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論　文
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Estimating the unsaturated hydraulic conductivity of Andisols using the evaporation method

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Abstract: Parameters of the bimodal van Genuchten (VG) hydraulic functions for two aggregated Andisols were inversely determined using the evaporation method. Initial estimates of the water retention parameters were determined from separate retention measurements, which facilitated rapid convergence of the parameter optimization process regardless of the number of optimized parameters. When the bimodal water retention parameters were fixed according to the independently measured retention data from near saturation to very low pressure heads down to -10^5 cm, it was possible to estimate the unsaturated hydraulic conductivity, $K(h)$, by optimizing only two conductivity parameters (K_s, ℓ). Since the flat region of the bimodal retention curve at intermediate pressures is difficult to measure precisely, however, we still recommend optimizing all bimodal VG parameters to yield the best overall results. Including water retention data at very low pressure heads in the dry range extended the applicable range of the model predictions, at least down to pressure heads of approximately -10^4 cm.
Key Words : unsaturated hydraulic conductivity, water retention curve, aggregated soil, Andisol, evaporation method

1. Introduction

Andisols generally are developed from volcanic ash consisting of noncrystalline materials such as allophone, imogolite, Al-humus complexes, and ferrihydrite (Shoji et al., 1993; Nanzyo, 2002). Andisols cover 17 % of the land surface in Japan, where they are widely used for agriculture. Water flow and solute transport processes in Andisols are of considerable interest because of their unique physical and chemical properties. They typically have a very low bulk density and a well-developed aggregated structure. Because of this, Andisols usually exhibit a composite (stepwise) water retention function reflecting distinct but interacting inter-aggregate and intra-aggregate pore regions (Miyamoto et al., 2003).

Several bimodal or multimodal functions have been proposed over the years to account for the additive effects of inter- and intra-aggregate pore regions to the overall soil hydraulic properties (Peters and Klavetter, 1988; Othmer et al., 1991; Gerke and van Genuchten, 1993, Mallants et al., 1997; Mohanty et al., 1997). One frequently used multimodal formulation stems from Durner (1992, 1994) who developed a composite retention function by summing multiple van Genuchten (VG) models (van Genuchten, 1980). The bimodal form of this function has been used in several recent studies (e.g., Coppola, 2000; Peters and Durner, 2008; Schelle et al., 2010), including for the water retention properties of Andisols (Miyamoto et al., 2003; Hamamoto et al., 2009; Chamindu Deepagoda et al., 2012). Most of these studies were concerned with the water retention properties of soils. By comparison, very few studies have applied the bimodal VG model to the unsaturated hydraulic conductivity function of aggregated soils. When used also for the hydraulic conductivity, most applications were concerned with improved descriptions of the unsaturated conductivity function near saturation in attempts to account for the effects of macropores or rock fractures (Peters and Klavetter, 1988; Zurmühl and Durner, 1998; Iden and Durner, 2007; Durner and Iden, 2011).

The bimodal VG model has considerable flexibility in describing the hydraulic properties of aggregated media. Unfortunately, optimization of the large number of parameters in the model against transient flow data (such as from multistep outflow or evaporation methods) is a major challenge. Since several of the hydraulic parameters are often correlated (Zurmühl and Durner, 1998), it is inherently difficult to find the global minimum of the objective function in the optimization process. Zurmühl and Durner (1998) showed that convergence of the parameter optimization process depends very much on the initial estimates of the unknown parameters. In addition to the transient measurements, the objective function could also include independently measured soil water retention or unsaturated hydraulic conductivity data points. Parameter uncertainty

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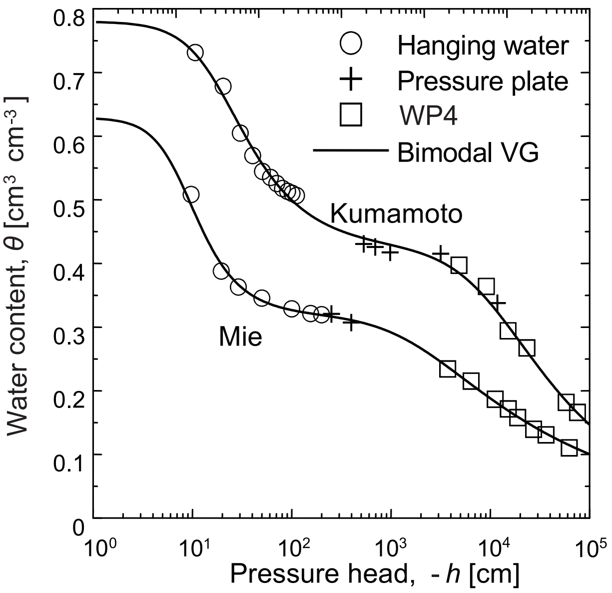

Fig. 1 Water retention curves for the Kumamoto and Mie Andisols fitted with the bimodal VG model (solid line). Retention data were obtained with a hanging water column (open circles), a pressure plate (crosses), and a WP4 dewpoint potentiameter (open squares).

(i.e., the reliable range of the optimized parameter values) generally will be reduced by including independently measured soil hydraulic property data in the objective function, but this may affect the goodness of fit between modeled and experimental data (Šimůnek et al., 1998; Hopmans et al., 2002). More rapid minimization of the objective function may be achieved by using as initial estimates water retention parameters fitted to observed retention data. For example, Spohrer et al. (2006) succeeded in estimating 25 parameters of the bimodal VG model for four soil layers of a tropical Acrisol from transient field data using initial values of the fitted water retention parameters.

When the hydraulic properties are estimated inversely using the evaporation method, the optimized hydraulic functions are generally assumed to be representative only within the range of the tensiometer data. No guarantee exists that the hydraulic functions can be extrapolated beyond the invoked pressure measurement range. Šimůnek et al. (1998) and Hopmans et al. (2002) suggested the applicable range of the model predictions could be extended by including independently measured hydraulic data in the objective function. Sakai and Toride (2007b) estimated the unsaturated conductivity of the model of Fayer and Simmons (1995) for a dune sand, as well as the bimodal VG model for an Andisol, using the evaporation method in combination with water retention data from close to saturation to very dry conditions down to pressure heads of approximately -10^5 cm. They showed that the observed pressure heads agreed well with the model predictions when an appropriate hydraulic function was used to describe the water retention data over a wide range of pressure heads. The validity of the estimated unsaturated hydraulic conductivity beyond the pressure measurement range, however, was not discussed in detail in their study.

