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An analysis of the influence of shrinkage on water retention characteristics of fen peat-moorsh soil

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The paper presents the results of laboratory- and field-measured soil moisture retention characteristics for different layers in peat-moorsh soil developed from a fen. Field determination was based on the measurements of the moisture content and pressure head values performed on undisturbed soil columns during a drying process. Laboratory measurements were performed with sand table and pressure chambers. In order to obtain moisture retention characteristics related to actual volumetric moisture content, the shrinkage characteristics were measured for different soil layers. The comparison of the laboratory and field measured moisture retention characteristics showed that the results of field measurements were very close to those of laboratory measurements, expressed in terms of fictitious volumetric moisture content. This expression of water content based on initial soil volume provides a better estimation of differential water capacity.

Key words: moisture retention characteristic, shrinkage, fen peat

INTRODUCTION

The soil moisture studies in peat-moorsh soils require the relationship between soil-moisture content and the soil-water matric potential, which is called the moisture retention characteristic or pF curve. The determination of a moisture retention characteristic of peat-moorsh soils results in soil volume changes. During a drying process the shrinkage of peat soils is observed, while during a wetting process the swelling takes place. Therefore, two following types of volumetric moisture content can be calculated (Kim et al. 1993), namely: the actual volumetric moisture content (θ_{AVMC}) and the fictitious volumetric moisture content (θ_{FVMC}). The actual volumetric moisture content, which accounts for the actual changes of soil volume upon deformation, is defined as:

$$\theta_{AVMC} = \frac{\vartheta}{1+e} \quad (1)$$

where ϑ = moisture ratio (volume of water per unit volume of solids) ($m^3\ m^{-3}$), e = void ratio (volume of voids per unit volume of solids) ($m^3\ m^{-3}$).

Fictitious volumetric moisture content is based upon the initial soil volume, regardless of the soil volume changes and is given by:

$$\theta_{FVMC} = \frac{\vartheta}{1+e_s} \quad (2)$$

where ϑ = moisture ratio ($m^3\ m^{-3}$), e_s = saturated void ratio (volume of voids at saturation per unit volume of solids) ($m^3\ m^{-3}$).

The moisture retention characteristic can be determined in the laboratory or in the field. For laboratory measurements undisturbed samples are collected and fully saturated with water then, during the application of different pressure heads, the shrinkage (decrease of the soil volume) of the peat samples is observed. As a result, the following problem arises: which volumetric moisture content should be used for the laboratory-determined soil moisture retention characteristic- θ_{FVMC} or θ_{AVMC}? Field measurements of soil moisture retention characteristics include the soil volume changes due to soil moisture changes.

The purpose of this paper is to compare field and laboratory-measured soil moisture retention characteristics of peat-moorsh soil developed from fen.

MATERIALS AND METHODS

Field and laboratory measurements of soil moisture retention characteristics were performed for a peat-moorsh soil profile located in Biebrza River Valley in Poland. The physical properties of the soil profile are presented in Table 1. From this soil two undisturbed soil columns were collected. A steel cylinder (diameter of 50 cm, length 70 cm), provided with a sharp-edged steel ring at the bottom end, was vertically driven into the soil by means of a hydraulic jack. The surrounding soil was gradually removed, in order to allow the downward movement of the ring. When the cylinder was completely forced into the soil, the monolith was cut off by horizontally driving a sharp-edged steel plate beneath the ring. This plate was then fixed with bolts to a second steel plate put on top of the monolith. This facilitated the insertion of the peat column and cylinder in the supporting column (slightly larger in diameter) which was closed at the bottom (Fig. 1). Such a construction permits feeding of the column by the capillary rise to be cut off. The two columns were installed in the peat-moorsh soil in such a way that the column surface levels corresponded to that of the surrounding buffer area. Grass was grown on the columns and the buffer area. In order to ensure the drying process, the soil columns were protected from rainfall by a mobile roof positioned at a height of 0.7 m above the soil surface.

