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AN EXPERT SYSTEM FOR PLANNING, CONTROLLING, AND ANALYZING LABORATORY MEASUREMENTS OF THE SOIL HYDRAULIC PROPERTIES

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Reliable measurements of the unsaturated soil hydraulic properties in the laboratory are difficult, time-consuming, and costly to obtain. A newly developed, fully automated measurement system is described that optimally integrates the duties expected from available laboratory personnel, the instrumental features of the measurement equipment, and computer software linked to the apparatus. An expert system package is used to (i) plan the experiments, (ii) control operations of all hardware involved, and (iii) analyze the measurement results. The system first obtains estimates for the hydraulic properties from the observed particle-size distribution, and related data if available (bulk density, organic matter content, clay mineralogy, etc.), before recommending specific measurement points on the water retention and hydraulic conductivity curves. Examples are given to illustrate the improved efficiency and accuracy of the system in measuring the water retention and hydraulic conductivity properties of unsaturated soils.

INTRODUCI'ION

Models currently used for simulating water flow in the unsaturated zone generally assume that soil air is at rest and at atmospheric pressure. This leads to the unsaturated flow equation:

$$\frac{\partial}{\partial z}[K(\frac{\partial h}{\partial z}-1)] = \frac{\partial \theta}{\partial t} = C\frac{\partial h}{\partial t} \qquad (1)$$

where K is the hydraulic conductivity of the soil, θ is the volumetric water content. C is the soil water storage capacity, h is the capillary soil water pressure head, z is the soil depth, and t is the time.

Implementation of the unsaturated flow equation requires knowledge of three parametric models describing the unsaturated soil hydraulic properties. These are the hysteretic soil water retention function, $\theta(h)$, the hysteretic soil water capacity function, $C(h)$, and the unsaturated hydraulic conductivity function, K(B). Following the analyses by Luckner et *al.* [1989], Luckner *and Schestakow* [*1991]* and *Nielsen and Luckner* [1992], we recommend the following expressions for these functions:

In: van Genuchten, M. Th., F. J. Leij, and L. J. Lund (eds.), Proc. Int. Workshop, *Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils.* pp. 621-632, University of California, Riverside.

$$\bar{\theta} = \frac{\theta - A}{\phi - A - B} = \frac{1}{[1 + (\alpha h)^n]^{1-1/n}} \tag{2}$$

$$C = (\phi - A - B)\frac{\alpha(n-1)(\alpha h)^{n-1}}{[1 + (\alpha h)^n]^{2-1/n}} \tag{3}$$

$$K(\theta) = K(\theta_o)\left(\frac{\bar{S}}{\bar{S}_o}\right)^{\beta}\left[\frac{1-(1-\bar{S}^{1/m})^m}{1-(1-\bar{S}_o^{1/m})^m}\right]^2 \tag{4}$$

where α is a scaling parameter, n is a slope parameter, A and B are scaling values of the soil water mobility range which depend on the residual water and air contents of the soil, and ϕ is soil porosity. The subscript o indicates the matching point for the measured unsaturated hydraulic conductivity function, while $\bar{S}$ is the scaled coordinate of the soil water retention curve:

$$\bar{S} = \frac{\theta - \theta_{w,r}}{\phi - \theta_{w,r}} \tag{5}$$

The above parametric models for θ, C and K require for each soil sample estimates of (i) the soil porosity ϕ, (ii) the residual air and water contents, $\theta_{w,r}$ and $\theta_{a,r}$, which are needed to define the scaling parameters A and B (*e.g., see* Eq. 11 of *Luckner et al.*, 1989), (iii) the parameters α_d, α_w, n_d, n_w, m_d, and m_w, where the subscripts w and d denote wetting and drying, respectively, and (iv) the connectivity parameter, β.

