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Design, construction and performance of a pressure chamber for water retention curve determination through traditional and nuclear methods

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Abstract We present in this work a detailed design of a small low-pressure chamber outfitted with a ceramic porous plate for evaluating the soil water retention curve (SWRC) in the water potential range from 0 to –100 kPa. The chamber is made of acrylic and permits the use of one unique soil sample each time. The use of this chamber allows quick measurements of soil moisture using nuclear (based on gamma-ray attenuation) and conventional methods and SWRC determinations made with the designed chamber are in agreement with those obtained using a commercial low-pressure chamber. The chamber was designed especially for testing the use of the nuclear method as an auxiliary tool for SWRC determinations but it can be easily adapted for routine investigations and a practical alternative for the conventional SWRC method.

Key words soil water potential • gamma-ray attenuation • soil water content • soil physics • radioisotope application • applied nuclear physics

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Introduction

The accurate determination of physical properties of structured soils is one of the major challenges in soil science. Of all the soil physical properties, the soil water retention curve (SWRC) that describes the relationship between the soil water content (θ) and the soil water matric potential (ψ_m) is one of the most important. This characteristic curve serves as the basis for important considerations such as the magnitude and rate of soil water movement [3].

There are several methods to measure the energy status of soil water such as tensiometers, vapor pressure measuring apparatus, centrifuges, suction tables, and pressurized equipments. The latter was first proposed by Richards [11] and involves the establishment of a series of equilibria between the water in the soil sample and the water at chosen potentials [5]. The soil sample is placed in a pressure chamber in contact with a porous plate and the water is removed through the application of gas pressure above atmospheric pressure. When the equilibrium is reached the water movement through the porous plate ceases and the soil water content is obtained by the gravimetric method. The gas pressure applied to the soil sample represents the value of the matric potential for the respective water content [11, 12].

The evaluation of SWRC by the Richards method is time consuming and presents some practical problems as described in Bacchi *et al*. [1]. To measure θ and its distribution in a porous media, X- and γ-ray attenuation can be considered as useful tools [2, 6]. The gamma-ray attenuation technique is a non-destructive and non-invasive method that permits simultaneous determination of the water content and of the soil density in a core sample based on the Beer-Lambert law [15].

In the present work, we present the construction and validation of a small and practical pressure chamber to measure the soil water retention curve by traditional and nuclear methods. The main objective of this study was to make a comparative analysis of SWRC obtained through a commercial pressure chamber and a pressure chamber designed by us. In the case of the small constructed pressure chamber we carried out measurements of θ using both the gravimetric [11] and the nuclear method [1].

Theory

According to the Beer-Lambert law the narrow-beam total mass attenuation coefficient μ ($cm^2 \cdot g^{-1}$) is defined by the relation:

$$I = I_0 e^{-\mu\rho x} \quad (1)$$

where I_0 and I are the incident and the transmitted beam intensities, x (cm) is the sample thickness and ρ ($g \cdot cm^{-3}$) is the physical density of the material. The Beer-Lambert law is related to the different electromagnetic processes that occur during the interaction of the radiation with the matter decreasing the number of transmitted photons N (number of photons·$m^{-2} \cdot s^{-1}$). The mass attenuation coefficient is derived from the linear attenuation coefficient, which measures the photon absorption or scatter probability per unit length while interacting within the sample. Therefore, the density independent mass attenuation coefficient can be derived from Eq. (1):

$$\mu = \left[\frac{1}{\rho x}\ln\left(\frac{I_0}{I}\right)\right] \quad (2)$$

For soil samples, considering the two phases, solid material and water, the Beer-Lambert law can be written as follows:

$$I = I_0 e^{-x(\mu_s\rho_s + \mu_w\theta\rho_w)} \quad (3)$$

where μ_s and μ_w are the soil and water mass attenuation coefficients, ρ_s and ρ_w the soil bulk and water densities and θ ($cm^3 \cdot cm^{-3}$) the soil water content.