Each column was equipped with three tensiometers, which were inserted vertically at different depths (Fig. 1). The pressure head readings were taken with a portable Thies-Clima pressure transducer. The water contents were measured by means of the Time Domain Reflectometry (TDR) technique (Topp et al. 1980), using a Tektronix 1502B cable tester. In each soil column, three TDR-probes were inserted horizontally at different depths (Fig. 1). The probes consisted of two parallel rods, 5 mm in diameter and 25 mm apart, 25 cm in length and were inserted into oval shaped holes, which allowed the vertical movement of the probes due to the soil subsidence caused by the shrinkage process. In order to avoid air exposing of TDR probes, caused by horizontal peat shrinkage, the position of probes was adjusted manually by pushing the probes into the soil. The adjustment was performed before each measurement. Soil moisture changes and pressure head

Table 1. Physical properties of fen peat-moorsh soil profile.

Depth (cm)	Ash content (% a.d.m.)	Bulk density ($g\ cm^{-3}$)	Particle density ($g\ cm^{-3}$)	Description
5–10	16.64	0.257	1.655	0–5 turf layer
15–20	13.41	0.238	1.620	5–20 moorsh layer
25–30	13.22	0.198	1.614	20–25 interlayer
35–40	13.68	0.181	1.620	25–35 moss peat
45–50	14.32	0.135	1.626	35–50 sedge peat
55–60	15.48	0.161	1.643	50–70 alder peat
65–70	17.56	0.183	1.667	

changes were measured daily during a drying period of about 70 days. The drying process was chosen for field measurements, in order to avoid hysteresis effect on soil moisture retention characteristics.

From the characteristic soil layers (0–15 cm, 15–25 cm and 25–35 cm), undisturbed samples for laboratory determination of moisture retention characteristics, shrinkage characteristics and calibration of TDR probes were also collected. The calibration was performed due to relatively large differences between TDR calibration curves for organic soils, which are presented in literature (Herkelrath et al. 1991, Pepin et al. 1992, Roth et al. 1992, Myllys & Simojoki 1996).

In the soils, which are changing their geometry due to swelling or the shrinkage process, the moisture content is very often characterised by the moisture ratio (Bronswijk 1988). Therefore the relationship between the apparent dielectric number (K_a) and the moisture ratio (ϑ) for considered peat-moorsh soil was determined empirically in the laboratory on undisturbed soil samples for three layers in two replications. The samples were taken in plastic cylinders with an inner diameter of 25 cm and a height of 10 cm. A TDR probe with two parallel wave-guides, 15 cm in physical length, 5 mm in diameter and 25 mm apart, was installed horizontally into the soil (in the middle of the soil sample height) into oval shaped holes. In order to avoid air exposing of the TDR probe caused by the soil shrinkage, the position of the probe was corrected by pushing it into the soil before each measurement. The sample was placed on a balance and allowed to dry at room temperature (20°C). The weights of the sample, as well as the K_a values of the soil were measured, at intervals during the drying time. The Tektronix 1502B cable tester was used for measuring of K_a values. The measurements were made until soil moisture changes were negligible and then samples were dried in the oven at 105°C in order to determine their final dry weights and to calculate moisture ratios. There was a difference in physical length of TDR probes used in the laboratory (15 cm) and in the field (25 cm) experiments. However, in both cases the waveform trace clearly allowed to detect point resulting from the reflected voltage returning to source.

Soil moisture retention characteristics were

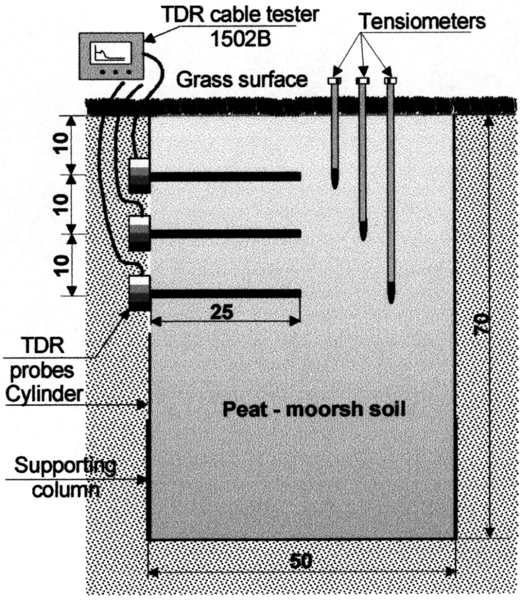

Fig. 1. Scheme of the soil column.

measured in the laboratory using standard sand table and pressure chamber methods (Klute 1986). The values in the range of pF between 0 and 2.0 were determined on a sand table, whereas the values in the range 2.7 to 4.2 were measured in pressure chambers.

