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Modified Pressure Plate Apparatus and Column Testing Device for Measuring SWCC of Sand

ABSTRACT: The determination of soil-water characteristic curve (SWCC) is of major concern in unsaturated soil mechanics. For decades experimental and theoretical studies are performed to investigate the constitutive relationship between soil suction and volumetric water content. The major objective of our study is to generate an extensive experimental database for sand with a relevant suction range of just a few kPa. This database enables to derive conclusions on the sensitivity of hydraulic properties regarding different experimental procedures. Further, one objective is the comparison of results for SWCC derived from steady state and transient state tests. While the first type of tests considers equilibrium states, the subsequent test is related to non-equilibrium states. Experimental results are generated from a so called homogenous element test (modified pressure plate apparatus) and an initial boundary value experiment (column testing device) considering different hydraulic loading path directions. The experiments are analysed for sand with different initial states. Finally results are presented for SWCC including initial curves, main curves, and scanning paths. Discussion is focused on transient state versus steady state flow tests. No significant dynamic effects are observed for the sand studied. Results of well controlled element tests compare very well to initial boundary value experiments implying higher experimental efforts.

KEYWORDS: unsaturated granular soils, Hostun sand, modified pressure plate apparatus, column testing device, SWCC, hysteresis, net stress

Introduction

There are many geotechnical and geoenvironmental engineering problems where unsaturated soils are encountered. An understanding of the hydraulic-mechanical behavior of the unsaturated soils is of great value in ensuring a proper engineering design. SWCC plays a key role in applying unsaturated soil mechanics in engineering practice. The suction versus volumetric water content, gravimetric water content, or degree of saturation is referred to as the soil-water characteristic curve (SWCC) or the water retention curve.

Experimental techniques for measuring the SWCC vary widely in terms of costs, complexity, and measurement range. It is possible to use different equipments to test the soil depending on whether the material is sand, silt, or clay. The Tempe pressure cell and other pressure plate apparatuses (Soilmoisture Equipment Corporation), thermal conductivity sensors (Phene et al. 1971; Fredlund and Wong 1989), thermocouple psychrometers (Spanner 1951; Richards and Ogata 1958), chilled-mirror hygrometers (Gee et al. 1992), and filter paper methods (Gardner 1937) can be used for the determination of the suction-water content relationship. Used techniques and measurement ranges of the above given equipments are summarized in Table 1. The Tempe pressure plate cell and other pressure plate apparatuses utilize the axis-translation technique (Hilf 1956) and have a measuring range between 0 and 1500 kPa depending on the ceramic disk placed in the device. These types of cells are often used to investigate porous material. For testing sand samples Eching and Hopmans (1993), Wildenschild et al. (1997), Wildenschild et al. (2001), and Chen et al. (2007)either used pressure cells or modified pressure cells.

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In order to identify SWCC from a certain type of experimental setup, several flow experiments are documented in literature (Schultze et al. 1997): (i) One-step flow experiment, (ii) multistep flow experiment, and (iii) continuous flow experiments. These experiments are performed under steady state condition (multistep flow) or transient state condition (one-step flow and continuous flow). By measuring flow data, water content, or suction during testing, an inverse simulation procedure enables to estimate hydraulic properties. Most reduced experimental approach is by just measuring outflow without any information on spatial and temporal variation of water content or suction in the specimens (Ligon et al. 1962; Kool et al. 1985; van Dam et al. 1992; van Dam et al. 1994). Authors report one-step outflow experiments from saturated conditions neglecting hysteresis effect, which is an important phenomenon in unsaturated soils. The interpretation of cumulative outflow measurements only and water content data leads to significant problems in the identification process (Carrera and Newman 1986; Toorman et al. 1992). Toorman et al. (1992) stated that the continuous measurement of both suction and cumulative outflow is the most adequate procedure for column outflow experiments (see also Carrera and Newman 1986). van Dam et al. (1992) found unreliable and non-unique estimates from one-step experiment using only outflow data. The authors suggest the outflow data to be a supplement with additional suction-water content measurements. Durner et al. (1999) reported on experimental work and sensitivity analysis using one-step, multistep, continuous outflow experiments, and instantaneous profile method. They conclude from their theoretical analysis that one-step outflow tests are ill posed from a mathematical point of view. They additionally observed dynamic effects for some type of soils, which are not in accordance with the common assumption of time invariant hydraulic properties. Effect of flow process to hydraulic behavior was presented also in earlier investigations (Topp et al. 1967; Smiles et al. 1971). Topp et al. (1967) found similar results when analysing static equilibrium and steady state results. Unsteady flow experiments in contrary lead to significant different hydraulic properties. Smiles et al. (1971) re-

TABLE 1—*Overview of equipment for measuring suction-water content relationship.*

Equipment	Technique	Type	Measurement Range 10^3 (kPa)
Tempe pressure cell	Axis-translation technique	Matric suction	0–1.5
Pressure plate apparatus	Axis-translation technique	Matric suction	0–1.5
Thermal conductivity sensor	⋯	Matric suction	0.01–1
Thermocouple psychrometer	Humidity measurement technique	Total suction	0.01–8
Chilled-mirror hygrometer	Humidity measurement technique	Total suction	1–450
Filter paper		Total or matric suction	0–1000

TABLE 2—*Literature review on flow experiments.*

Author	Experiment	Equipment	Method	Loading Direction	Material
Vachaud and Thony (1971)	Column device	3 T, GRA	Infiltration	Drainage, imbibition	Sand
Kool et al. (1985)	Tempe pressure cell	⋯	OM	Drainage	Sandy loam, silt loam, sandy clay loam, clay
van Dam et al. (1992)	Tempe pressure cell	⋯	OM	Drainage	Loamy sand, clay loam
Toorman et al. (1992)	Outflow apparatus	3 T, 3 TDR	OM	Drainage	Synthetic soil
Eching and Hopmans (1993)	Modified pressure cell	1 T	OM, MM	Drainage	Silt loam, loam, sandy loam, fine sand
van Dam et al. (1994)	Tempe pressure cell	⋯	OM, MM	Drainage	Loam
Wildenschild et al. (1997)	Modified pressure cell	PT	OM, TM	Drainage	6 different sands
Lehmann et al. (1998)	Column device	3 T, 7 TDR	TM	Drainage, imbibition, scanning curves	Sand
Ruan and Illangasekare (1999)	Column device	6 T	TM	Imbibition	Sand
Rassam and Williams (2000)	Column device	2 T, 1 TDR	TM	Drainage	Tailing samples, sand
Stauffer and Kinzelbach (2001)	Column device	4 T, GRA	MM	Drainage, imbibition	Sand
Wildenschild et al. (2001)	Modified pressure cell	2 T	OM, MM, TM	Drainage	Sand, fine sandy loam
Fujimaki and Inoue (2003)	Modified pressure cell	2 T	MM	Drainage	Loamy sand, sandy loam, loam
Chen et al. (2007)	Pressure cell	PT	M	Drainage, imbibition, scanning curves	Fine sand, ultra fine sand, silt

ported on dynamic effect on hysteresis for the desorption path but not for the sorption one. Good results were derived from tests including additional suction measurements or from steady state type tests, i.e., multistep flow method (see also Toorman et al. 1992; Eching and Hopmans 1993; Dam et al. 1994; Wildenschild et al. 2001). These authors did not take into account the hydraulic behavior during imbibition curves or scanning curves. However, some researchers also studied hysteresis effects measuring both water content and suction as a function of time and measurement position (Watson 1967; Vachaud and Thony 1971) in column tests. For different flux and pressure boundary conditions, Lehmann et al. (1998) analysed the water dynamics in a sand column with fluctuating capillary fringe by measuring water content [time domain reflectometry (TDR)] and suction (tensiometer). Lehmann et al. (1998) performed column experiments in which TDR sensors and tensiometer were not located in the same horizontal section. Due to different vertical coordinates of the sensors a direct link of measured suction and water content data was not possible. The influence of this irrigating capillary fringe is that the water content and suction distributions were increasingly dampened and shifted in time with increasing distance from the capillary fringe. Rassam and Williams (2000) developed an apparatus for determining SWCC using a dynamic method. The apparatus is equipped with two tensiometers and one TDR sensor. Whereas the tensiometers gave local measurements in the specimen, the TDR sensor measured water content above a height of 25 mm. Also the authors used the apparatus only for performing drainage cycle on coarse material. Another column for prediction of SWCC was developed by Chapius et al. (2007). However this cell was only used for determining drainage curves. Yang et al. (2004) presented a column device where TDR and tensiometer sensors in different depths measure water content and pore-water pressure. Their study is focused mainly on the equipment and gives only view results of suction-water content data. Table 2 gives an overview of former works on flow experiments.