The objective of this study was to determine parameters of the bimodal VG model for Andisols over a wide range of pressure heads as determined using the evaporation method. In addition to the pressure heads we also used water retention data in the objective function. The saturated hydraulic conductivity, K_s, and the pore-connectivity factor, ℓ, in the VG hydraulic conductivity function, along with several water retention parameters, were optimized. Different sets of optimizations were conducted by restricting the pressure head range of the water retention and tensiometer measurements in the objective function. We were especially interested in the role of water retention data at very at low (negative) pressure heads in the objective function. We furthermore used the measured pressure head profiles of the samples at the end of the evaporation experiment to confirm the shape of the estimated hydraulic functions beyond the tensiometer measurement range.

2. Material and methods

2.1 Evaporation experiment

For the evaporation experiments we used two different Japanese Andisols collected from the surface horizons of two sites. One set of soil samples was obtained from the NARO Kyushu Okinawa Agricultural Research Center in Kumamoto, and one from the NARO Institute of Vegetable and Tea Science in Mie, Japan. Collected soil samples were sieved using a 2 mm mesh. The disturbed Andisols were packed uniformly in 16-cm long, 3.8-cm diameter acrylic columns to bulk densities, ρ_b, of 0.48 and 0.75 g cm^{-3} for the Kumamoto and Mie soils, respectively. The saturated hydraulic conductivity, K_s, based on the falling head method was estimated to be approximately 200 cm d^{-1} for the Kumamoto Andisol, and 1000 cm d^{-1} for the Mie Andisol. Fig. 1 shows water retention curves as measured using a hanging water column for the pressure head (h) range $-200 < h < -5$ cm, using a pressure plate for $-1.2 \times 10^4 < h < -250$ cm, and a WP4 dew point potentiameter (Decagon Devices, Pullman, WA) based on relative humidity measurements equilibrated with the soil water pressure for the range $-10^5 < h < -3 \times 10^3$ cm. Although WP4 measurements are generally used for pressure heads below -10^4 cm, we applied the WP4 potentiameter to the higher pressure heads up to approximately -3×10^3 cm with considerable care as suggested by Maček et al. (2013). Volumetric water contents for the WP4 measurements were determined from the gravimetric water contents and the bulk density of the soil.

After slowly saturating the soil samples from the bottom, the water supply was closed and evaporation was al-low to start using a fan to blow air away from the soil surface in a 25 °C constant temperature room. Pressure heads were monitored using five tensiometers connected to pressure transducers at 1, 2, 3, 5 and 10 cm depths. Cumulative amounts of evaporation were calculated from measurements of the soil column weights using an electrical balance connected to a data logger. The evaporation experiment for the Mie Andisol continued until the pressure head became less than -600 cm at 1 cm depth. The evaporation period for the Kumomoto Andisol was allowed to continue longer, until the pressure head at 10 cm depth became less than -500 cm. The valves connected to the tensiometers above 10 cm depth were closed at h values of about -500 cm to prevent water leakage from the tensiometer cups (Durner and Or, 2005; Schindler et al., 2010). Volumetric water content profiles at the end of experiments were determined gravimetrically by sectioning the soil columns. Pressure head profiles near the surface at the end of experiments for the Kumamoto Andisol were measured using the WP4 potentiameter.

2.2 Bimodal van Genuchten model

The bimodal water retention (Durner, 1992, 1994) and unsaturated hydraulic conductivity (Priesack and Durner, 2006) functions based on the van Genuchten-Mualem model (van Genuchten, 1980; Mualem, 1976) were used to describe the hydraulic properties of the two Andisols:

$$S = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \sum_{i=1}^{2} w_i S_i \tag{1}$$

where S_i is given by:

$$S_i = \left[1 + (\alpha_i |h|)^{n_i}\right]^{-m_i} \tag{2}$$

$$K(h) = K_s \left(\sum_{i=1}^{2} w_i S_i\right)^{\ell} \times \left\{ \frac{\sum_{i=1}^{2} w_i \alpha_i \left[1 - \left(1 - S_i^{1/m_i}\right)^{m_i}\right]}{\sum_{i=1}^{2} w_i \alpha_i} \right\}^2 \tag{3}$$

The subscript i in these equations represents the number of subregions ($i = 1, 2$ in our application), S_i is effective saturation [$-$] of the i-th subregion, h is the soil water pressure head [L], θ is the volumetric water content [L^{3}L^{-3}], θ_s and θ_r are the saturated and residual water contents [L^{3}L^{-3}], respectively, n_i [-], α_i [L^{-1}], and m_i $(= 1 - 1/n_i)$ are shape parameters subject to $\alpha_i > 0$ and $n_i > 1$, w_1 and w_2 are the weighing factors subject to $0 < w_i < 1$ and $w_1 + w_2 = 1$, K is the hydraulic conductivity [LT^{-1}], K_s is the saturated hydraulic conductivity [LT^{-1}], and ℓ is a pore-connectivity coefficient [-]. The S_1 variable (subject to $\alpha_1 > \alpha_2$) is associated with the first subregion of $\theta(h)$ at the higher water contents, while S_2 corresponds to the second subregion at the lower water contents. The hydraulic functions given by Eqs. (1) to (3) are further referred to here as the bimodal VG model. Note that the hydraulic functions contain a total of nine parameters. Seven of these parameters (θ_s, θ_r, α_1, n_1, w_2, α_2, n_2) relate primarily to the water retention curve, and two additional parameters (K_s, ℓ) to the unsaturated hydraulic conductivity function.

2.3 Parameter optimization

Parameters of the bimodal VG model for our two Andisols were optimized using version 4.08 of the HYDRUS-1D software package (http://www.pc-progress.com/en/Default.aspx?hydrus-1d) of Šimůnek et al. (2008). The calculations assumed applicability of the Richards equation to one-dimensional vertical water flow under isothermal condition as follows:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z} + K(h)\right) \tag{4}$$

where z is the vertical coordinate [L] positive upward, and t is time [T].