Shrinkage characteristics were measured by the "saran resin" method, as described by Brasher et al. (1966). The samples were collected in three replications and sizes of the samples ranged from 34 to 107 cm^3. Each soil sample was completely saturated by placing it on a saturated sandbox for approximately two weeks and then was briefly immersed in a solution of butanone saran resin (solvent ratio 1:5, w/w) and allowed to dry. The saran coating allows the passage of water vapour from the sample, during drying, and remains tightly fitted around the sample during shrinkage. However, it acts as a barrier to liquid water when the volume of the sample is determined by water immersion. By repeatedly weighing the sample in air and under water, both its mass and volume during shrinkage were determined daily in a non-destructive way. After about 3 weeks, weight losses became negligible and the resin-coated samples were dried in the oven at 105°C, in order to measure their final dry volume and dry mass. The void and moisture ratios were calculated using

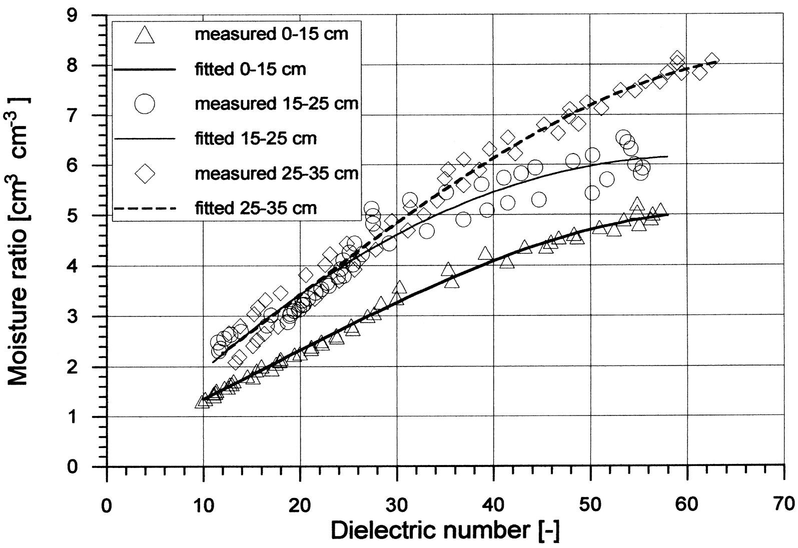

Fig. 2. TDR calibration curves for different peat-moorsh soil layers.

measured values of density of the solid phase, which were determined by the pycnometer method.

RESULTS AND DISCUSSION

Due to soil volume changes during the TDR calibration the calibration curve was presented as the relation between the moisture ratio and the dielectric number. Measured TDR calibration data were fitted using the following form of a third-degree polynomial equation:

$$\vartheta = \left(A + BK_a + CK_a^2 + DK_a^3\right)10^{-4} \qquad (3)$$

where ϑ = moisture ratio (–), K_a = dielectric number (–), A, B, C, D = polynomial coefficients (–).

Polynomials were fitted to the data values of K_a and ϑ by the least squares method using the STATGRAPHICS package (STSC 1996). The fitted values of the polynomial coefficients, together with standard errors of estimation for different soil layers in the studied peat-moorsh soil profile, are listed in Table 2. The results of measurements and fitted TDR calibration curves are presented in Fig. 2. The effect of different bulk densities on the calibration curves is observed. It is clearly seen from the figure that, at the same water content, a low bulk density (soil layer 25–35 cm) results in a lower dielectric number than does a high density (soil layer 0–15 cm). The empirical TDR calibration equations were used for determination of the soil moisture ratio during the drying process of undisturbed soil columns in field conditions.

The measured values of moisture ratio and pressure heads, versus time during the drying process for the soil columns, are presented in Fig. 3. From this figure systematic decrease of the val-

Table. 2. The parameters of TDR calibration equation for fen peat-moorsh soil.