TABLE 3—*Properties of Hostun sand.*

Specific gravity ρ_s [g/cm^3]	2.65
d_{60}	0.37
d_{30}	0.29
d_{10}	0.21
Coefficient of uniformity C_u	1.72
Coefficient of curvature C_c	1.05
Classification (USCS)	SP

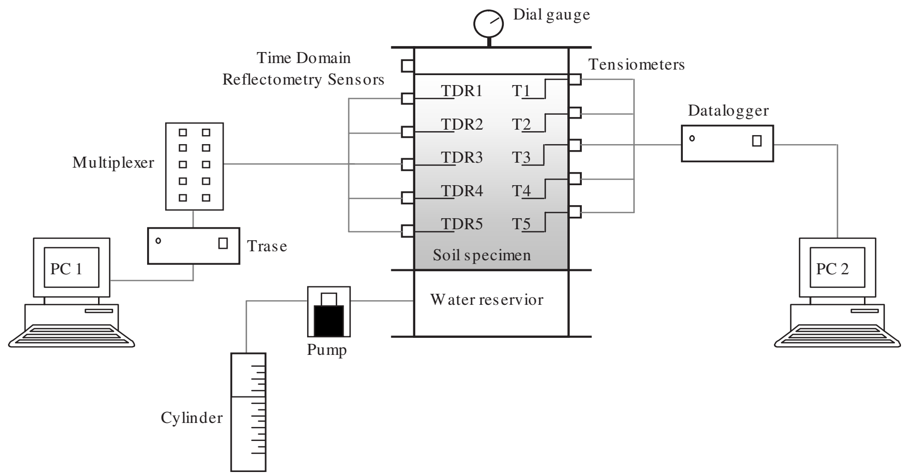

FIG. 1—*Setup of column testing device.*

In this investigation a data set of hydraulic measurements of unsaturated Hostun sand is given. Whereas former investigations are focused on drainage process, this work includes data obtained during drainage as well as imbibition processes and scanning process. Transient state tests were performed in a column testing device, where paired tensiometer and TDR sensors locally measure suction and water content in several depths. Thus inverse estimation of SWCC is not required. To prevent influence of dynamics on the hydraulic measurements, steady state tests were performed in the column testing device and in a modified pressure plate apparatus and compared to the transient state results.

Material

The experimental program associated with this study was conducted on pre-sieved Hostun sand, a reference sand that has been well studied in the literature (Flavigny et al. 1990; Schanz 1998). Hostun sand is quartz sand with grain sizes ranging from 0.1 to 1.0 mm in diameter. The material classifies as poorly graded medium sand (SP) according to the Unified Soil Classification System (USCS). Properties of the sand are summarized in Table 3.

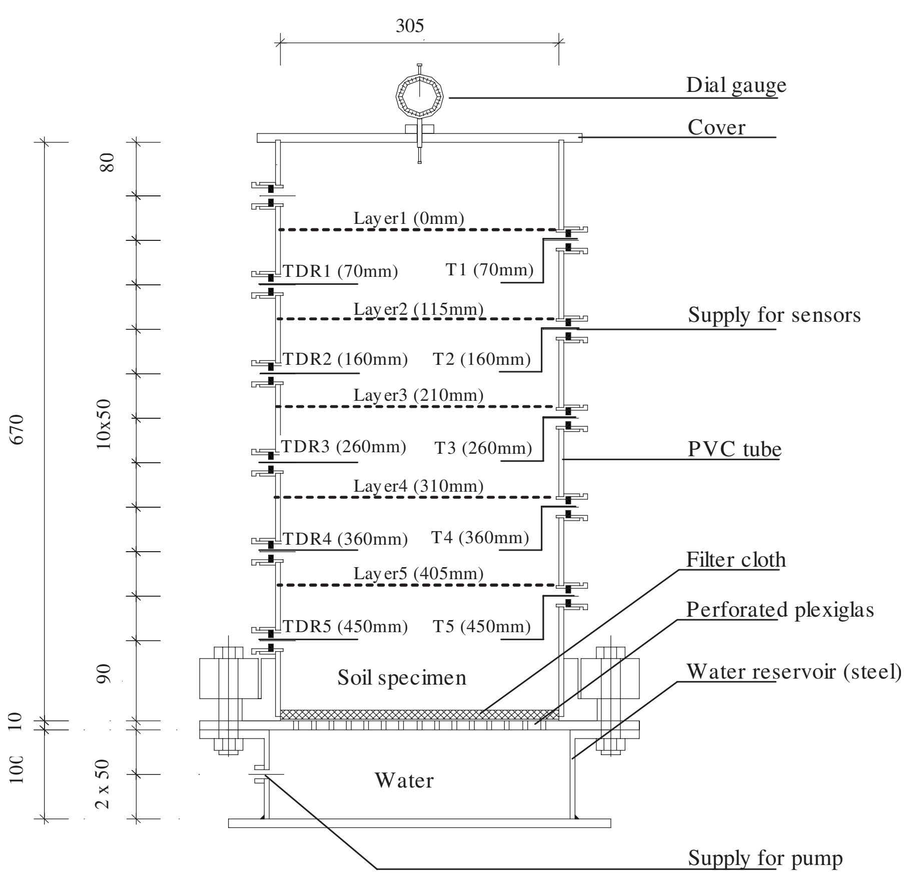

FIG. 2—*Cross sectional area of column testing device.*

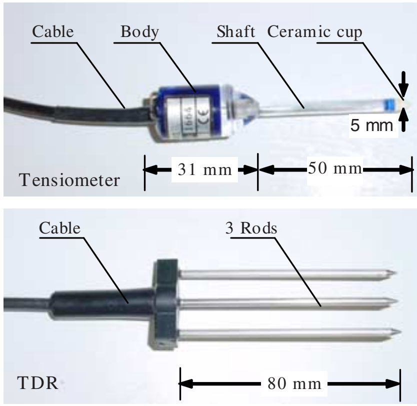

FIG. 3—*Tensiometer sensor (top) and TDR sensor.*

Description of the Apparatuses

Column Testing Device

A schematic sketch of the experimental setup is shown in Fig. 1. The setup consists of a Trase System including a multiplexer and five TDR sensors (TDR), five tensiometers connected to a datalogger, two computers for collecting experimental results, an electronic pump and a cylinder, and the main column. Details of the column device are shown in Fig. 2. In total the column is 780 mm high and 305 mm in diameter. A 540 mm high specimen was placed in the column by water pluviation technique. The bottom part of the column consists of a water reservoir made of steel. The top part of the column consists of a polyvinyl chloride (PVC) tube. The water reservoir and the PVC tube are separated by a perforated plexiglass plate. A highly permeable geotextile was placed between the soil specimen and the perforated plexiglass plate to avoid flushing soil grains into the water reservoir. Several ports along the column were