ESTIMATING THE HYDRAULIC PROPERTIES OF UNSATURATED SOILS

Soil porosity, ϕ, is commonly estimated from the density of solids and the sample volume. The hydraulic conductivity, $K(\theta_o)$ at a given water content, θ_o may be derived from a Darcian flow experiment. The parameters β and m in (4) may be obtained from the measured unsaturated soil hydraulic conductivity curve. This approach assumes that m is decoupled from the parameter m = 1-1/n used in the original retention model of van Genuchten [1980]. The procedure requires several independently measured conductivity data in addition to the point $K(\theta_o)$. If, besides $K(\theta_o)$, no additional data are available, then m in (4) should be approximated with $m = 1-1/n$ [Nielsen and *Luckner*, 1992]. The parameters $\alpha, n, \theta_{w,r}$ and $\theta_{a,r}$ may be estimated from measured drying and wetting soil water retention data, $(\theta_w, h)_i$. Hydraulic conductivity data $K(\theta)_i$ could be obtained from one-step or multi-step outflow/inflow experiments. Finally, soil texture and related data may be used to obtain estimates for the retention parameters $\alpha, n, \theta_{w,r}$ and $\theta_{a,r}$, and the conductivity parameter m.

Hydraulic Conductivity

Measuring the unsaturated soil hydraulic conductivity is time-consuming and relatively expensive in terms of the required laboratory equipment. Two of the main experimental problems are the application of a constant capillary pressure during the experiment, and the accurate measurement of low flux rates. While difficult and time-consuming, routine direct measurement of the hydraulic conductivity is important for verification of results obtained with indirect methods.

Soil Water Retention

The hydraulic properties of soils are commonly estimated from measured soil water retention data during drying and wetting. This approach requires measured capillary pressure or pressure head data, and measured volumetric soil water content data. The amount of time needed for the measurements depends primarily on soil type and the height of the soil sample being tested. The demands on laboratory equipment are fairly high, particularly to provide constant capillary pressures and temperatures during each test step, accurate data for the volumetric soil water content, and independence of the capillary pressure in the sample from the pressure in the collected soil water sample. We recommend that water retention curves be measured as part of any routine experimental program in a laboratory.

One-Step or Multi-Step Outflow/Inflow Tests

With today's available PC software and hardware it is useful to estimate the unknown parameters in (2) (3) and (4) from cumulative outflow/inflow data $V_i = f(t_i)$ resulting from one-step or multi-step outflow/inflow experiments. The time needed for this approach depends on soil type and sample height. Requirements on laboratory equipment are high in terms of providing constant capillary pressures and temperatures during the experiment, accurate data of the cumulative inflow/outflow function V = f(t), and ensuring independence of the capillary pressure in the sample from the pressure in the burette. Outflow/inflow methods should be used primarily to estimate the unsaturated hydraulic conductivity function $K = K(\theta)$.

Soil Texture Analysis

Several models have been developed to correlate the unsaturated soil hydraulic properties with soil texture data, and other soil properties such as bulk density, organic matter content, cation exchange capacity, clay content, and/or soil structure. Most of these models are empirical and do not take advantage of recently developed pore-size and particle-size distribution theories [e.g., *Gupta and* Larson, 1979; *Seliger and Voronin,* 1988].

As an alternative, the measured particle-size distribution could be transformed first into a pore-size distribution, and subsequently into a water retention curve. Models distinguishing between the distributions of bottle-necks and bottle-bellies of the pore channels are until now not available. Disadvantages of both types of models are that they cannot be used to estimate hysteretic soil water retention functions, while the presence of residual soil-water and soil-air contents is ignored.

The requirements on reliable laboratory equipment are high, especially for accurate measurements of the particle-size distribution of the silt and clay fractions. Figure 1 compares results obtained with a pipet method and an optical particle analyzer for a silty sandy soil. The figure shows that imprecise results may be expected with the pipet method. For example, the assumption that each soil particle has a spherical shape restricts the applicability of pipet results. Figure 2 shows the impact of the particle-size distribution results on the predicted water retention curve. The plots in Figures 1 and 2 illustrate the difficulties which may arise when data are measured or analyzed with different hardware and/or software tools.