Depth (cm)	n	Polynomial parameters				S_{yx}
		A	B	C	D	
0–15	53	4 038.85	883.11	6.50	– 0.14	0.097
15–25	54	822.15	2 000.19	– 16.47	0.00	0.296
25–35	54	6 402.70	1 261.91	9.92	– 0.18	0.240

n = number of measurements.

S_{yx} = standard error of estimation (dimensionless).

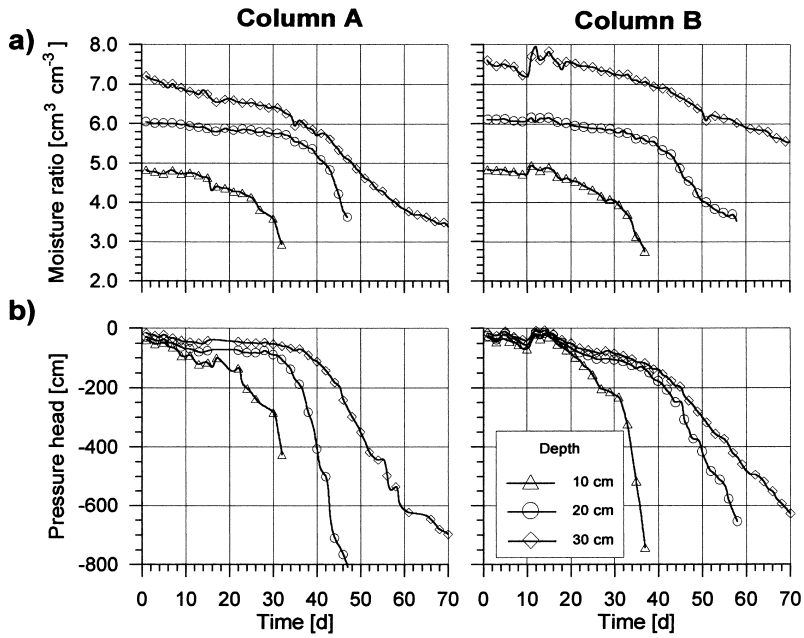

Fig. 3. Moisture ratio (a) and pressure head (b) changes during the drying of peat-moorsh soil columns.

ues of soil moisture ratio, as well as pressure heads were observed. During the drying process shrinkage of the soil columns occurred. Due to this process soil volume changes, as well as soil surface subsidence, was observed. The water contents and pressure heads measured in the soil columns offer the possibility to obtain an in-situ moisture retention curve. This data was used to determine field measured soil moisture characteristics for different soil layers (Fig. 4). In this figure laboratory measurements of pF curve are also presented. The laboratory measured values were fitted using the van Genuchten equation (van Genuchten 1980) in the following form:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{\vartheta - \vartheta_r}{\vartheta_s - \vartheta_r} = \frac{1}{\left[1 + (\alpha h)^n\right]^m} \quad (4)$$

where S_e = effective saturation (–), θ = volumetric moisture content ($m^3\,m^{-3}$), ϑ = moisture ratio ($m^3\,m^{-3}$), θ_s, θ_r = saturated and residual volumetric moisture content, respectively ($m^3\,m^{-3}$), ϑ_s, ϑ_r = saturated and residual moisture ratio, respectively ($m^3\,m^{-3}$), α, n, m = 1–1/n = empirical parameters m and n (–) , α (cm^{-1}), h = pressure head (cm).

Fitting was performed using the RETC program (van Genuchten et al. 1991). Moisture ratios required in equation (4) were calculated from measured values of the saturated void ratio using equation (2). The obtained values of van Genuchten's parameters, describing laboratory measured soil moisture characteristics for different soil layers measured in a laboratory, are listed in Table 3.

A comparison of laboratory- and field-measured data, presented in Fig. 4, show a generally good agreement. Only for the data of the upper soil layer (Fig. 4a) was a slight overestimation of field measurements by laboratory measured data observed.