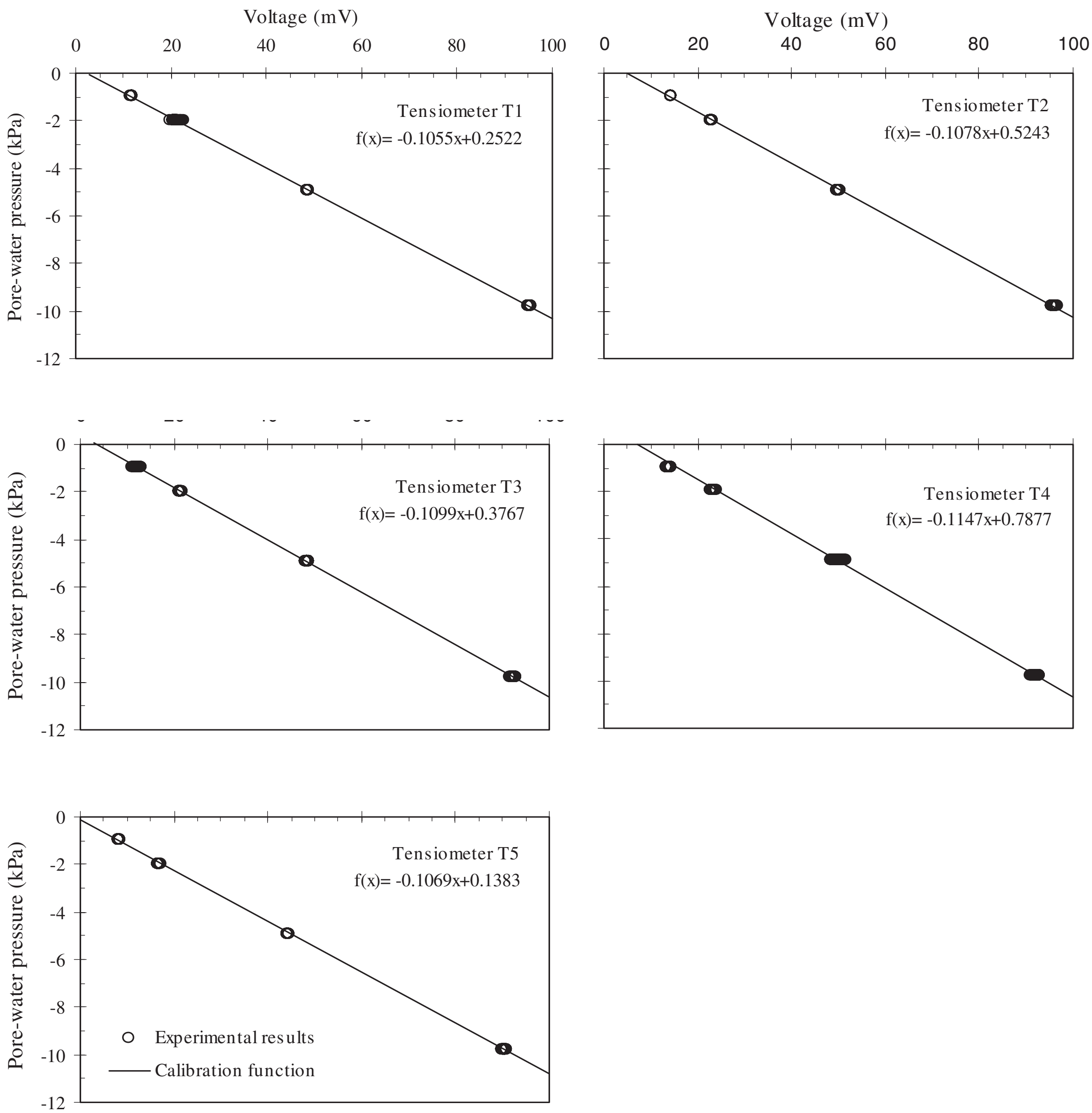

FIG. 4—*Calibration of tensiometers.*

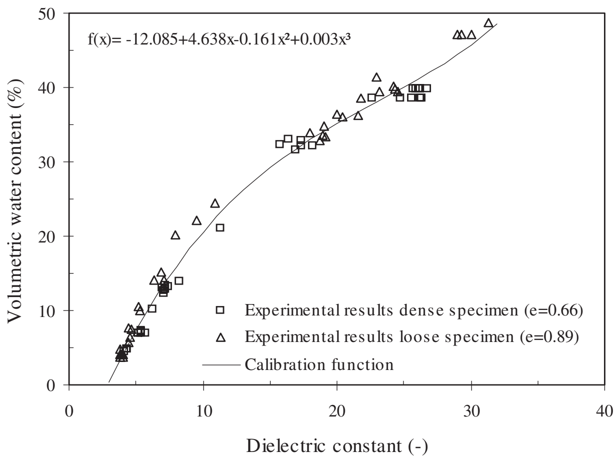

FIG. 5—*Calibration of TDR sensors for different initial void ratios.*

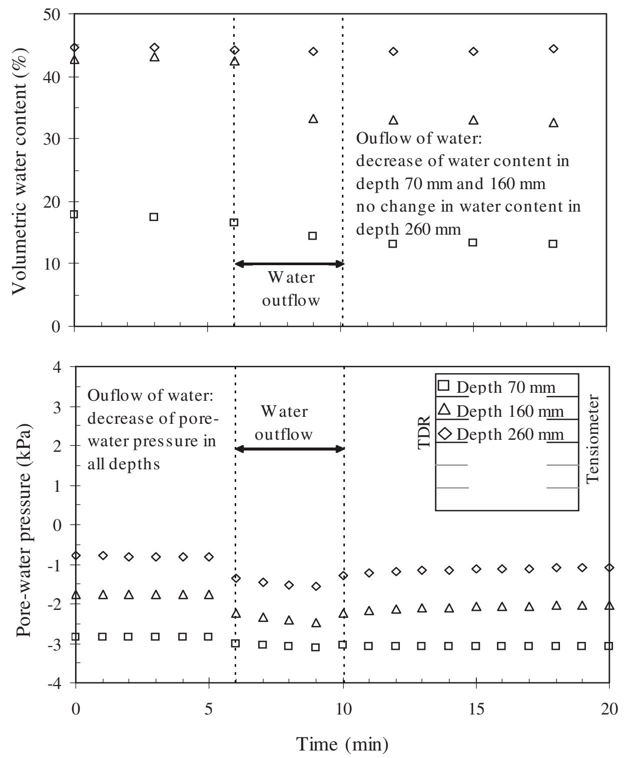

FIG. 6—*Verification of response time and suitability of TDR sensor and tensiometer measurements in column testing device.*

used for the insertion of measurement sensors. Five miniature tensiometers (UMS Umweltanalytische Mess-Systeme GmbH) and five three-rod miniature TDR probes (Soilmoisture Equipment Corporation) were placed in a row along the height of the column with a distance of approximately 100 mm between measurement points from the top of the sample. The three-rod TDR sensors were installed horizontally along the soil specimen. A TDR sensor and a tensiometer sensor were installed in each depth. The tensiometers have a measuring range from 100 kPa positive pore-water pressure to 85 kPa negative pore-water pressure with an accuracy of +/−0.5 kPa. The TDR probes measure volumetric water content over a range of 0–100 % with an accuracy of +/−2 % full scale. The sensors are shown in Fig. 3. An electric pump was connected to the reservoir at the bottom of the column to control the flow of water in and out of the column specimen at flow rates of 10–150 mL/min. Atmospheric pressure acted on the top of the sand column. To measure volume changes during the experiment a dial gauge was placed on the top of the specimen. The tensiometers were calibrated using predefined negative pore-water pressures (i.e., −1, −2, −5, and −10 kPa) through the use of a hanging water column. Results are given in Fig. 4, where the measurements on the tensiometers are related to the applied pore-water pressures. Each tensiometer showed a linear calibration relationship. The TDR probes were calibrated using Hostun sand samples with predefined water contents and void ratios. The calibration was done on separate plastic container with a height of 200 mm and a diameter of 300 mm, where the minimum distance between sensor and cell wall was maintained (Suwansawat and Benson 1999). The TDR probes were placed in the plastic cylinder, and the dielectric constant was measured, k_a, for wet sand specimens. After receiving constant value measurements, the water content was calculated by oven-drying the sand specimen. Knowing the water content, w, and the dry density, ρ_d, the volumetric water content, θ, was calculated and the dielectric constant, k_a, was related to the volumetric water content, θ. The dielectric constant, k_a, directly evaluated from the Trase System was used, that is, calculated from the following equation:

$$k_a = \left(\frac{t \cdot c}{L}\right)^2$$

where:

L=length of the waveguides;
c=speed of the light; and
t=transit time.