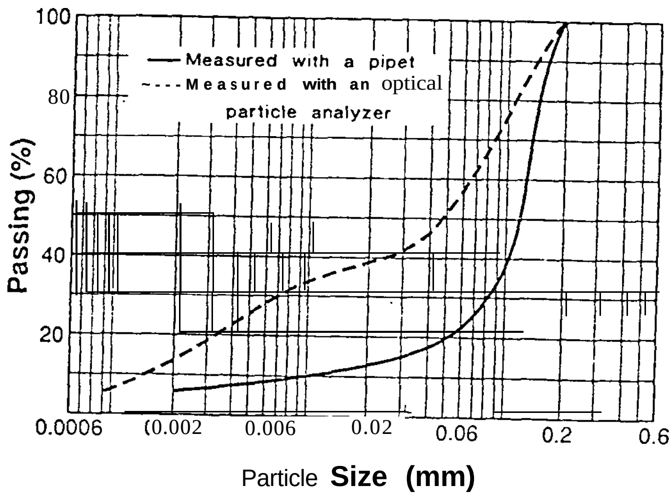
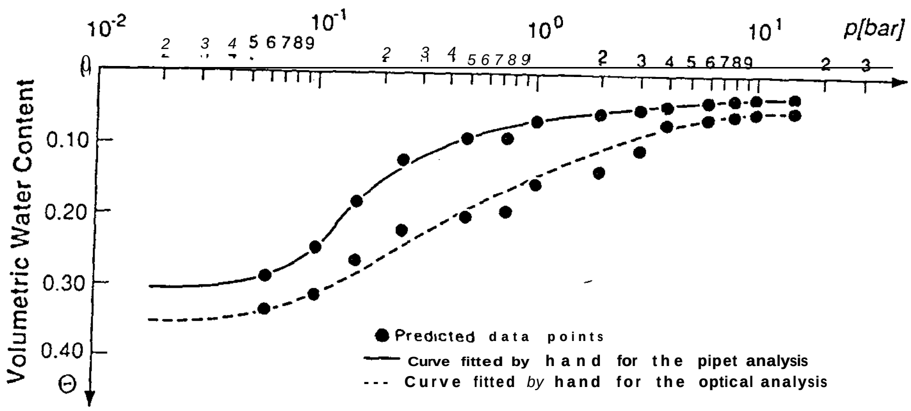


Fig. 1. Particle size distribution data of a silty sandy soil as measured with a pipet and optical particle analyzer.



Fii. 2. Soil water retention curves predicted from the particle-six distribution data in Figure 1.

Disadvantages of Today's Technology

Today's commercially available laboratory equipment generally does not meet the requirements necessary for accurately and expeditiously estimating the unsaturated soil hydraulic properties and related data. Especially needed is a new generation of automated laboratory equipment combined with appropriate software for computer-aided design, control, and analysis of the experiments. We note that the sophistication of equipment currently used in soil physics laboratories generally lags far behind that considered standard in most soil chemistry and soil microbiology laboratories.

Another problem is the applicability of available software for identification of the hydraulic parameters of unsaturated soils. Optimization results often depend too much on the initial values of the hydraulic parameters to be identified. Figure 3 shows a poorly defmed global minimum in the objective function for a particular inverse problem involving the unknown parameters α and n. The results indicate the importance of first finding good initial estimates for the hydraulic parameters in the vicinity of the global minimum. Alternatively, the objective function may need to be modified to include additional information for a particular soil (e.g., multi-step rather than one-step outflow/inflow data, or independently measured water retention data collected at relatively low water contents). Currently available computer software also does not offer much help in an interactive mode to improve the inverse procedure. Still, many improvements in the parameter optimization analysis can be expected in the near future [van Dam et al., 1990; ***Toorman et al*, 1991**].

Additional technical problems are linked to the selected optimization method. Table 1 lists parameters identified by using Fibonacci's and Powell's algorithm for the same data set. Figure 4 shows the impact of these different estimates on the calculated main drainage curve.

TABLE **1.** Hydraulic Parameters Obtained by Using Different Optimization Methods

Method	α	n	*A*
Fibonacci	- **14.99**	**1.40**	**0.062**
Powell	10.39	1.54	**0.062**