When the bulk density remains constant during soil water content changes as, e.g., for sandy soils; if μ_s, μ_w, ρ_s and x are known, it is possible to obtain θ by the gamma-ray attenuation technique, solving Eq. (3) for θ:

$$\theta = \frac{1}{x\mu_w\rho_w}\cdot\left[\ln\left(\frac{I_0}{I}\right) - x\mu_s\rho_s\right] \quad (4)$$

The determination of θ by the nuclear method has associated experimental errors. Through the error propagation of Eq. (4), it is possible to estimate the error associated to θ measurement:

$$\sigma^2\theta = \left(\frac{\partial\theta}{\partial I_0}\right)^2\sigma^2(I_0) + \left(\frac{\partial\theta}{\partial I}\right)^2\sigma^2(I) + \left(\frac{\partial\theta}{\partial x}\right)^2\sigma^2(x) + \left(\frac{\partial\theta}{\partial\rho_s}\right)^2\sigma^2(\rho_s) + \left(\frac{\partial\theta}{\partial\mu_w}\right)^2\sigma^2(\mu_w) + \left(\frac{\partial\theta}{\partial\mu_s}\right)^2\sigma^2(\mu_s) \quad (5)$$

where σ(θ) is the total standard deviation; σ(I_0) and σ(I) are the standard deviation of I_0 and I, respectively. In laboratory conditions the parameters x, ρ_s, μ_w and μ_s can be minimized turning very small the third, fourth, fifth, and sixth terms in Eq. (5). In this case, the spatial rates of change of θ may be considered directly related to the uncertainty of the radioactive decay process (√I). Solving the first and second partial derivatives in Eq. (5) the uncertainty in θ can be obtained using:

$$\sigma\theta = \frac{1}{x\cdot\mu_w\cdot\rho_w}\cdot\sqrt{\frac{\sigma^2(I_0)}{I_0^2} + \frac{\sigma^2(I)}{I^2}} \quad (6)$$

Material and methods

Pressure extraction apparatus

Figure 1 shows the dimensions of the pressure chamber projected for this experiment. The chamber permits the

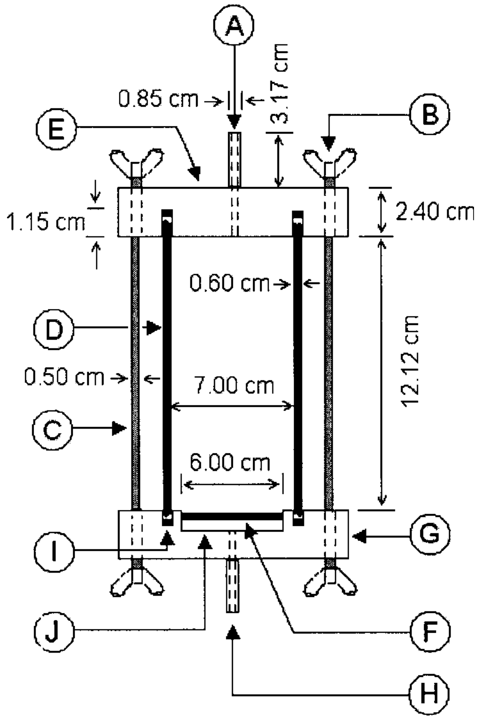

Fig. 1. Schematic diagram of the projected pressure chamber. A – air connection; B – bolt at 120° intervals; C – clamp bolts; D – acrylic wall of the cylindrical section of the chamber; E – top part of the chamber; F – porous plate; G – bottom part of the chamber; H – drainage tube; I – rubber O-ring; J – water reservoir.

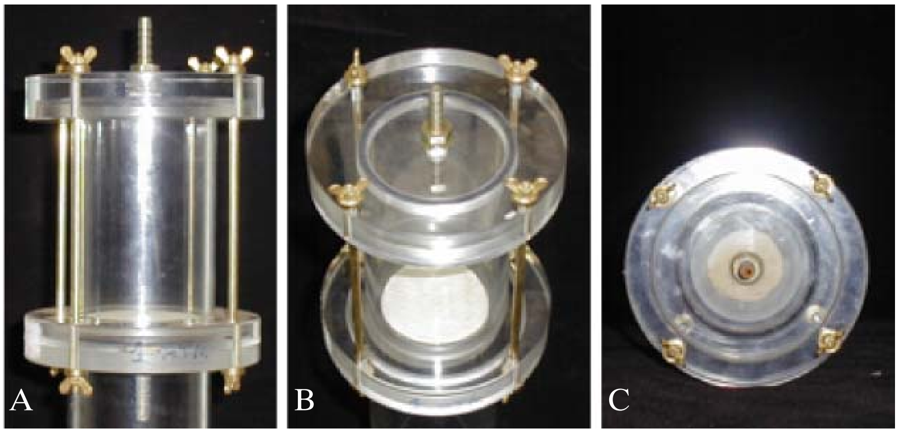

Fig. 2. A – side view of the projected pressure chamber; B – view of the top, the bottom and the porous plate; C – view of the top part diameter, rubber O-ring and cylindrical section diameter, and porous plate diameter.

use of one unique soil sample each time. The dimensions of the cylinders for determining SWRC may be in the range of 3.0 to 5.0 cm high and 5.0 cm diameter.