The transit time is automatically estimated by the Trase System. The calibration results for the TDR sensors are shown in Fig. 5, where the dielectric constant, k_a, corresponds to the calculated volumetric water content. Since the electrical conductivity of sand is extremely small, the density of the specimen does not influence this relationship. A polynomial function of third order was used to fit the dielectric constant to the volumetric water content.

To check reasonability and time response of TDR and tensiometer measurements, both sensors were checked in a previous test. However, a saturated sand specimen was prepared in the column testing device and drained. Both sensors show the response once the specimen is drained and reaches unsaturated condition as presented in Fig. 6. The results of the three top sensors are given. Other sensors are still in saturated condition. The sensors react fast and the measurements are reasonable.

Modified Pressure Plate Apparatus

The modified pressure plate apparatus allows the SWCC to be measured for both drainage and imbibition cycles as well as scanning drainage and scanning imbibition cycles (i.e., phenomena of hysteresis). The influence of net stress on the behavior of the SWCC can be determined by applying various total stresses to the soil specimen. A detailed cross section of the modified pressure plate apparatus is shown in Fig. 7. The apparatus has a specimen ring with a diameter of 71 mm and a height of 20 mm. A coarse porous stone is placed on the top of the soil specimen, and a ceramic disk is placed on the bottom of the specimen. In this study, the ceramic disk used below the soil specimen had an air-entry value of 100 kPa. A water reservoir is located below the high air-entry disk. A burette with a capacity of 25 cc was connected to the water reservoir. Water inflow and outflow were measured using the burette.

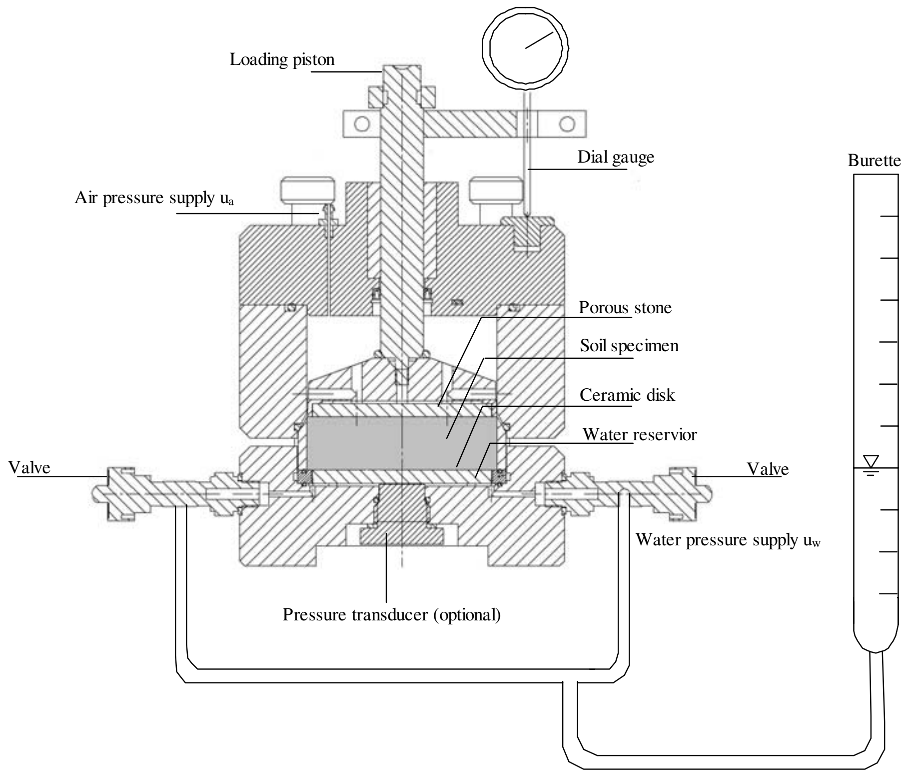

FIG. 7—*Modified pressure plate apparatus.*

Several wetting and drying paths were followed. An air pressure was applied to the top of the specimen through a coarse porous stone. Net stress can be applied to the specimen by placing the modified pressure plate apparatus in an oedometer loading frame. Volume changes of the specimens were measured using an attached vertical deformation dial gauge. For obtaining low suction values, hanging water column technique was used (Haines 1930). By lowering the attached burette with respect to the top of the ceramic disk, suctions of up to 4.0 kPa in steps of 0.1 kPa can be applied to the specimen. In this way, the initial points along the scanning imbibition curves on the main drainage curve, and vice versa, the initial points of the scanning drainage curves along the main imbibition curve, can be precisely applied. The burette has a resolution of 0.05 cc enabling precise readings of water inflow and outflow. Suctions up to 100 kPa can be applied to obtain test results along the SWCC. Air pressure was applied to the top of the cell using the axis-translation technique (Hilf 1956). Ceramic disk was saturated before to start the test.

Laboratory Testing Program

The laboratory program (see Table 4) consists of determining the SWCC under various loading conditions. Steady state as well as transient state tests were performed using the column testing device. Several drying and wetting curves were measured to investigate the influence of the loading history (i.e., drainage process, imbibition process, and scanning process), void ratio (i.e., loose specimen $e_0=0.89$ and dense specimen $e_0=0.66$), and water flow conditions on the shape of the SWCC. However, steady state tests only were performed using the modified pressure plate apparatus. The influence of loading path history (drainage process, imbibition process, and scanning process) and void ratio (loose specimen $e_0=0.89$ and dense specimen $e_0=0.66$) was examined. All tests were performed in a climate-controlled room ($21°C \pm 1°C$).

Tests Performed Using the Column Testing Device

Steady state experiments as well as transient state experiments were carried out using the column testing device. The sand used in this study is a poorly graded medium sand with insignificant amount of fine particles, where segregation is not influencing homogeneity. Therefore water pluviation technique was used to produce homogeneous sand specimen. Different procedures exist to prepare uniform and saturated sand specimens (Emery et al. 1973; Vaid et al.