The initial and boundary conditions for the evaporation experiment are given by (e.g., Šimůnek et al., 1998):

$$h(z,0) = h_i(z) \tag{5}$$

$$-K(h)\left(\frac{\partial h}{\partial z} + 1\right) = q_{\mathrm{evap}}(L,t) \tag{6}$$

$$q(0,t) = -K(h)\left(\frac{\partial h}{\partial z} + 1\right) = 0 \tag{7}$$

where $h_i(z)$ is the initial pressure head [L] distribution in the column, $q_{\mathrm{evap}}(t)$ is the time-variable evaporation rate [LT^{-1}] at the soil surface, and L is the z coordinate of the soil surface [L]. The initial condition, $h_i(z)$, was linearly interpolated using the initial tensiometer readings, while $q_{\mathrm{evap}}(t)$ was described with a polynomial function fitted to the observed evaporation rate as shown in Fig. 2. A no-flow boundary condition was imposed at the bottom boundary. We note that vapor flow was not included in the flow model, thus assuming that the effects of vapor flow

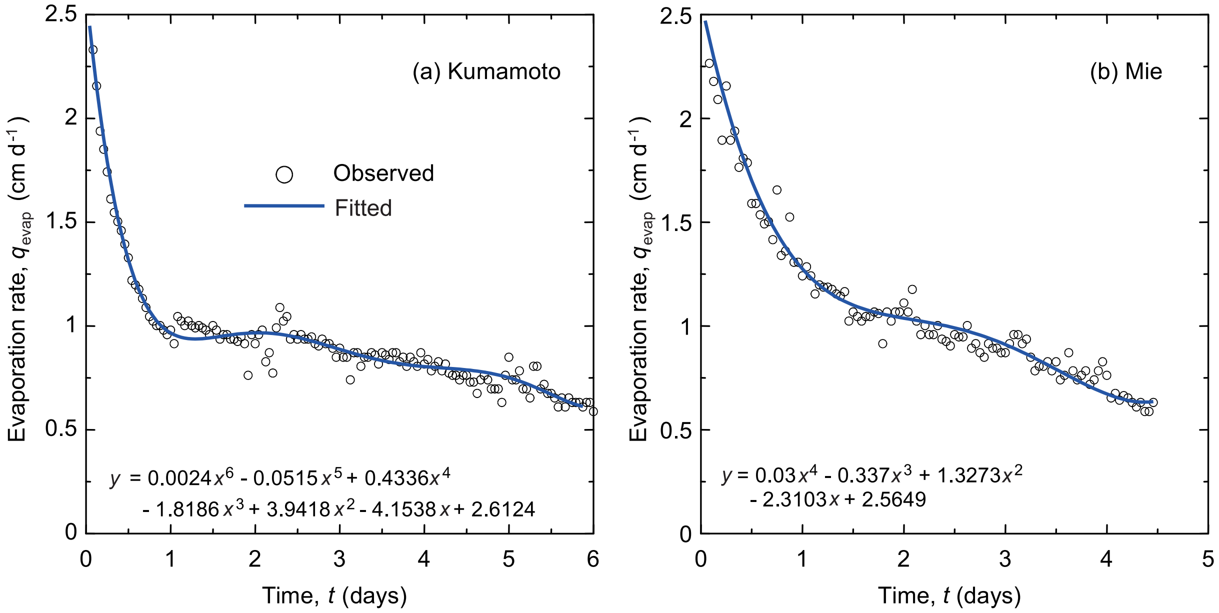

Fig. 2 Evaporation rate from the surface of the Kumamoto (a) and Mie (b) Andisol soils samples. Sown are the observed evaporation rate data (open circles) and the fitted polynomial equation (solid line).

on the parameter optimization process using the evaporation method can be neglected (Sakai and Toride, 2007b).

The objective function, Φ, to be minimized during the parameter estimation process consisted of pressure heads measured at several depths as well as the independently measured water retention data shown in Fig. 1 (Hopmans et al., 2002; Šimůnek et al., 2008):

$$\begin{aligned}\Phi &= v_\mathrm{h} \sum_{i=1}^{n_\mathrm{h}} \left[h_\mathrm{obs}(t_i) - h_\mathrm{fit}(t_i)\right]^2 \\ &+ v_\theta \sum_{i=1}^{n_\theta} \left[\theta_\mathrm{obs}(h_i) - \theta_\mathrm{fit}(h_i)\right]^2\end{aligned} \tag{8}$$

where n_h and n_θ are the number of observed pressure heads (in the column) and independently measured water retention data, respectively, $v_\mathrm{h} = 1/(n_\mathrm{h}\sigma_\mathrm{h}^2)$ and $v_\theta = 1/(n_\theta\sigma_\theta^2)$ are weights for each data type (in which σ is the variance of the observed data), while the subscripts obs and fit indicate observed and model fitted values, respectively, at time t_i.

Šimůnek et al. (1998) recommended including the final water content of the evaporation experiment in the objective function in order to anchor the retention curve along the θ axis. Instead of including the final water content in the objective function, we fixed the value of θ_s by applying a mass balance to the column. The value of θ_s was estimated from the final water content of the column and the cumulative amount of evaporation during the evaporation experiment as determined from the loss of weight of the sample after the experiment. Estimates of the remaining water retention parameters (θ_r, α_1, n_1, w_2, α_2, n_2) in Eqs. (1) to (3) were determined first from the observed water retention data in Fig. 1 using version 6.02 of the RETC code (http://www.pc-progress.com/en/Default.aspx?retc) of van Genuchten et al. (1991). In order to reduce the number of optimized parameters, the value of θ_r was assumed to be zero for our two Andisols since we found that optimization of θ_r did not improve the fit of the data in Fig. 1. We similarly found that the restrictions $m_i = 1 - 1/n_i$ in the bimodal VG model did not affect the goodness of fit. Fig. 1 shows excellent visual matches of the bimodal VG soil water retention functions to the data.

Following Spohrer et al. (2006) and Sakai and Toride (2007b), the fitted retention parameter values were used next as initial estimates in the overall optimization of the evaporation experiment. In our study we optimized the hydraulic conductivity parameters K_s and ℓ since these two parameters are generally difficult to measure directly. The initial value for K_s was fixed at the value obtained with the falling head method, while ℓ was initially assumed to be 0.5 as suggested by Mualem (1976). The values of θ_s and K_s in an evaporation experiment may be slightly different from observed static water retention measurements and the falling head method because of entrapped air during saturation or the length of soil column used (Hopmans and Dane, 1986; Dane and Hopmans, 2002; Sakaguchi et al., 2005). The value of K_s can easily change with very small

Table 1 Values of the optimized hydraulic parameters of the bimodal VG model, and their standard errors (SE) and coefficients of variation (CV), obtained with the evaporation method for cases 1, through 7 of the Kumamoto and Mie Andisols.