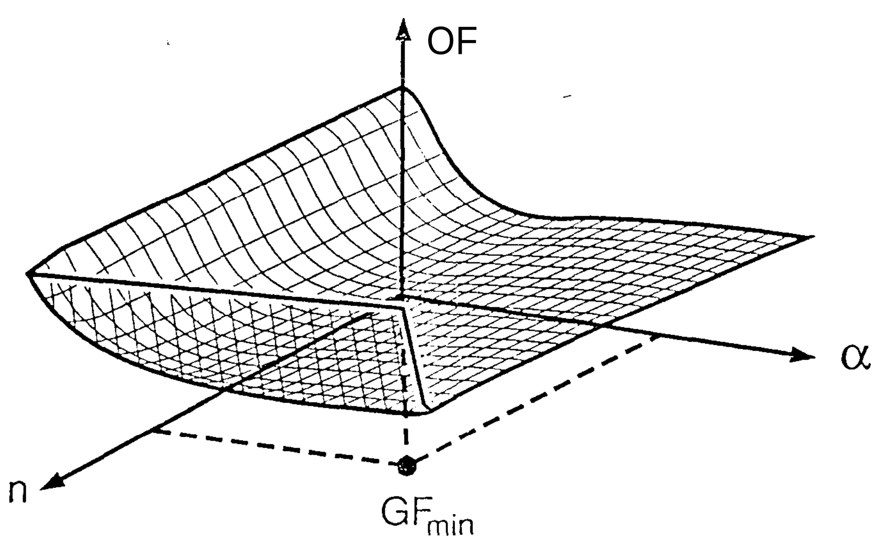


Fig. **3. Objective function surface for identification problem involving α and n.**

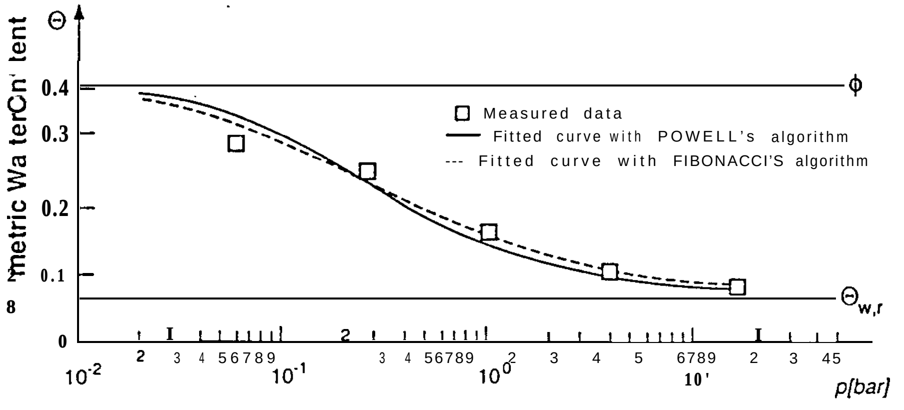


Fig. 4. Water retention curves predicted with the hydraulic parameters in Table 2.

THE AMHYP SYSTEM

To overcome some of the major disadvantages and limitations of current techniques and methods for estimating the unsaturated soil hydraulic properties, a new laboratory device called the AMHYP system (Automated Measurement of the Soil Hydraulic Properties) is being developed and tested at the Groundwater Research Center of the Dresden University of Technology in Germany, in cooperation with the U.S. Salinity Laboratory in Riverside, California, and the Department of Land, Air and Water Resources of the University of California, Davis. The system is designed to collect the following data:

1. Soil water retention data for the primary drainage curve starting at complete saturation, and for one of the scanning wetting curves,
2. Volumetric soil-water outflow/inflow data of the same sample at pre-selected capillary pressure heads,
3. Soil hydraulic conductivity data of the same sample at preselected water contents,
4. Identification of the unknown model parameters $\theta_{w,r}$, $\theta_{a,r}$, α_w, a,, n_d, n_w, m_d, m_w, and β from the observed retention and outflow/inflow data using computerized optimization techniques, and
5. Graphical representation of the final soil hydraulic functions given by (2) (3), and (4)

Hardware Structure of the AMHYP System

Figure 5 shows the hierarchical hardware structure of the AMHYP system. The system comprises three different levels: (i) a central or "master" level, (ii) a basic or "slave" level which executes commands received from the master level, and (iii) a process level consisting of the soil sample and instrumentation for process control and data collection.