TABLE 4—*Laboratory program.*

			Measurements			
Equipment	Test Method	Test Condition	TDR	Tensiometer	Cumulative Water	Loading
Column device	Transient state	Loose, dense	Yes	Yes	Yes	Drainage, imbibition
Column device	Steady state	Loose, dense	Yes	Yes	Yes	Drainage, imbibition
Modified pressure plate	Steady state	Loose, dense	No	No	Yes	Drainage, imbibition

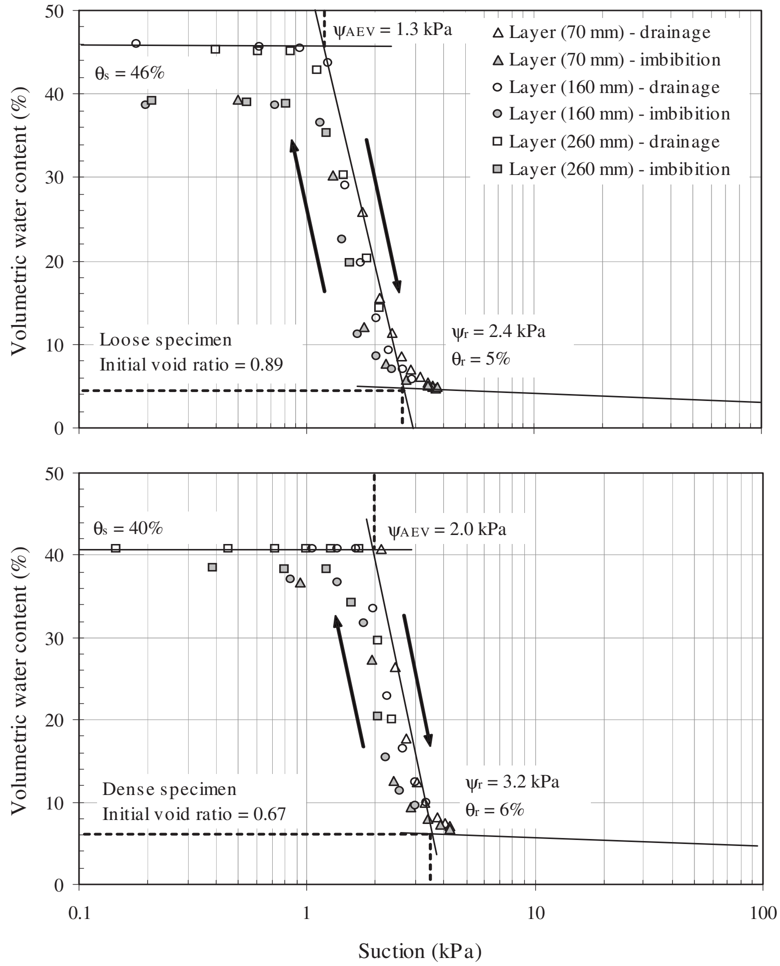

FIG. 8—*Readings from tensiometers and TDR sensors linked to drying and wetting path of suction-water content relationships of loose and dense specimens from steady state column test.*

1999). In this study the technique by water pluviation as described by Vaid and Negussy (1988) was followed. Saturation for the initial state was validated by two different approaches: (i) Knowing the initial void ratio and the volume of water infiltrated initial degree of saturation can be determined and (ii) initial water content measured by the TDR was compared to calculated saturated water content. Initial degree of saturation determined by these two methods was 1.0 for all samples. Loose and dense specimens with a height of about 540 mm were prepared. Starting with an initially saturated specimen, the sand was dried and wetted following various paths. Steady state tests performed in the column device involve withdrawing (drainage process) and injecting (imbibition) water in several steps (each 1000 mL) to the specimen. However, the next step was not applied to the specimen before reaching equilibrium ($\Delta\theta = \Delta\psi = 0,\ q = 0$) condition in the soil. Transient state tests performed in the column device include a continuous change in suction by withdrawing and injecting water to the specimen [(1) initial drainage process, (2) imbibition process, and (3) drainage process] with a constant flow rate (q=constant), where no equilibrium in the soil occurs. With a flow rate of 30 mL/min the outflow and inflow of water from the sand specimens were initiated using the electronic pump attached to the lower water reservoir. Transient state tests were performed to study the influence of water flow condition on the SWCC. Water was pumped out of the specimen until the water level reached the bottom of the sand specimen (drainage process), and then water was pumped into the specimen until the water level reached the top of the specimen (imbibition process). The applied flow rate caused a continuous change in suctions throughout the specimen.

Tests Performed Using the Modified Pressure Plate Apparatus

During steady state tests carried out in the modified pressure plate apparatus, suction was changed in several steps by applying negative pore-water pressure (hanging water burette) or air pressure to the specimen. The next suction step was not induced before reaching equilibrium condition ($\Delta V_w = 0,\ q = 0$) in the specimen. All tests were started at water saturated conditions. The testing procedure consisted of preparing a dry specimen with a predetermined void ratio, as a fixed ring specimen. The specimen was saturated by supplying required amount of water from the burette through the bottom ceramic disk. Full saturation of the specimen was assumed when the water table in the attached burette was equal to the top of the specimen. The specimens were subjected to a predetermined suction using either a suction mode test (i.e., applying a negative water pressure by hanging water column) or a pressure mode test (i.e., axis-translation technique). After the specimen had reached equilibrium (i.e., no water inflow or outflow), it was subjected to

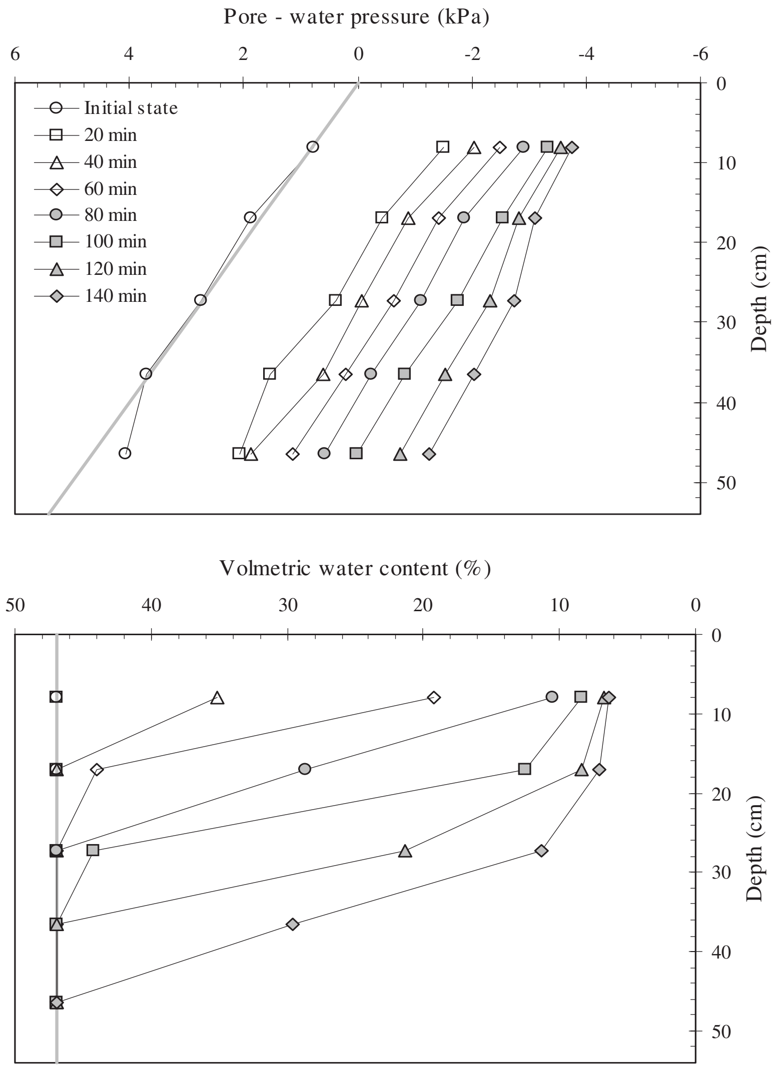

FIG. 9—*Pore-water pressure and volumetric water content elevation versus depth measured after each 20 min during initial drainage process in column testing device—loose specimen (transient state test).*

the next suction increment. The final gravimetric water content was calculated by oven-drying (ASTM Standard D2216, 1998: "Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass") the specimen at the end of the test. Volumetric water contents, degrees of saturation, and gravimetric water contents corresponding to each suction step were back calculated from these final values using incremental amounts of water flow from each step. To investigate the SWCC of the unsaturated sand, initially saturated loose and dense specimens were drained by applying suctions of up to 50 kPa and then wetted by applying suctions of up to 0.1 kPa. Scanning curves were determined by performing further drainage up to 2.2 kPa, imbibition to 1.0 kPa, and drainage to 2.2 kPa.