Case	θ_r	θ_s	α_1	n_1	K_s	ℓ	w_2	α_2	n_2
	(cm^3	cm^{-3})	(cm^{-1})	(-)	(cm d^{-1})	(-)	(-)	(cm^{-1})	(-)
Kumamoto									
initial	0	0.78	0.057	1.88	200	0.5	0.544	0.00011	1.44
1	-	-	-	-	703	0.751	-	-	-
SE	-	-	-	-	11	0.107	-	-	-
CV	-	-	-	-	0.016	0.142	-	-	
2	-	-	0.045	1.92	312	0.054	0.544	-	-
SE	-	-	0.001	0.03	26	0.022	0.003	-	-
CV	-	-	0.022	0.015	0.083	0.418	0.005	-	-
3	-	-	0.044	1.96	343	0.436	0.549	0.00013	1.39
SE	-	-	0.001	0.03	32	0.214	0.003	0.00001	0.02
CV			0.023	0.017	0.093	0.492	0.006	0.076	0.011
4	-	-	0.055	1.87	312	0.614	0.541	0.00025	1.55
SE	-	-	0.001	0.04	38	0.231	0.008	0.00006	0.31
CV	-	-	0.018	0.020	0.122	0.377	0.014	0.232	0.203
5	-	-	-	-	971	2.301	-	-	-
SE	-	-	-	-	18	0.227	-	-	-
CV	-	-			0.019	0.099	-	-	-
6	-	-	-	-	208	0.007	-	-	-
SE	-	-	-	-	42	0.016	-	-	-
CV	-	-	-	-	0.202	2.167	-	-	-
7	-	-	-	-	28	0.001	-	-	-
SE	-	-	-	-	6	0.012	-	-	-
CV	-	-	-	-	0.214	15.250	-	-	-
Mie									
initial	0	0.629	0.129	2.41	1000	0.5	0.509	0.00062	1.28
1	-	-	-	-	969	0.040	-	-	-
SE	-	-	-	-	66	0.016	-	-	-
CV	-	-	-	-	0.068	0.389	-	-	-
2	-	-	0.101	4.36	968	0.044	0.532	-	-
SE	-	-	0.002	0.06	50	0.006	0.003	-	-
CV	-	-	0.020	0.013	0.052	0.145	0.005	-	-
3	-	-	0.111	3.57	555	0.011	0.545	0.00125	1.25
SE	-	-	0.002	0.07	34	0.004	0.003	0.00009	0.01
CV	-	-	0.018	0.020	0.061	0.381	0.005	0.072	0.005
4	-	-	0.131	2.42	507	0.330	0.513	0.00072	1.74
SE	-	-	0.002	0.04	176	0.608	0.002	0.00004	0.07
CV	-	-	0.015	0.016	0.347	1.844	0.005	0.056	0.043
5	-	-	-	-	850	0.620	-	-	-
SE	-	-	-	-	223	0.378	-	-	-
CV	-	-	-	-	0.262	0.610	-	-	-
6	-	-	-	-	617	0.407	-	-	-
SE	-	-	-	-	39	0.059	-	-	-
CV	-	-	-	-	0.063	0.145	-	-	-
7	-	-	-	-	391	0.018	-	-	-
SE	-	-	-	-	22	0.014	-	-	-
CV	-	-	-	-	0.056	0.765	-	-	-

Note: Entries indicated by- were not included in the optimization but fixed at the initial values

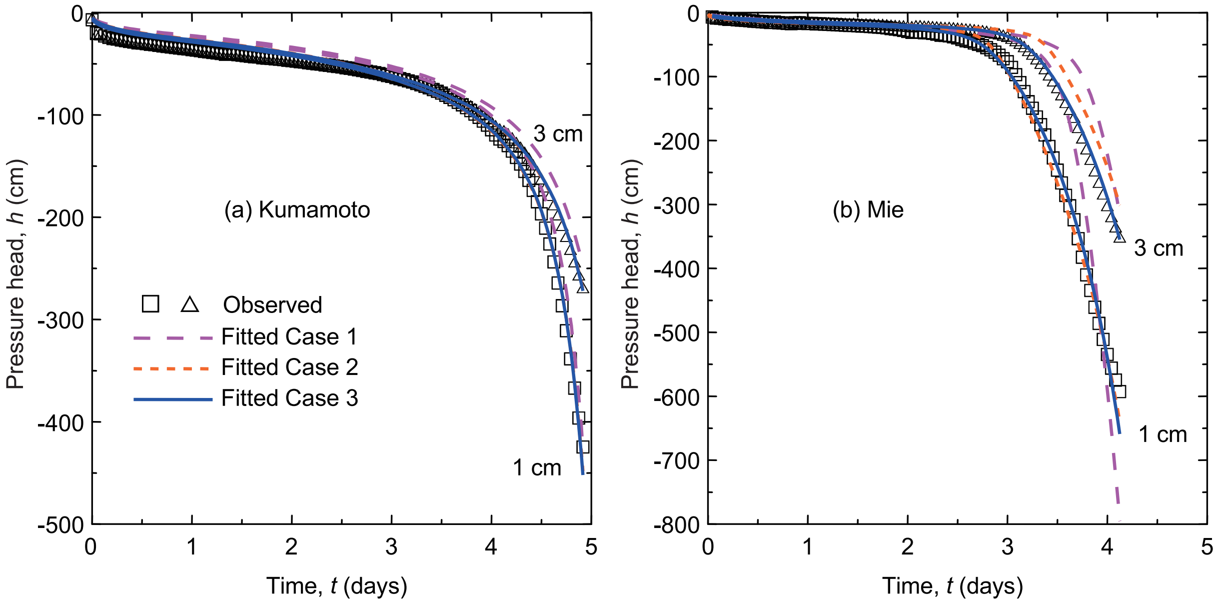

Fig. 3 Observed and fitted pressure heads as a function of time for the Kumamoto (a) and Mie (b) Andisols. Case 1 (long dash line), case 2 (short dash line) and case 3 (solid line).

variations in θ_s. Since Andisols have a large porosity (especially the Kumamoto soil in our study), direct measurement of saturation can be quite vulnerable also to small measurement errors. Since we fixed θ_s based on water mass balances of the sample, K_s is probably best treated as fitting parameter in the evaporation method. Initial values of all of the parameters used in the optimizations for the two Andisols are listed in Table 1.

We optimized the K_s and ℓ values for three cases involving different combinations with the water retention parameters: (1) only two hydraulic conductivity parameters (i.e., K_s, ℓ) while keeping the water retention parameters fixed according to the independently measured water retention functions, (2) adding the water retention parameters of the first subregion (i.e., K_s, ℓ, α_1, n_1, w_2) in the optimization, and (3) further including the retention parameters of the second subregion (i.e., K_s, ℓ, α_1, n_1, w_2, α_2, n_2). The values of θ_s and θ_r (= 0) remained fixed in all optimizations.