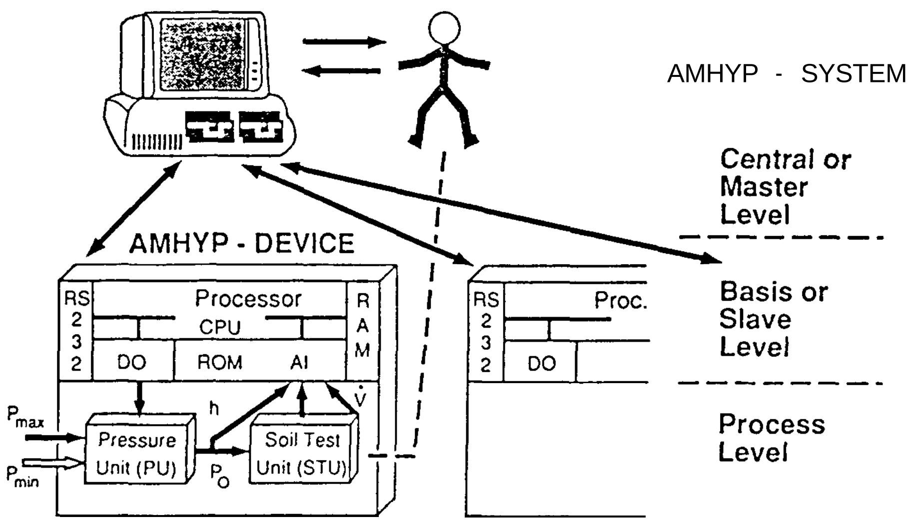


Fig. 5. Schematic of the AMHYP hardware.

Centml or Master Level. The central or master level consists of the AMHYP master computer in conjunction with laboratory personnel operating the computer. A personal computer such as an IBM-PC or compatible with a color graphics monitor and a printer to provide hard-copy capability, is well suited to fulfii the requirements. Most soil science laboratories are equipped with such computers for various tasks including data storage and analysis. Laboratory personnel interacts with the AMHYP master computer during design, control, analysis, and evaluation of the AMHYP experiments as shown in Figure 5, but does not interact directly with the computer facilities at the control or slave levels. Activities of laboratory personnel at the process level includes the placement and removal of soil samples prior to and after the tests.

Basic or She Level. This level contains processor units which communicate on-line but discontinuously with the master computer via RS 232 connection ports. The process units are, for this purpose, equipped with ROM- and RAM-units, analog input interfaces (AI), and digital output units (DO). The main task for the RAM-units in these processes include

1. Implementing instructions received from the "master" level.
2. Recording information such as sample data, results, and sending warnings or accident messages during automatic operation of the AMHYP device, and
3. Execution of the computer program which monitors and controls separate soil test units.

Thus, the master computer writes instructions into the slave's RAM units and reads from these units the recorded data. The ROM of the processor units are required to store the operational system, while the DO-units discontinuously emit amplified electrical signals to operate the control valves of the soil test units. This controlling operation must implement the required constant capillary pressure or pressure head and temperature in each soil sample until the volumetric water content θ approaches its equilibrium value.

The AI-units receive analog signals from **pressure** sensors which monitor the capillary pressure heads within the soil sample, from ***water level sensors*** which monitor the water level changes in the vessels, and from ***salinity*** or other ***water quality sensors*** which monitor continuously the quality of the extracted water sample. Analog-digital converters must adapt the received AI-signals to the BUS-signals of the CPU.

Process LeveL This level comprises the pressure units (PU) and soil test units (STU), including the temperature unit. The PU's produce and maintain any pressure or vacuum head as specified by the slave processor. Depending upon the selection of the experimental method (i.e., using pressure or suction) an external air pressure source and/or a vacuum source is required. The STU's permit testing of disturbed or undisturbed soil samples. They allow application of separate pressure or vacuum to each individual soil sample at a constant temperature. Water drained from the **soil** sample, or water used to re-wet the sample, is monitored by volumetric measurements with specially designed glassware or acrylic vessels equipped with water level sensors. The construction guarantees that the water level or water pressure in each vessel has no feed-back to the pressure head within the soil sample.

Option***al Extensions. The*** important effects of the particle-size distribution, particularly of the silt and clay fractions, on the soil water retention and hydraulic conductivity properties of soils are well established. Sieving machines with mesh and micro-sieves. and optical or laser equipped particle analyzers, are required tools in any soil-physics or soil-hydraulics laboratory. Figure 6 indicates schematically how particle-size distribution measurements can be integrated in the AMHYP system.

