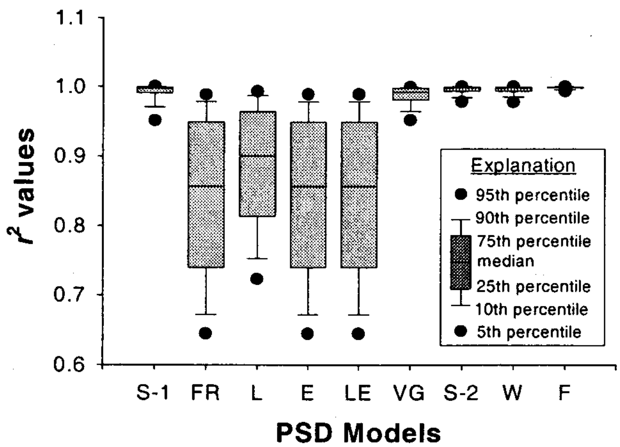
An illustration of the comparative fit of different models for a loam soil is shown in Fig. 2. Note that the shapes of S-1 and S-2 models were too close to be differentiated. The S-1, S-2, VG, W, and F models showed relatively good fitting performance and the FR, E, and LE models showed similar shape and prediction (Fig. 2).

For all of the soils and all of the PSD models, value of r^2 ranged approximately from 0.64 to 1.00 (Fig. 3). Lower values of r^2 were obtained with four two-parameter models (FR, L, E, and LE). This indicates that the PSD of Korean soils did not have fractal characteristic and logarithm, exponential, and log-exponential functions were not appropriate for representing the cumulative PSDs. On the other hand, the W function showed good fitting ability. It was interesting to find that the S-1 model showed great fitting performance although it has no fitting parameter. The two-parameter S-2 model (Skaggs et al., 2001), whose form is similar to a logistic growth curve, showed better fitting ability than the VG model. Its performance was similar to that of the W model with three fitting parameters.

The F model with four parameters had the highest r^2 values because it may have the highest number of fitting parameter among the models studied.

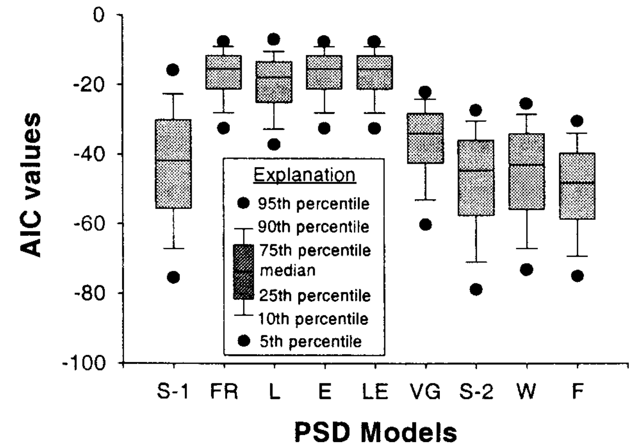


<Figure 2> Comparative fit of nine models for a loam soil(Hak-Seong soil).



<Figure 3> Box plot for r^2 percentiles as the goodness-of-fit of nine models for all soils.

Results of AIC analysis that includes penalty for extra parameters were partly similar to those of r^2 analysis (Fig. 4). Although the F model showed the outstanding fitting ability in r^2 criterion (see Fig. 3), its performance under AIC criterion was not extremely good. This resulted from the characteristic of the AIC criterion that gives more penalties to extra fitting parameters. The S-2 and W models showed comparable performance with the F model.



<Figure 4> Box plot for AIC percentiles as a criterion of the performance of nine models for all soils.

On the basis of the r^2 and AIC tests, the S-2, W, and F models showed better performance with the Korean soils. Interestingly, the S-1 model, the model estimating the continuous PSD using only three mass fractions (i.e., clay, silt, and fine plus very fine sand), showed relatively good performance. The S-1 model can be used as a preliminary evaluation model for a soil if information for the three mass fractions is available in that soil. The S-1 and S-2 models are originated from the generalized logistic model (Skaggs et al., 2001). So, it is thought that the PSD of the Korean soils could be reasonably represented by the Weibull distribution function, the logistic function, and the Fredlund model that is based on the water retention curve.

Ⅳ. CONCLUSIONS

Nine models were compared for the PSD of the Korean soils. The results from r^2 values indicated that the four-parameter F model provided the best fit over all samples, and the S-2 and W models showed higher r^2 values than other models. It is interesting to find that S-1 model with no fitting parameters showed great fitting performance. Based on the AIC with a penalty for additional fitting parameters, the F model performed slightly better than other models for the majority of the soils studied. On the basis of the r^2 and AIC tests, it is thought that the PSD of the Korean soils could be reasonably represented by the Weibull distribution function, the logistic function, and the Fredlund model that is based on the water retention curve.

The results from this work provide a starting point for the selection of soil PSD models for the estimation of soil hydraulic properties of the Korean soils. Other soil databases, such as the UNSODA (Leij et al., 1999), deserve further testing for validating these results more ubiquitously.

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