Experimental Results

Experimental results for the steady state tests and for the transient state tests (i.e., TDR measurements as well as tensiometer measurements and SWCC) carried out in the column testing device are presented first. Then the experimental results (i.e., cumulative outflow and inflow measurements and suction-volumetric water content relationships) for the steady state tests performed in the modified pressure plate apparatus are given. The volume changes measured were less then $\Delta e \pm 0.006$ in the tests performed in this study.

Experimental Results from Column Testing Device

Results from the steady state test performed are shown in Fig. 8, where the SWCC is given for loose and dense specimens for drainage and imbibition process. The air-entry value, ψ_{aev}, is approximately 1.3 kPa for the loose specimen and 2.0 kPa for the dense specimen. The residual suction, ψ_r, is equal to 2.4 kPa with a residual water content, θ_r, equal to 5 % for the loose sand as well as $\psi_r = 3.2$ kPa and corresponding $\theta_r = 6$ % for the dense sand. The observed imbibition curves found are scanning imbibition curves.

Results from transient state test are shown in Figs. 9–12. Figure 9 gives pore-water pressure and volumetric water content elevation versus depth for loose specimen from the initially saturated specimen. Figures 10 and 11 present exemplary results of loose specimen observed from TDR and tensiometer sensor measurements. Figure 10 presents readings from the drainage process. Tensiometer T (450 mm) measures a lower positive pore-water pressure than

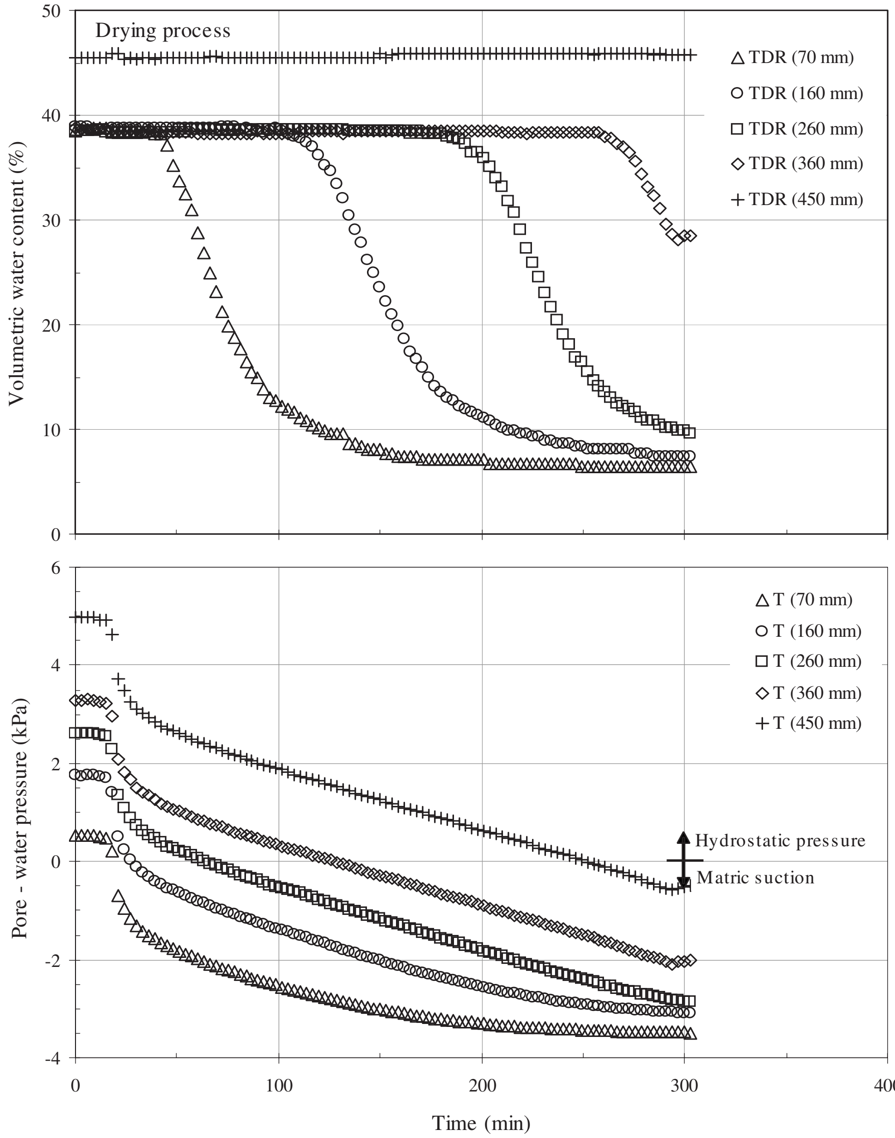

FIG. 10—*Variation in pore-water pressure and volumetric water content with respect to time during drainage process in column testing device—loose specimen (transient state test).*

tensiometer T (70 mm), indicating a higher hydrostatic pressure at the bottom of the specimen. The sand specimen is saturated and the measurements from the TDR sensors, TDR (450 mm) to TDR (70 mm), correspond to a degree of saturation close to 100 %. When draining the sand specimen, the positive pore-water pressures decrease until reaching negative pore-water pressures. The measured negative pore-water pressures (matric suction) at the end of the drying process are lower at the top of the specimen than at the bottom of the specimen. Consequently, the suction is higher at the top of the specimen than at the bottom of the specimen. During drying the volumetric water contents are decreasing, first at top of the specimen and then at the bottom of the specimen. Figure 11 presents readings from the imbibition process measured in a loose sand specimen. Tensiometer T (70 mm) measures a lower negative pore-water pressure than tensiometer T (450 mm), meaning that there was a higher suction at the top of the sand specimen. The measured volumetric water content at the top of the specimen is also lower than the volumetric water content at the bottom of the specimen. During wetting, the volumetric water content increases in relation to the decreasing suction. Saturated conditions are reached when the tensiometers measure positive pore-water pressures. During the wetting process the volumetric water content increases first at the bottom of the specimen and then at the top of the specimen. The wetting process is finished when the water table reaches the top of the specimen. Even when the water table is at the top of the specimen, measurements in sensors TDR (70 mm) to TDR (450 mm) correspond to water contents smaller than saturated volumetric water content, θ_s. The measured volumetric water contents reveal the influence of occluded air bubbles. Only the TDR (450 mm) sensor at the bottom of the specimen measures the volumetric water content corresponding to water saturated conditions. This portion of the specimen remains saturated during the entire testing procedure and consequently includes no occluded air bubbles. The tensiometer and the TDR probe measurements enable direct measurement of negative pore-water pressure and volumetric water content. Therefore, the generated SWCC directly can be plotted. For loose and dense sand specimens the measured SWCC is presented in Fig. 12. The drainage and the imbibition path measured in different depths are shown. It was observed that after the first wetting, complete water saturation was not subsequently recovered. The oc-