In order to relate moisture retention characteristics measured in a laboratory to actual volumetric moisture content, shrinkage characteristics (the relationship between void ratio and moisture ratio) were determined. The shrinkage characteristic data obtained as a result of laboratory measurements was fitted using the following three straight-line model:

$$\begin{aligned} e &= a_1 + b_1\vartheta \qquad \vartheta_2 \le \vartheta \le \vartheta_s \\ e &= a_2 + b_2\vartheta \qquad \vartheta_1 \le \vartheta \le \vartheta_2 \\ e &= a_3 + b_3\vartheta \qquad 0 \le \vartheta \le \vartheta_1 \end{aligned} \quad (5)$$

where e = void ratio ($m^3\,m^{-3}$), ϑ = moisture ratio ($m^3\,m^{-3}$), ϑ_s = moisture ratio at saturation ($m^3\,m^{-3}$), ϑ_1, ϑ_2 = moisture ratios at the boundaries of straight lines ($m^3\,m^{-3}$), a_1, a_2, a_3, b_1, b_2, b_3 = fitted

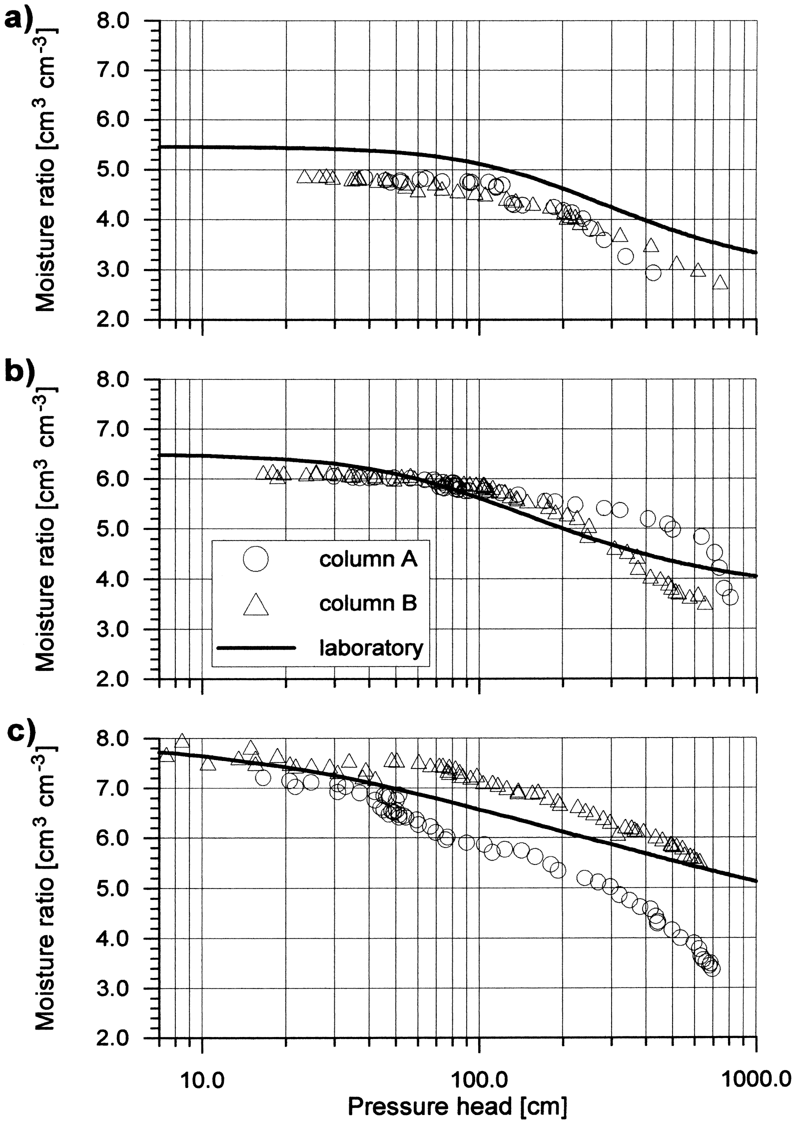

Fig. 4. Comparison of laboratory and field measured soil moisture characteristics for the following soil layers: a) 0–15 cm, b) 15–25 cm, c) 25–35 cm.

Table 3. Parameters required in van Genuchten's equation, fitted to laboratory measurements of soil moisture retention characteristics as related to the fictitious volumetric moisture content for different soil layers.