3. Results and discussion

3.1 Parameter estimation

In earlier work, Šimůnek et al. (1998) showed that a single set of tensiometer readings near the sample surface was sufficient to yield accurate estimates of the soil hydraulic parameters using the evaporation method. Our experiments confirmed this in that similar results were obtained irrespective of including pressure head data from points deeper in the columns. Sakai and Toride (2007a) found that using pressure heads at two different depths in the objective function produced smaller standard errors for K_s and ℓ than when data from only one depth were used. Since K_s and ℓ were our primary concern, we will show below results when using pressure heads at 1 and 3 cm depths in the objective function given by Eq. (8). Still, obtaining additional tensiometer measurements at other depths may well be useful for backup information in case some of tensiometers failed to work properly (Hopmans et al., 2002).

Fig. 3 shows fitted and observed pressure heads as a function of time at the 1 and 3 cm depths for the Kumamoto and Mie Andisols. Estimated water retention and unsaturated hydraulic conductivity functions corresponding to the three optimization cases of our study are shown in Fig. 4. The optimized parameter values and their standard errors, as well as the coefficients of variations (defined as the optimized values divided by the standard errors) for the bimodal VG model are listed in Table 1.

For the Kumamoto Andisol, all three optimization scenarios (i.e., case 1 with (K_s, ℓ) optimized, case 2 with (K_s, ℓ, α_1, n_1, w_2) optimized, and case 3 with (K_s, ℓ, α_1, n_1, w_2, α_2, n_2) optimized) gave almost identical results. All three cases produced excellent agreement with the observed pressure heads at the 1 and 3 cm depths (Fig. 3a). Predicted pressure heads for cases 2 and 3 were almost identical. The three cases also produced close agreement with the observed water retention data (Fig. 4a). In fact, as shown in Fig. 4b, the estimated hydraulic con-

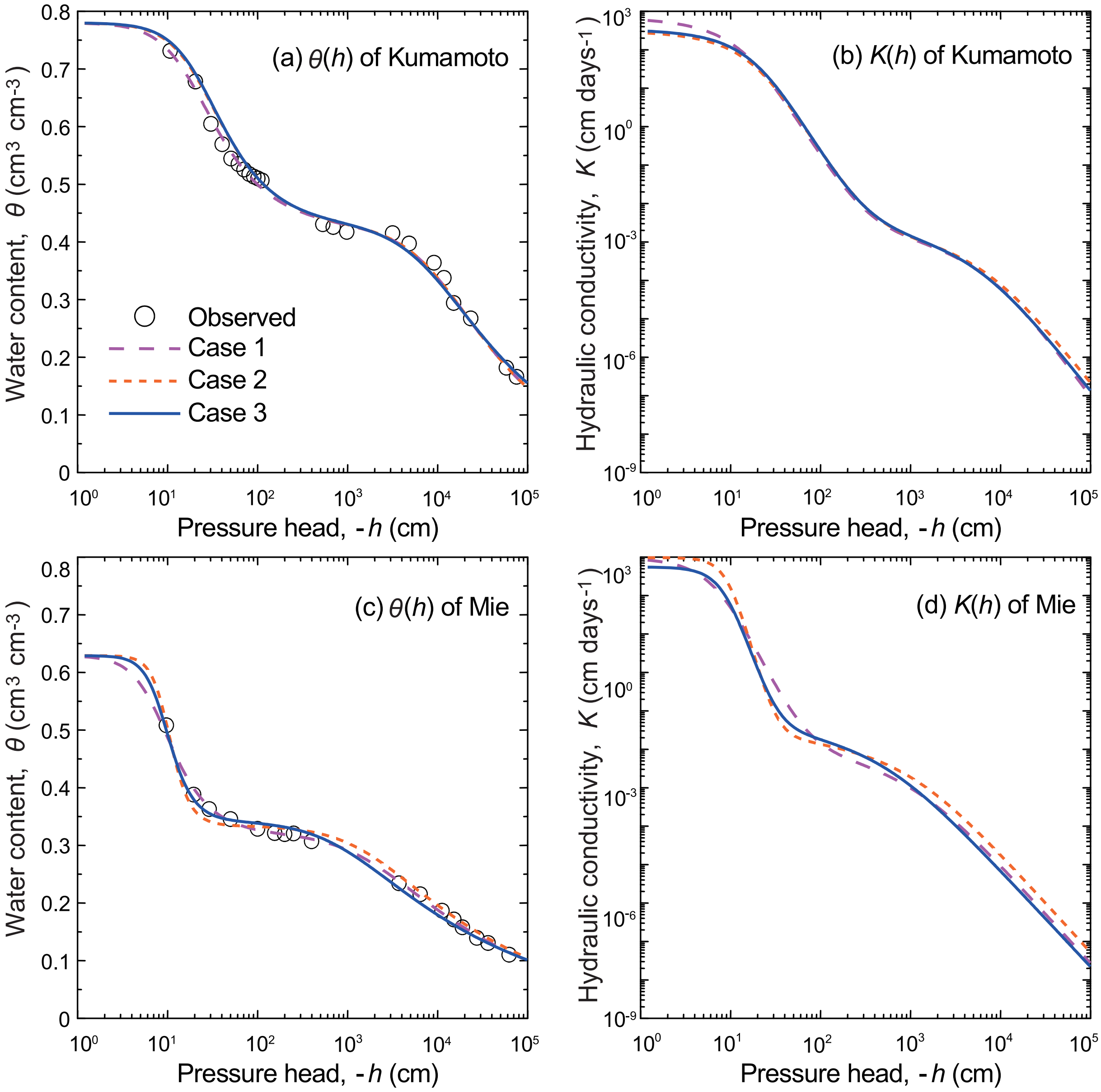

Fig. 4 Estimated water retention (a, c) and unsaturated hydraulic conductivity (b, d) curves for the Kumamoto (top) and Mie (bottom) Andisols: case 1 (long dash lines), case 2 (short dash lines) and case 3 (solid lines).

ductivities were almost identical for all three Kumamoto optimizations. In addition, all of the optimized parameters had small standard errors as reflected by the narrow confidence intervals shown in Table 1. These results suggest that when reliable water retention data are available and used in the objective function, it is possible to predict $K(h)$ by optimizing only the two conductivity parameters (K_s, ℓ). This implies that as long as the water retention parameters can be properly determined using observed water retention data, the number of parameters in Mualem-type soil hydraulic functions, even for the bimodal VG model as given by Eq. (3), should not pose a problem in the optimization.