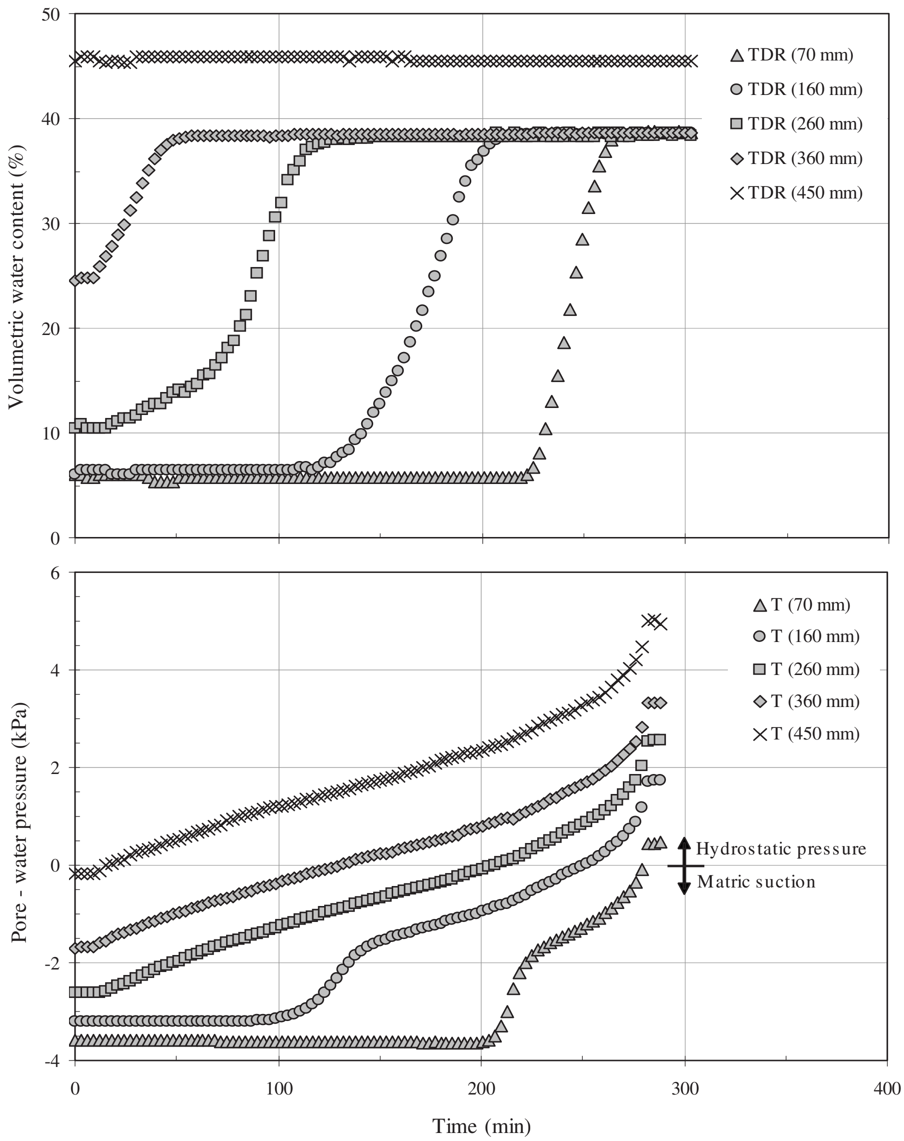

FIG. 11—*Variation in pore-water pressure and volumetric water content with respect to time during imbibition process in column testing device—loose specimen (transient state test).*

cluded air could not be displaced during subsequent wetting cycles. The air-entry value, ψ_{aev}, is approximately 1.5 kPa for the loose specimen and 2.1 kPa for the dense specimen. After reaching the air-entry value, the water content decreases rapidly for both sand specimens. The transition zone is between 1.5 and 2.8 kPa for the loose specimens and between 2.1 and 3.0 kPa for the dense specimens. The residual zone starts at relatively low suction values (2.8 kPa for loose specimen and 3.0 kPa for dense specimen) in the drying cycle for both sand specimens. The wetting processes result in different scanning curves. Different initial suctions and volumetric water contents along the column cause different scanning wetting curves. For the loose and the dense specimens the scanning curves measured in the upper part of the sand specimen start at a higher suction value than the scanning curves measured in the lower part of the sand specimen.

Experimental Results from Modified Pressure Plate Apparatus

Results of the steady state tests performed in the modified pressure plate apparatus are shown in Figs. 13–15. Experimental results of cumulative outflow and cumulative inflow of water during the drainage process, as well as during the imbibition process, are plotted in Figs. 13 and 14, exemplary for loose specimen. It took an elapsed time of 1000–8000 min to reach equilibrium conditions in the specimen depending on the suction level. After reaching the air-entry value, ψ_{aev}, the time required for equalization significantly increased for the drying path because large pores start to drain and large amount of water is leaving the specimen. During wetting path the elapsed time period to reach equilibrium conditions increased when passing the residual suction, ψ_r, where large pores start to absorb water. Back calculated SWCCs, including appropriate scanning curves, are presented in Fig. 15 for loose and dense sand. The air-entry value, ψ_{aev}, is approximately 1.4 kPa for the loose sand specimen. This value is smaller than that for the dense sand specimen that was approximately 2.0 kPa. After reaching the air-entry value, ψ_{aev}, the water content rapidly decreases with an increase in suction for both sand specimens. The transition zone is between 1.4 and 2.8 kPa for the loose specimen and between 2.0 and 3.1 kPa for the dense specimen. The residual zone starts at a relatively low suction value for the drainage cycle for the dense and loose sand speci-

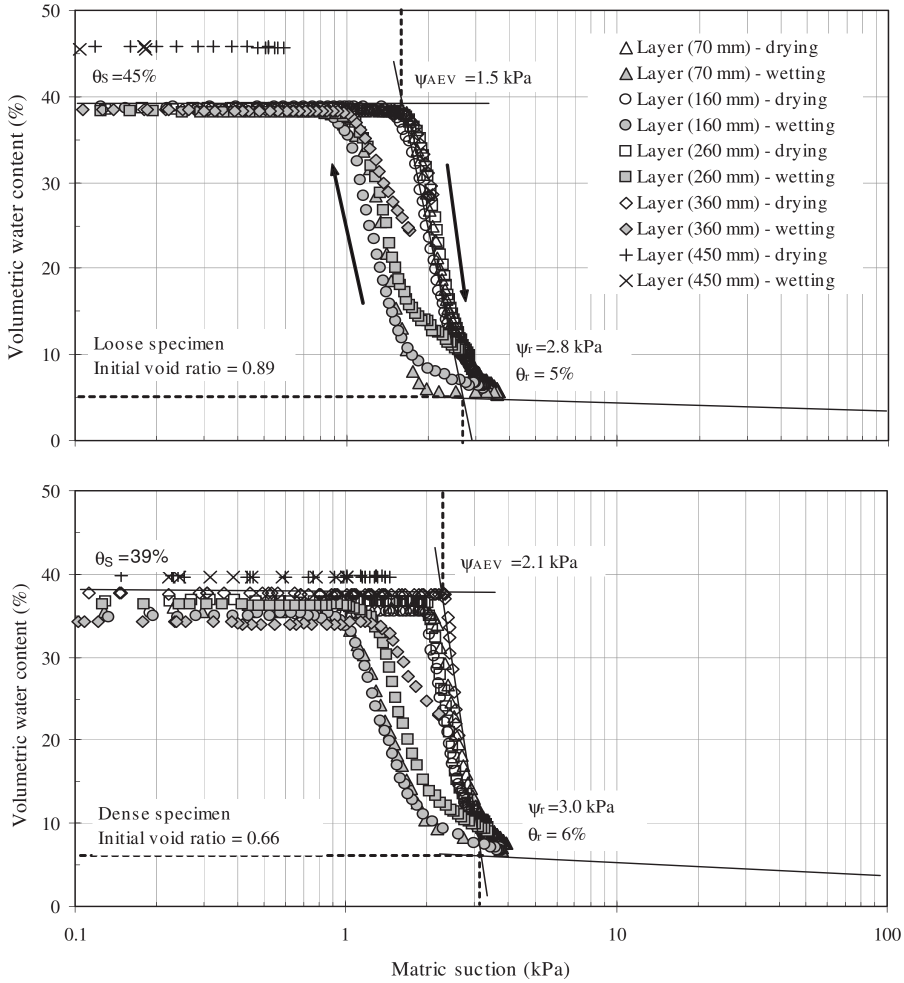

FIG. 12—*Readings from tensiometers and TDR sensors linked to drainage an imbibition path of suction-water content relationships of loose (top) and dense (bottom) specimens from transient state column test.*