Depth (cm)	Parameters					
	ϑ_s (cm³ cm⁻³)	ϑ_r (cm³ cm⁻³)	θ_s (cm³ cm⁻³)	θ_r (cm³ cm⁻³)	α (cm⁻¹)	n (–)
0–15	5.454	2.697	0.8304	0.4106	0.0055	1.8518
15–25	6.491	3.545	0.8577	0.4684	0.0119	1.7182
25–30	7.900	0.000	0.8876	0.0000	0.0424	1.1155

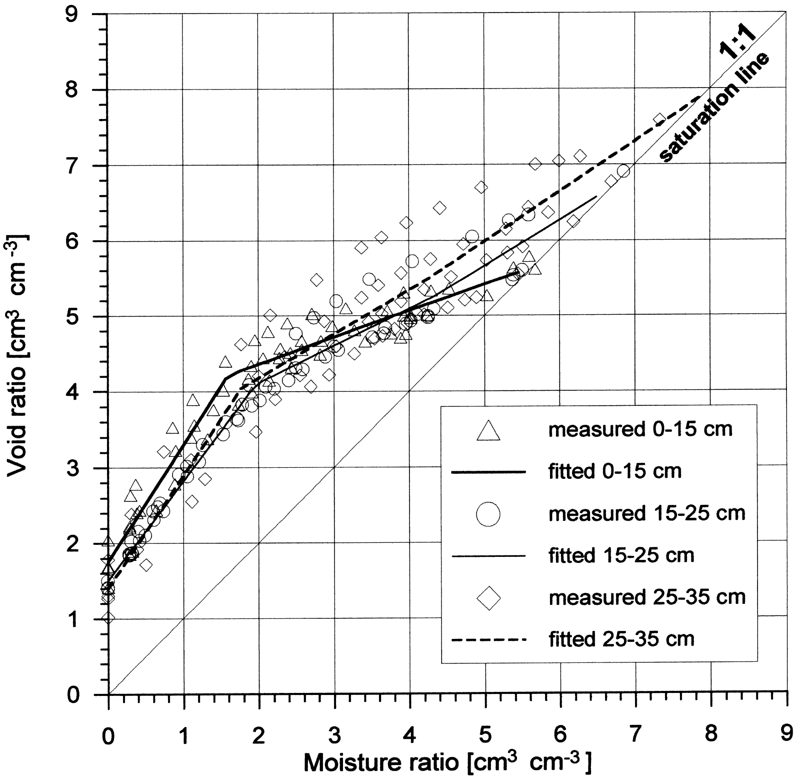

Fig. 5. Measured and fitted shrinkage characteristic curves for different soil layers.

parameters.

The three straight-line model of the shrinkage characteristic was fitted to measured data using Fletcher-Reeves' algorithm (Wesseling 1981). Estimated values of the model parameters are presented in Table 4. Measured and fitted shrinkage characteristics data are shown in Fig. 5. From the analysis of the shrinkage experimental data it can be seen that the peat-moorsh soil shrinkage characteristics are completely different from those of clay soils (Szatyłowicz et al. 1996). The soil horizons show an intensive shrinkage, clearly visible from the drastic decrease of the void ratio of the drying samples. In all soil samples shrinkage starts with the first water extraction from saturation. From the shape of the curves presented in Fig. 5 it can be seen that the shrinkage characteristic for the considered peat-moorsh changes with depth.

Table 4. Estimated values of the parameters required by three straight-line model of shrinkage characteristics for different soil layers.

Depth (cm)	Parameters									R^2 (%)
	ϑ_s	a_1	b_1	ϑ_2	a_2	b_2	ϑ_1	a_3	b_3	
0–15	5.454	3.692	0.344	3.413	3.635	0.360	1.591	1.746	1.548	95.81
15–25	6.491	2.615	0.609	4.356	3.121	0.493	1.961	1.495	1.322	97.46
25–35	7.900	2.672	0.662	4.261	3.004	0.584	1.768	1.393	1.496	91.32