Results for the Mie Andisol were different. Case 1 for this soil failed to fit the sudden pressure drop at $h = -50$ cm after about 3.5 days in Fig. 3b, with the fitted pressure heads being greater than the observations. Cases 2 and 3 improved the agreement between observed and fitted pressure heads. As the number of optimized parameter increases, the bimodal VG model clearly has more flexibility in fitting the pressure head data. Improved fitting of the pressure head data could be achieved also by sacrificing the close fit of the water retention data. However, compared to the differences between the fitted and observed pressure heads in Fig. 3b, the fitted water retention curves in Fig. 4c were very similar for all three cases. The bimodal water retention curve of Fig. 4c has a relatively flat region between about -50 cm and -10^3 cm. Since the soil water capacity ($d\theta/dh$) is small in that flat region, the abrupt pressure drop below $h = -50$ cm in Fig. 3b should not change the water content very much. This ex-

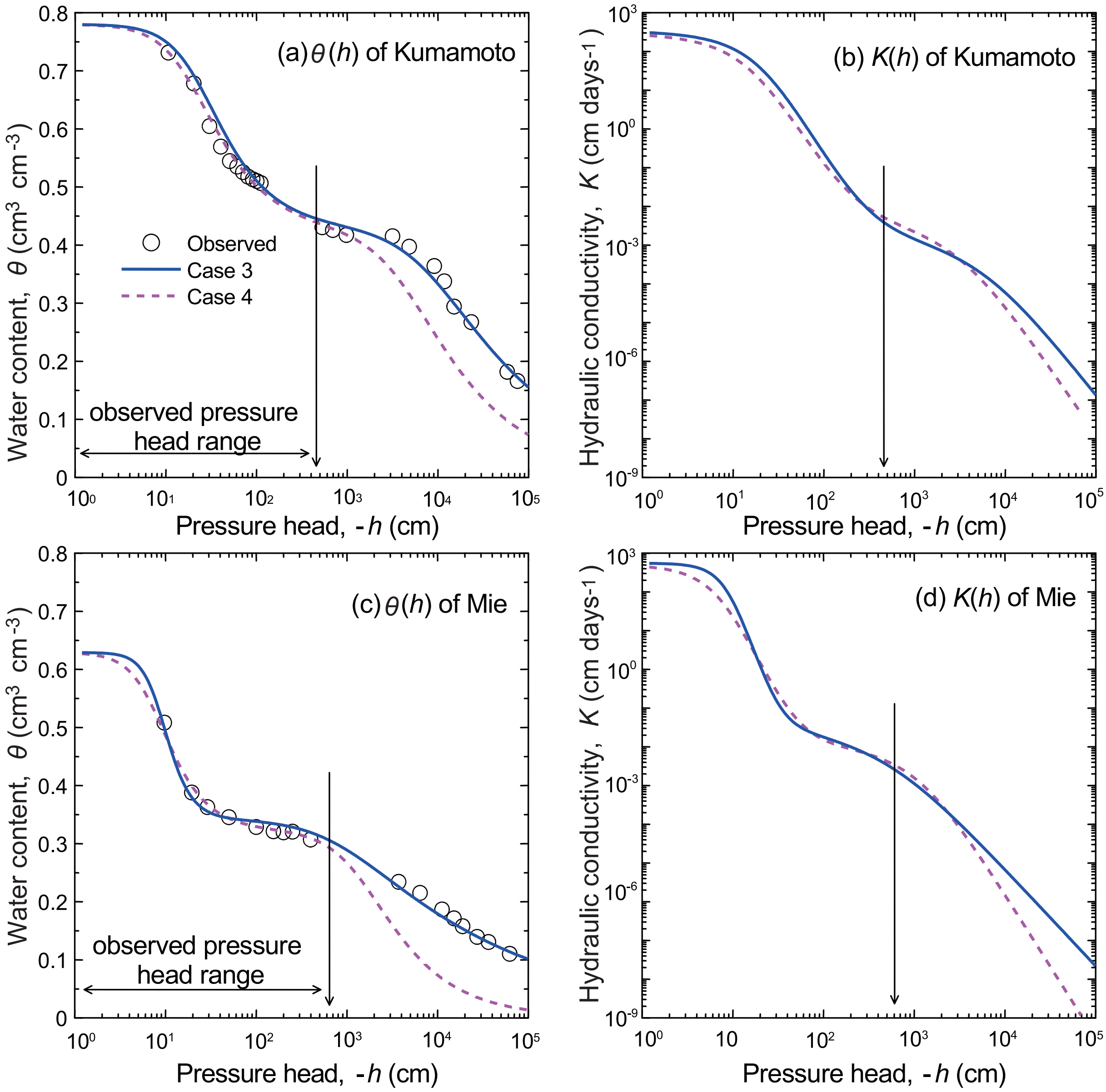

Fig. 5 Estimated water retention (a, c) and unsaturated hydraulic conductivity (b, d) curves for the Kumamoto (top) and Mie (bottom) Andisols. Results were obtained with (solid lines) and without (dashed lines) including water retention data at the low pressure heads in the objective function.

plains why the small change in the water retention curve obtained by additionally optimizing the first subregion retention parameters (α_1, n_1, w_2) still produced a significant improvement in the pressure head simulations. By comparison, the pressure range of the flat region of the Mie Andisol is wider and the soil water capacity smaller than of the Kumamoto Andisol (Fig. 4a versus and 4c). We emphasize that the discrepancies in the pressure head were apparent when optimizing only the conductivity parameters (case 1), and then only for the Mie Andisol, but not for the Kumamoto soil.

We also note that measurements of water retention data in the flat part of the retention function are often subject to errors. It is not easy to precisely determine the water content and pressure head relationships when the soil water capacity is very small. Pressure plates are generally used to measure water retention in this region. Nonequilibrium conditions, poor contact between the soil sample and the plate (Cresswell et al., 2008; Bittelli and Flury, 2009), and hysteresis in the sample preparation often affect the measurements. For this reason it may be better to optimize at least the first subregion parameters (α_1, n_1, w_2) also. But as long as water retention data over a wide range of pressure heads are available and can be used in the objective function, as Durner (1994) also suggested, case 3 optimization should yield the best overall results.