Software Structure of the AMHYP System

Figure also 6 shows the recommended structure of the AMHYP software package. The package includes software for operating the database (DB/LAB), and for analyzing particle size data (APSM) and soil hydraulic measurements (ASHT).

The DB/LAB Data Bank The database software, DB/LAB, uses the dBase IV database operating system. The software is written for laboratory personnel and students who have little or no knowledge of dBase IV. DB/LAB is implemented at the AMHYP master computer level and makes use of two software packages (APSM and ASHT) as shown in Figure 6.

APSM-Software. The APSM-software is used for

1. Correlating data of sieve analyses with data of optical particle analyzers,
2. Regression analysis of particle-size distribution data in a Logarithmic Normal Distribution Net, or in a the Double Logarithmic Net, and
3. Calculating integral characteristics such as specific surface and particle size distribution indexes.

The APSM-software generates graphical output of the final particle-size distribution and the selected soil type in terms of the textural triangle as shown in Figure 6.

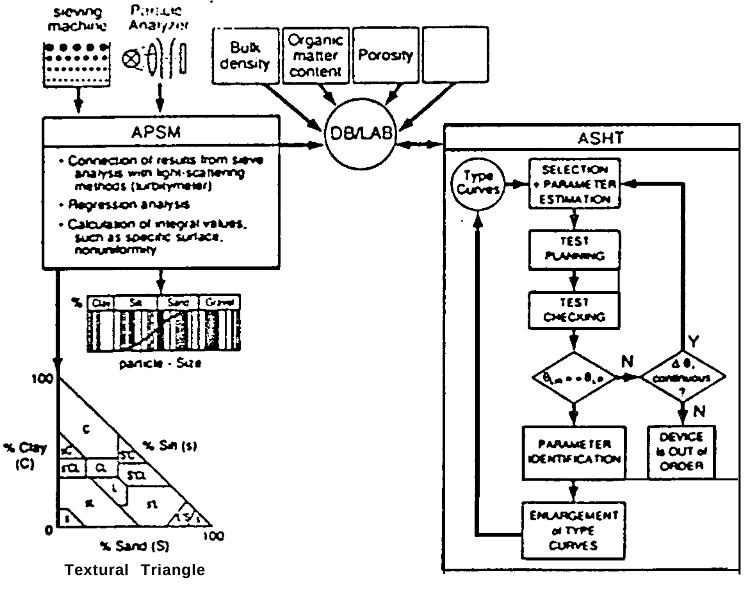


Fig. **6.** Suggested structure of the AMHYP software.

The ASHT Software. The ASHT software package contains software for test planning, automatic operation of the AMHYP system, and parameter identification [Nitsche and Luckner, 1987].

Test Planning. Test planning proceeds at the AMHYP master computer level. Based upon soil type, estimated porosity, bulk density, and optionally also soil texture and related data, the ASHT software provides initial estimates of the unknown hydraulic parameters embedded in (2). (3) and (4). For this purpose, **ASHT** extracts information from its type curve database and uses optionally also retention curves calculated from soil texture data. Results are presented in graphical form on the monitor.

Using the computer graphs, the user may interactively select target points $(\theta,h)_i$ on the drying or wetting retention curves. The target points should be selected such that they provide maximum information for the parameter identification process. Having these target points, ASHT calculates the amount of time necessary to execute the various pressure steps. The ASHT software also computes optimal target points $(H,t)_i$ for the Darcy-flux test procedure. The final test plan is stored into the memory of the "master", and from there into the memory of the "slave" computer. The test plan provides a basis for deriving control instructions.

Operation. After installing a water-saturated soil sample in the AMHYP device, the first target pressure head and temperature are imposed and automatically held constant until hydraulic equilibrium is reached (i.e., until the water level in the measuring vessel remains unchanged). AMHYP measures and stores the following data: (i) capillary pressure heads versus time (h,t), , (ii) water levels in the measuring vessel versus time $(H,t)_i$, (iii) data point (h,θ) of step i calculated from the final data points $(h,t\to\infty)$ and $(H,t\to\infty)$, (iv) temperatureversus *time,* $(T,t)_i$, and optionally, (v) $K(\theta)$ calculated from the data points $(H,t)_i$

Successive pressure steps are automatically imposed until the entire test program is completed. At any time the "master" can check the "slave's" records. After the data are transferred to the "master," a comparison of the measured data points with the predicted data points is displayed on the screen. The. AMHYP operator must now answer interactively a series of questions such as:

1. Are the monitored data points usable, or must the test be repeated?
2. Are the previous instructions valid for the next automatic operation period, or are new instructions required?
3. Which of the available software should be used for estimating the new instructions?