The pressure chamber is especially suited for measurements in the matric potential range from 0 to –300 kPa. The circular porous plate (6.0 cm diameter) employed in the chamber was developed by the Soil Moisture Equipment Co. (California, USA). The ceramic porous plate used presents a bubbling pressure of about 500 kPa. The cylindrical body of the chamber is made of acrylic with inner diameter of 7.0 cm, height of 12.12 cm, and wall thickness of 0.60 cm. The top and bottom parts of the chamber are also made of acrylic having heights of 2.40 cm and diameters of 10.0 cm. Rubber O-rings (0.50 cm thickness) are placed in the connections between the cylindrical body and the top and bottom parts in order to prevent air leak when the chamber is pressurized. The porous plate was installed in the bottom part, in which there is a small reservoir with the same diameter of the plate and volume of approximately 30 cm^3. A drain tube was connected to this small reservoir and serves as the outlet for the water passing through the plate. At the top part is located a cylindrical tube (0.85 cm diameter) for pressure input. To close the chamber for pressure application, clamp bolts of 0.50 cm diameter are used. To saturate the porous plate before SWRC measurements, a water column of 5.0 cm height is applied inside the chamber over a period of two days. An illustration of the idealized pressure chamber is presented in Fig. 2.

Soil sample and experimental setup

Core samples (3.0 cm high, 4.8 cm diameter, 55 cm^3 volume) were collected from profiles of a soil characterized as Geric Ferralsol (66% sand; 6% clay; 28% silt) at an experimental field in Piracicaba, Brazil (22°4' S; 47°38' W; 580 m above sea level). Twelve soil samples were collected at the soil surface layer (3–8 cm depth) with aluminum cylinders. In the laboratory, the excessive soil was carefully trimmed off each cylinder so that the volume of the ring was completely filled with the soil. The soil saturation process was capillary rise, soaking soil cores in water at a level just below the top of the core [5]. This procedure was made over a period of 2 days to obtain best saturation of the samples, minimizing entrapped air in soil pores. After saturation the cores were placed on the saturated ceramic plate inside the pressure chamber and respective air pressures were applied to the system allowing the samples to lose water and to come to the next step of equilibrium.

Water retention curves were obtained using (i) a commercial low-pressure extraction chamber (CAT No. 1600 – Soil Moisture Equipment Co.) that supports pressures up to 500 kPa and (ii) the constructed acrylic pressure chamber (Fig. 3). Experimental data by the traditional and the nuclear method were obtained in the matric potential range from –15 to –100 kPa. Details about the experimental setup to obtain SWRC by the Richard method can be found in Klute [5].

Apparatus for the nuclear method and data analysis

Figure 4 is a schematic representation of the experimental apparatus for the nuclear method. The gamma-ray radioactive source consisted of ^{241}Am with an energy peak of 59.54 keV. The acrylic pressure chamber containing the soil sample was placed between the radioactive source and the NaI(Tl) scintillation crystal detector. Circular lead collimators (0.4 cm diameter) were placed near the source and the detector and were adjusted and aligned in order to produce a circular gamma-ray photon beam. The objective of the collimation system is to reduce the maximum solid angle of scattering from sample to detector. Signals from the photomultiplier are amplified and fed through a single-

Fig. 3. Side view of the projected pressure chamber and the commercial low-pressure chamber.