We mention some concern about the value of the pore-connectivity coefficient, ℓ, which is often fixed at 0.5 fol-

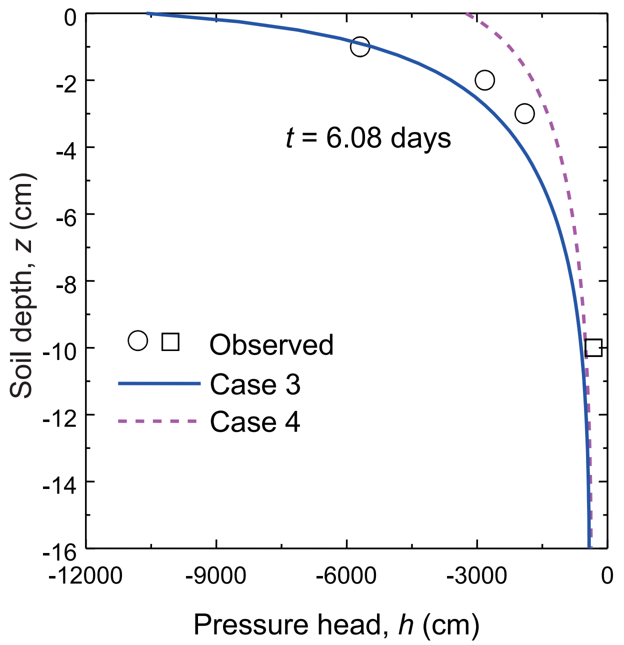

Fig. 6 Observed and predicted pressure head profiles after 6.08 days for the evaporation experiment of the Kumamoto Andisol. Results were obtained with (solid lines, case 3) and without (dashed lines, case 4) including water retention data at the low pressure heads in the objective function. Circles represent WP4 data and the square a tensiometer datum.

lowing Mualem (1976). As pointed out in several studies (e.g., Wösten and van Genuchten, 1988; Kaveh and van Genuchten, 1992; Schaap and Leij, 2000; Spohrer et al., 2006), ℓ can be quite variable depending upon soil type. Using the case 3 optimization, ℓ was found to be 0.436 for the Kumamoto Andisol and 0.011 for the Mie Andisol. More data are clearly needed to obtain a better definition of possible ℓ values for Andisols.

Our parameter optimizations were found to converge quickly, in all cases less than 10 iterations (5, 8 and 8 iterations for cases 1 to 3, respectively, of the Kumamoto Andisol and 8, 9 and 9 iterations for cases 1 to 3 of the Mie Andisol). This included case 3 which had the largest number of optimized parameters. Our results suggests that using water retention parameters fitted to independently observed retention data as initial estimates will facilitate convergence.

3.2 Water retention data at low pressure heads

In addition to the pressure head measurements obtained during the evaporation experiments for $h > -600$ cm, we included in the objective function thus far also all of the independently measured water retention data between -10^5 and -5 cm (Fig. 1). This is to obtain reliable estimates of $K(h)$ in the low pressure head range as recommended by Šimůnek et al. (1998) and Hopmans et al. (2002). To test the need for retention data in the dry range, we compared hydraulic functions optimized with (case 3) and without (case 4) including the independent water retention data at the low pressure heads in the objective function. The optimized conditions for case 4 were the same as for case 3, including the initial estimates, except that case 4 considered only water retention data for $h > -10^3$ cm. The estimated parameter values for case 4 are also listed in Table 1. For both Andisols, good agreement between the observed and fitted pressure heads in the columns was obtained, very similar to case 3 as shown in Fig. 3.

Fig. 5 shows the observed and fitted water retention curves and the estimated unsaturated hydraulic conductivity functions for cases 3 and 4. The observed water retention data in the dry range were severely underestimated using case 4 relative to case 3. Since no information was given for $h < -10^3$ cm for the case 4 optimizations, it is not surprising that this case converged to different values of the second subregion parameter (α_2, n_2). The discrepancies shown in Fig. 5 for case 4 are a reason why optimized hydraulic functions are generally assumed to be reliable only within the range of the tensiometer measurements (Šimůnek et al., 1998; Hopmans et al., 2002). Table 1 shows that most of the standard errors of the estimated parameters for case 3 were smaller than those for case 4, which indicates that including water retention data at the lower pressure heads in the objective function will reduce parameter uncertainty and lead to more reliable parameter values.

Although observed pressure head data over a 5-day period were used for parameter optimization of the Kumamoto Andisol (Fig. 3a), the evaporation experiments continued for 6.08 days until the pressure heads at 10 cm depth reached approximately -500 cm. To confirm the accuracy of the hydraulic properties of cases 3 and 4 for the Kumamoto Andisol, pressure heads were simulated for a longer time period using case 3 and 4 properties. Fig. 6 shows observed WP4 data near the surface with one tensiometer datum at the 10-cm depth, and predicted final pressure head profiles after 6.08 days. The simulation using case 3 parameters agreed well with the observed pressure profile near the surface, whereas the prediction using case 4 parameters overestimated the pressure heads. These