Depending upon the answers, the test may be continued or terminated.

Parameter Identification. The ASHT software also includes parameter identification procedures. The inverse procedures require initial estimates and optional range limits of the unknown hydraulic parameters. These values may be determined with the ASHT software package using type curves from the database. The resulting parametric models according to (2) (3) and (4) are displayed on the monitor, together with the measured data points. If the user accepts these results, the type curve database in ASHT is immediately updated. Final results are provided as printouts, or optionally as plots.

DATA VALIDATION

As an example we compare results obtained with the AMHYP system and the pressure membrane extractor. The experiment with the pressure chambers used the internationally agreed-upon U.S. Standard scheme. The soil was sieved through a 2-mm mesh and subsequently made into a paste by adding distilled water. The paste was transferred into polymer rings placed on ceramic plates. After post-saturation and allowing for a swelling period of approximately 18 hours, the desired boundary pressure was applied. Final measurements of the soil moisture content were done gravimetrically.

Undisturbed soil samples were used for the AMHYP measurements. The membrane test results for the main drainage curve showed significant deviations from those obtained with the AMHYP system(Figure 7). The deviations illustrate the importance of preserving the complete particle size distribution, the natural macro- and micro-pores, and the original organic matter content. Table 2 lists the hydraulic parameters as identified with the ASHT software.

The test results in Figure 7 demonstrate again the general need to standardize laboratory test equipment. Soil hydraulic properties determined with different hardware and software are often incompatible and should not be lumped immediately into the same hydraulic database.

TABLE 2. Identified Hydraulic Parameters Obtained with the ASHT Software†

Type of Curve	α	n	$\theta_{w,r}$	$\theta_{a,r}$	ϕ
DC - PME	34.56	1.51	0.024	0.0	0.225
PDC - AMHYP	26.24	2.77	0.03	0.0	0.225
MDC - AMHYP	26.87	2.70	0.03	0.015	0.225
MWC - AMHYP	43.96	2.36	0.03	0.015	0.225

† DC-PME : drainage curve measured with pressure membrane extractor
PDC - AMHYP : primary drying curve measured with the AMHYP
MDC - AMHYP : main drainage curve measured with the AMHYP
MWC - AMHYP : main wetting curve measured with the AMHYP

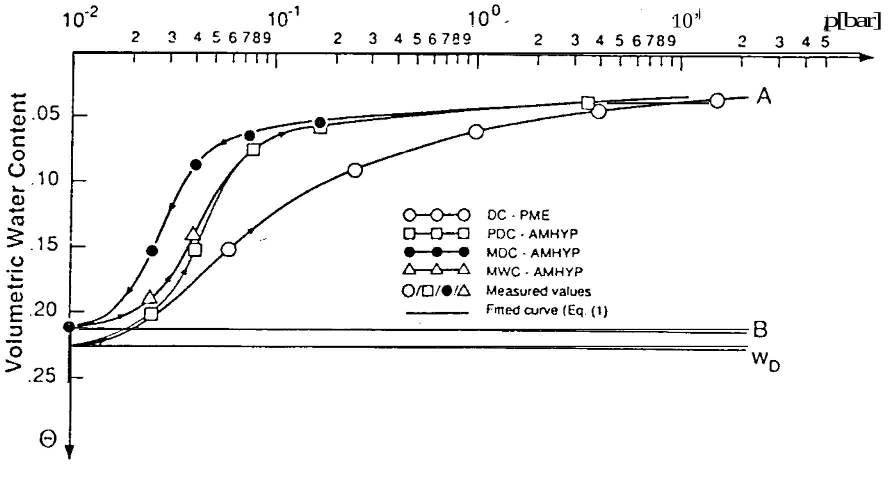


Fig. 7. Measured and fitted soil water retention curves using data from Table 2.

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