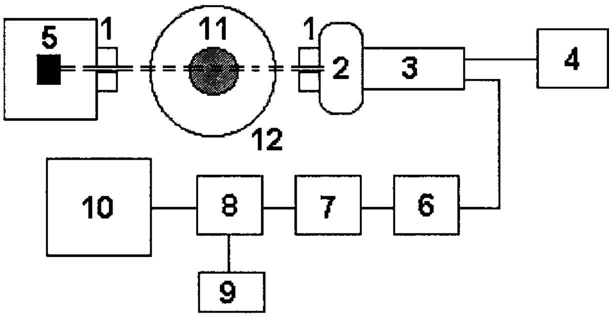

Fig. 4. Experimental diagram of the nuclear experimental apparatus: 1 – lead collimators; 2 – NaI(Tl) detector; 3 – photomultiplier; 4 – high-voltage unit; 5 – ^{241}Am radioactive source; 6 – amplifier; 7 – single channel analyzer; 8 – counter; 9 – timer; 10 – microcomputer; 11 – soil sample; 12 – acrylic chamber.

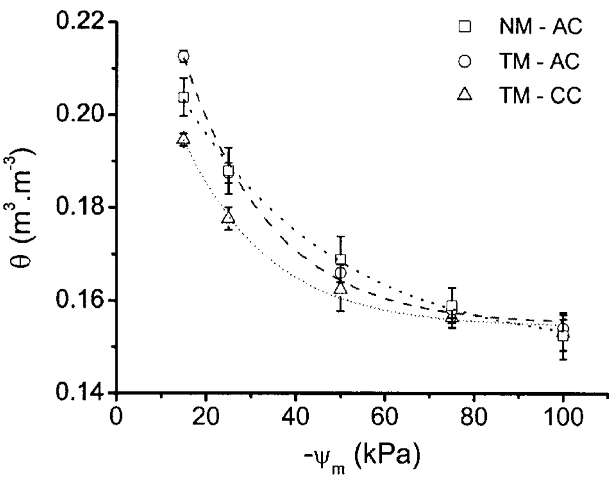

Fig. 5. Soil water retention curves in the matric potential range from 0 to –100 kPa obtained by the traditional (acrylic and commercial pressure chamber) and the nuclear method. NM – nuclear method; TM – traditional method; AC – acrylic chamber; CC – commercial low-pressure chamber. The theoretical adjustment of the θ values for the nuclear (dot line) and traditional methods (AC – dash line and CC – short dot line) was obtained through the van Genuchten equation [13].

channel analyzer to a preset time/counter system. The counter is interfaced with a PC, which allows an easy automation of data acquisition.

For the evaluation of μ_s, air-dried soil was passed through a 2.0 mm sieve and packed into a thin wall acrylic container (10 × 10 × 10 cm). The intensities of monoenergetic photons were measured in different positions of the soil into the container. The linear attenuation coefficient determined represents an arithmetic mean value of twenty repetitions and it was obtained from Eq. (2).

The pressure chamber was positioned between the source and the detector with the gamma-ray beam always crossing the center of the chamber and the soil sample (Fig. 4). The monoenergetic beam was used to evaluate soil water contents θ since the employed soils have a rigid structure. Soil water content values were measured using Eq. (4).

Results and discussion

Table 1 and Figure 5 show the soil water retention curves obtained by the traditional (commercial pressure chamber and acrylic chamber) and the nuclear method (acrylic chamber).

From Table 1 and Fig. 5, it is possible to compare the results obtained by the two methods. The values of the mass attenuation coefficients used in the nuclear method were: 0.24922 ± 0.00312 $cm^2 \cdot g^{-1}$ for soil and 0.19890 ± 0.00245 $cm^2 \cdot g^{-1}$ for water. These coefficients are in agreement with those found in the literature for photon gamma of ^{241}Am [4]. As can be seen from Table 1, θ values present small deviations between methods for the water potential range utilized (15–100 kPa), showing that the constructed pressure chamber can be used with assurance for SWRC evaluations. Higher deviations between methods (Fig. 5) were observed in the region of high matric potential, probably, due to the natural soil heterogeneity or saturation process [5, 16]. The time required for the whole SWRC determination by the traditional method (commercial low-pressure chamber and acrylic chamber) was practically the same. This result is coherent, because the porous plates used for both chambers have similar conductance and bubbling pressures. On the other hand, the time required by the nuclear method was reduced due to the fact that

Table 1. Matric potential (ψ_m) and soil water content (θ) for each applied pressure for the traditional (commercial pressure and acrylic chamber) and the nuclear method