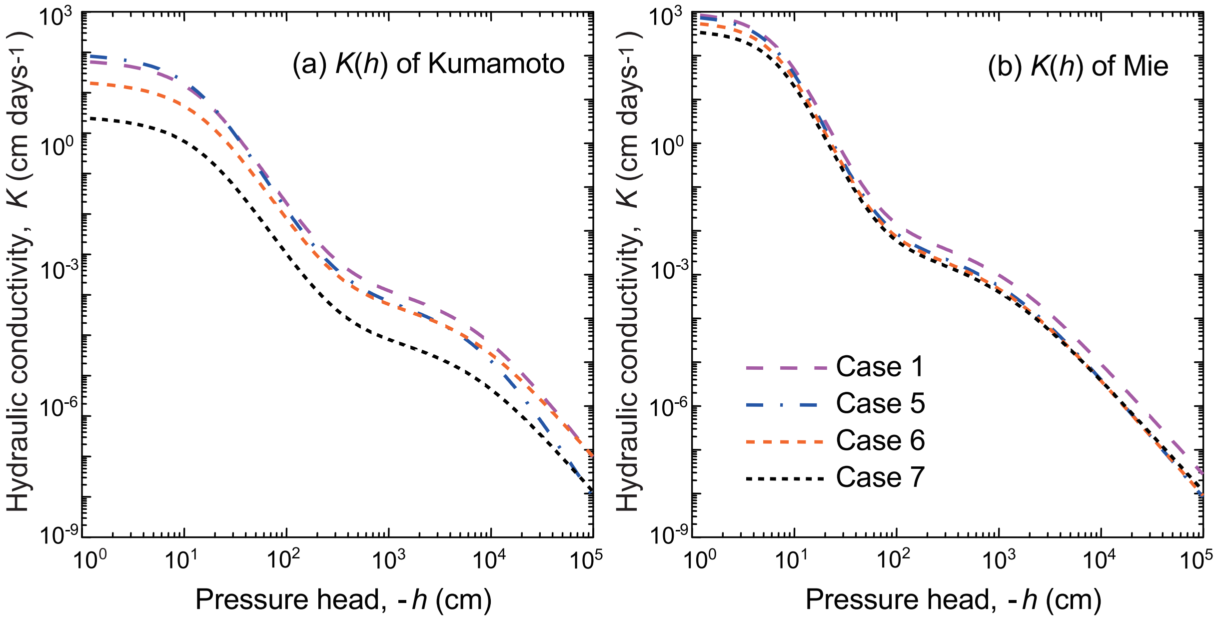

Fig. 7 Impacts of the pressure head range in the objective function on the estimated unsaturated hydraulic conductivity for the Kumamoto (a) and Mie (b) Andisols: case 1 used all data, case 5 only $h > -200$ cm, case 6 only $h > -100$ cm, and case 7 only $h > -50$ cm.

results again indicate that including water retention data at pressure heads below the tensiometer range (about -500 cm) will improve the estimates of the soil hydraulic parameters.

Since water retention at low pressure heads now can be measured relatively easily and accurately using dew point potentiameters (e.g., WP4), we strongly recommended to include in the optimization also water retention data in the measurement range of the dew point potentiameter ($-10^5 < h < -3 \times 10^3$ cm) to extend the applicable range of the model predictions. On the other hand, estimates of the hydraulic conductivity at the very low pressure heads (e.g., $h < -10^4$) may require further investigations because of the possible effects of film flow (Peters and Durner, 2008), diffusion of water vapor (Saito et al., 2006; Peters and Durner, 2010) and the effect of shrinkage (Dorel et al., 2000).

3.3 Pressure head measurement range

We next demonstrate the effect of using different ranges of the pressure head data measured in the columns during the evaporation experiments in the inverse analysis, while fixing in the objective function the bimodal water retention parameters (θ_r, θ_s, α_1, n_1, w_2, α_2, n_2) as determined from the independently measured retention data. These scenarios are the same as case 1 in that only the conductivity parameters (K_s, ℓ) are optimized, except that we used different ranges of the measured pressure heads in the optimizations: only data for which $h > -200$ cm (case 5), $h > -100$ cm (case 6), and $h > -50$ cm (case 7). The estimated parameter values for these three cases (5 to 7) are given in Table 1.

Fig. 7 shows the estimated $K(h)$ plots for the Kumamoto and Mie Andisols obtained with the different pressure head measurement ranges. The conductivity function for case 1 is the same as shown in Fig. 4. Except for the much lower $K(h)$ curve for case 7 of the Kumamoto Andisol, the plots neglecting the lower pressure data did not affect the $K(h)$ results very much; they produced almost identical $K(h)$ curves as for case 1. For the Mie Andisol, even case 7 did give a good estimate of $K(h)$, likely because $h > -50$ cm covered the entire region of the first slope of the water retention curve (Fig. 1). We conclude that independently measured water retention data covering a wide range of pressure heads provide very useful information to the parameter estimation process, leading to a much more robust optimization of the remaining parameters (K_s, ℓ in this case). Note that the standard errors and coefficients of variation have a tendency to increase as the pressure range becomes narrower (Table 1). This means that one should still use all available tensiometer data in the objective function.

4. Conclusions

Parameters of the bimodal VG model for two aggregated Andisols were inversely determined using the evaporation method. Independently measured water retention data from near saturation to very low pressure heads down to -10^5 cm were included in the objective function in addition to soil pressure head data at two depths measured during the evaporation experiments. The saturated hydraulic parameter, K_s, and the pore-connectivity factor, ℓ, along with several sets of water retention parameters were optimized. Since direct θ_s measurements are often quite variable for high-porosity Andisols, the saturated water content was determined from the final water content and the measured cumulative amount of evaporation. When the value of θ_s is fixed from these water mass balance considerations, K_s should be estimated in the evaporation method.

Since the initial estimates of the water retention parameters were determined from the independently measured water retention data, parameter estimation succeeded to converge quickly regardless of the number of optimized parameters. When water retention data from near saturation to very low pressure heads are available and used in the objective function, it is possible to predict $K(h)$ by optimizing only two conductivity parameters (K_s, ℓ). Since the flat region of the bimodal water retention curve is difficult to measure precisely, we recommend optimizing all of the bimodal VG parameters except θ_s and θ_r to yield the best overall fit.

In order to demonstrate the role of water retention data at low pressure heads in the objective function, we compared hydraulic functions optimized with and without water retention data at low pressure heads. Although almost similar matches to observed pressure heads were obtained with or without the low pressure data in the dry range, the second subregion parameter (α_2, n_2) converged to different values if the low pressure data were omitted from the objective function. Predictions based on the hydraulic functions optimized with the low pressure data agreed well with observed pressure heads near the surface after a longer period of evaporation than used for the tensiometer measurements. The results indicate that including water retention data at low pressure heads can extend the applicable range of the model predications, at least down to approximately -10^4 cm.

The benefit of using independently measured water retention data was further studied by including different pressure head measurement ranges in the objective function. Neglecting the lower pressure data did not affect the $K(h)$ estimation process very much, leading to almost similar $K(h)$ functions. This confirms that collecting water retention data over a wide range of pressure heads will give very useful prior information to the parameter estimation process.

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要　　旨

団粒構造を持つ 2 種類の黒ボク土に対して，蒸発法を用いて bimodal van Genuchten（VG）モデルのパラメータを逆解析により決定した．モデルを水分保持曲線の実測値に適合した初期値を用いると，推定パラメータの数にかかわらず収束は速い．また飽和付近から -10^5 cm 程度の低圧力水頭までの実測データに適合した bimodal VG モデルの水分保持曲線のパラメータ値を固定すると，透水係数の 2 個のパラメータ（K_s, ℓ）のみの最適化により不飽和透水係数 $K(h)$ の推定が可能であった．しかし階段状の水分保持曲線の平坦な中間圧力領域における正確な測定は難しいため，結果全体に対する最適な結果を得るために bimodal VG モデルのパラメータはすべて適合することが望ましい．乾燥領域の低圧力領域までの水分保持曲線のデータを目的関数に含めると，モデルの適用範囲は，-10^4 cm 程度まで広がった．

キーワード：不飽和透水係数，水分保持曲線，団粒土，黒ボク土，蒸発法