R^2 = coefficient of determination

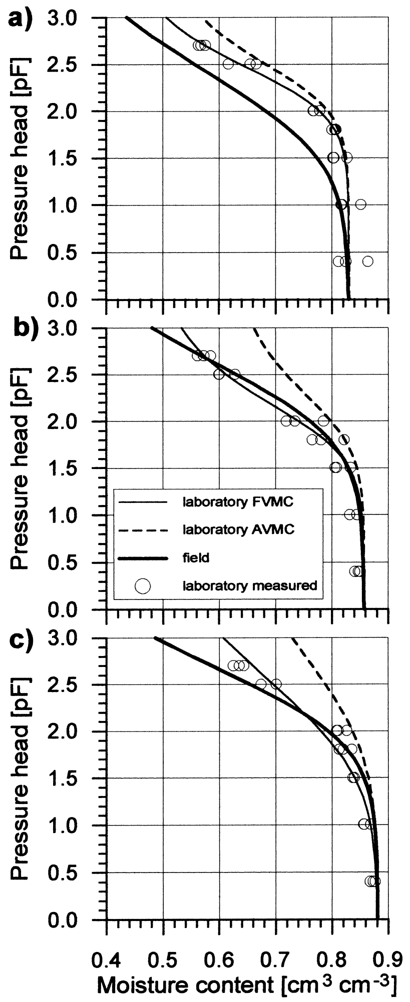

Fig. 6. Comparison of soil moisture retention characteristics measured in the laboratory as related to fictitious (FVMC) and actual volumetric moisture content (AVMC) with field measurements for the following soil layers: a) 0–15 cm, b) 15–25 cm, c) 25–35 cm.

The lower soil layers show a larger shrinkage than the upper layer, as is clearly visible from the large decrease of void ratio of the drying soil samples. This is in agreement with research results reported by Päivänen (1982), who found an increase in peat shrinkage with increasing sampling depth.

The fitted shrinkage characteristics were used to calculate actual volumetric moisture content values from laboratory-determined soil moisture retention characteristics. Combining equation (1) and (2), the following formula was obtained for calculation of the actual volumetric moisture content:

$$\theta_{AVMC} = \theta_{FVMC}\left(\frac{1+e_s}{1+e}\right) \qquad (6)$$

where all the symbols as previously defined in equation (1) and (2).

Laboratory-measured soil moisture retention data, presented as the relationship between pressure heads and actual volumetric moisture content, were fitted with van Genuchten's equation (4) the using RETC code. The obtained values of the parameters are listed in Table 5. The field-measured data, expressed in terms of moisture content and pressure head values, were also fitted using the same equation and the estimated values of the parameters are listed in Table 6.

In order to examine which volumetric soil moisture content should be used (θ_{FVMC} or θ_{AVMC}) for the laboratory-determined soil moisture retention characteristic, the comparison of laboratory- and field-determined characteristics was performed and the results are shown in Fig. 6. The moisture retention characteristic, determined by the actual volumetric moisture content, results in a different shape, showing a smaller change in

Table 5. Parameters required in van Genuchten's equation, fitted to laboratory measurements of soil moisture retention characteristics as related to the actual volumetric moisture content for different soil layers.

Depth (cm)	Parameters			
	θ_s (cm³ cm⁻³)	θ_r (cm³ cm⁻³)	α (cm⁻¹)	n (–)
0–15	0.8304	0.4806	0.0050	1.8250
15–25	0.8577	0.6020	0.0098	1.6382
25–30	0.8876	0.0000	0.0231	1.0656

Table 6. Parameters required in van Genuchten's equation fitted to field measurements of soil moisture retention characteristics for different soil layers.

Depth (cm)	Parameters			
	θ_s (cm³ cm⁻³)	θ_r (cm³ cm⁻³)	α (cm⁻¹)	n (–)
0–15	0.8304	0.0000	0.0167	1.2260
15–25	0.8577	0.0000	0.0079	1.2719
25–30	0.8876	0.0000	0.0074	1.2846

moisture content for a given change of pressure head. Furthermore the use of the soil moisture retention characteristic, related to actual volumetric moisture content, leads to underestimation of differential water capacity because the loss of water cannot be evaluated correctly due to changes in soil volume.

CONCLUSIONS

From the comparison of the laboratory- and field-measured moisture retention characteristics in peat-moorsh soil, it was found that the results of field measurements were very close to laboratory measurements, expressed in the terms of fictitious volumetric moisture content, which is based on the initial soil volume, regardless of the soil volume changes. Construction of moisture retention characteristics with the use of laboratory measurements based on actual volumetric moisture content, which accounts for the actual changes of soil volume may lead to an incorrect estimation of differential water capacity, as a results of the fact that the amount of water loss cannot be evaluated correctly due to changes in the soil volume.

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