$-\psi_m$ [kPa]	θ [$m^3 \cdot m^{-3}$] NM-AC	TM-AC	TM-CC
15	0.2038 ± 0.0041	0.2126 ± 0.0013	0.1946 ± 0.0014
25	0.1879 ± 0.0050	0.1874 ± 0.0021	0.1776 ± 0.0025
50	0.1689 ± 0.0050	0.1659 ± 0.0019	0.1624 ± 0.0046
75	0.1590 ± 0.0038	0.1581 ± 0.0017	0.1564 ± 0.0022
100	0.1525 ± 0.0050	0.1541 ± 0.0020	0.1532 ± 0.0038

NM – nuclear method. TM – traditional method. AC – acrylic chamber. CC – commercial chamber.

θ ± σθ for the nuclear method is related to the maximum and minimum θ values considering the error associated to the uncertainty of the radioactive decay process (see Eq. (6)).

θ ± σθ for the traditional methods (AC and CC) represent the scatter of the 5θ values for each specific ψ_m.

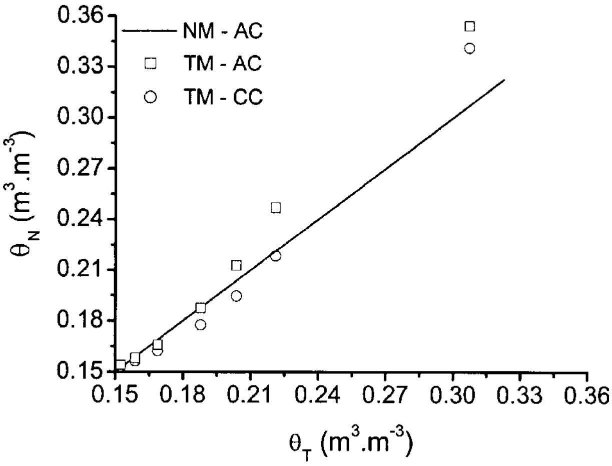

Fig. 6. Data correlation of the soil water content by the traditional method (AC and CC) in relation to the nuclear method (straight line 1:1).

the soil water content was continuously monitored through software elaborated for data acquisition of θ vs. time [8, 9].

The SWRC shown in Fig. 5 was determined using θ data obtained from a theoretical adjustment [13, 14]. The very close behavior observed for the retention curves evaluated by the methods indicates that the idealized pressure chamber gives consistent values. The θ data measured for the acrylic chamber were higher than those for the commercial pressure chamber in the water potential range from 0 to about –100 kPa. Possible reasons for these deviations could be the variability among samples or small differences in the soil structure caused by the sampling procedure [7].

In order to evaluate the differences between methods, we compared the soil water retention curves determined by the traditional method (AC and CC) with those determined by the nuclear method in the water potential range from 0 to –100 kPa (Fig. 6).

Since in the nuclear method the soil sample is submitted just one time to the wetting and drying cycle, less changes on the original soil structure can be expected as compared to the traditional method in which the number of cycles is higher [10]. Higher deviations between the nuclear and the traditional (commercial pressure and acrylic chamber) method occurred for θ near the saturation. After the water potential of –50 kPa these differences between methods become insignificant (see Table 1).

Concluding remarks

The data obtained with the projected pressure chamber are in agreement with those evaluated with the commercial pressure chamber, as indicated in Table 1 and Figs. 5 and 6. The very close behavior in θ values for the traditional method (AC and CC) suggests that the constructed chamber is suitable for SWRC evaluations.

Preliminary tests indicate that the designed pressure chamber may be used with assurance for extracting θ over a range from 0 to 200 kPa. Pressures above 200 kPa may damage the material used in the construction of the chamber. The range described above covers the interval between 0 and 100 kPa, which is related to the largest pores of the soil and that have great importance in agricultural research and practical agriculture.

Measurements by the nuclear method are possible only using the projected chamber due to the high gamma-ray attenuation by the wall chamber of the commercial steel pressure chamber and its large diameter that decreases too much the intensity of the photons reaching the detector. The distance between the radioactive source and detector using the acrylic chamber is reduced to 18 cm, while for the commercial pressure chamber this distance is at least 40 cm (see Fig. 3).

Although our experimental acrylic chamber operates with only one sample, it could be improved in order to work with large number of samples and then became an interesting alternative method for SWRC determinations using the gamma-ray attenuation method.

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