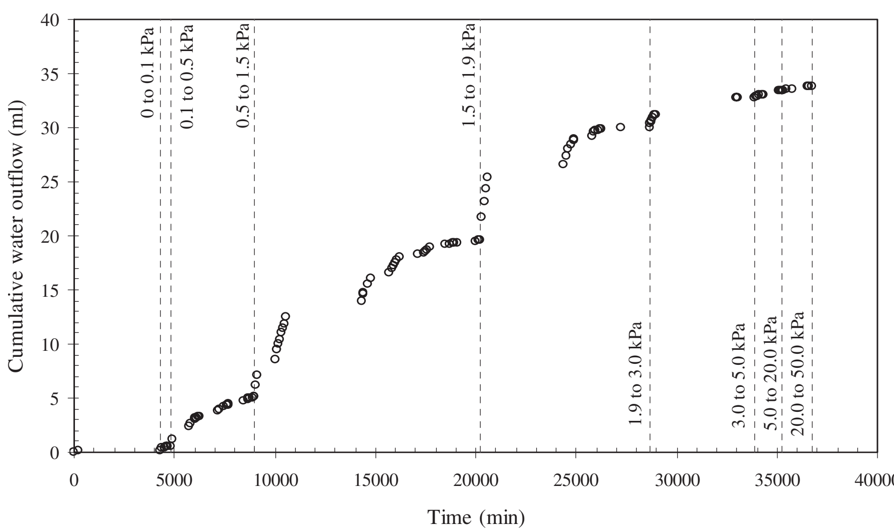

FIG. 13—*Effect of suction on drainage process in the modified pressure plate apparatus (steady state test).*

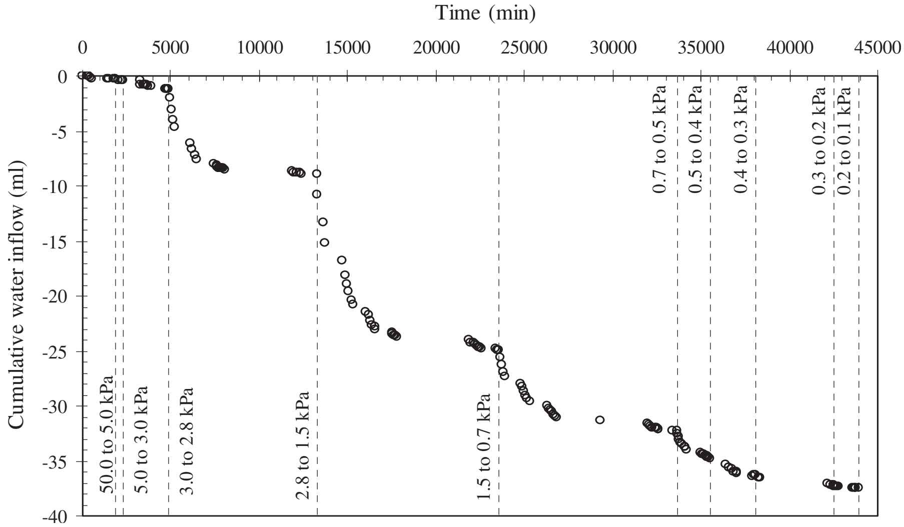

FIG. 14—*Effect of suction on imbibition process in the modified pressure plate apparatus (steady state test).*

mens. Along the imbibition path there is no significant change in water content measured in a range from approximately 50.0 to 3.0 kPa. The transition zone for dense specimen starts at a water-entry value ψ_{wev} of 2.9 kPa and for the loose specimen the water-entry value ψ_{wev} is 2.2 kPa. For the dense specimen the transition zone extends up to 0.5 kPa and up to 0.27 kPa for the loose specimen. The saturation zone falls within a relatively narrow range of suctions for both the dense and loose specimens. The scanning drainage cycle and the imbibition cycle were performed from a suction of 2.2 kPa on the drainage curve. Comparison of the scanning cycles for the loose and dense sand clearly shows that the dense specimen is retaining a larger quantity of water. The smaller voids in the dense specimen scanning cycle are located in the top part of the hysteresis loop.

Comparison and Discussion of the Results

SWCC parameters derived from sand column testing device (steady state method and transient state method) as well as modified pressure plate apparatus (steady state method) are summarized in Table 5. The comparison shows that independent of the equipment and the test method similar parameters were found for saturated water content, θ_s, air-entry value, ψ_{aev}, residual suction, ψ_r, and residual water content, θ_r, for each density. The overall behavior of the loose and dense sand specimens is comparable to the results from steady state tests in the modified pressure plate apparatus. The results are similar in a quantitative and qualitative sense. The performed experiments in the transient state tests (column testing device) respectively give similar results as the performed steady state tests. This leads to the conclusion that dynamic flow has no influence to the SWCC of this kind of material.

Comparison of the parameter observed for loose specimen and dense specimens shows larger air-entry value, ψ_{aev}, residual suction, ψ_r, and residual water content, θ_r, for the dense specimen. The dense specimen retains water up to larger suction values in its smaller pores. The saturated water content, θ_s, is smaller for the dense specimens than for the loose specimens, where a larger amount of water is required for full saturation of the pores. The experimental results for both loose and dense sand specimens showed significant hysteresis behavior. During the drainage cycle the suction, ψ, corresponded to lower volumetric water content, θ, than during the imbibition cycle. The hysteresis for the loose specimen enclosed a larger area than the hysteresis for the dense specimen. The results show also the phenomena of occluded air bubbles. This phenomenon was more significant for the transient state tests than for the steady state tests and is attributed to occluded air bubbles resulting from the initial drying process.

From the experiences derived by performing the presented experiments, we additionally can conclude the following remarks of advantages and disadvantages on the testing devices. The advantages of the column testing device are that steady state tests as well as transient state tests under various flow rates can be performed. The attached pump enables to determine the influence of flow rate on the hydraulic behavior of unsaturated sand. Because a permeable plate is used at the bottom of the cell, the procedure is a fast method to obtain hydraulic properties when sand is the investigated material in the equipment. Due to attached sensors, the results include volumetric water content versus time, $\theta(t)$, and suction versus

TABLE 5—*Determined parameters of suction-water content relationships.*

Equipment	Test method	Test condition	θ_s (%)	ψ_{aev} (kPa)	θ_r (kPa)	ψ_r (kPa)
Sand column	Steady state	Loose	45.0	1.3	5.0	2.4
Sand column	Steady state	Dense	39.0	2.0	6.0	3.2
Sand column	Transient state	Loose	46.0	1.5	5.0	2.8
Sand column	Transient state	Dense	40.0	2.1	6.0	3.0
Modified pressure plate	Steady state	Loose	46.0	1.4	4.0	2.8
Modified pressure plate	Steady state	Dense	39.0	2.0	3.1	3.8

time, $\psi(t)$, measurements. These measurements can be used for direct estimation of hydraulic conductivity (Instantaneous profile method). The hydraulic conductivity additionally can be indirectly estimated using the measured SWCC. The disadvantage is the expensive purchase of the required equipment (i.e., TDR sensors, tensiometers, and two computers). The equipment requires careful calibration procedure. The preparation of the specimen is time consuming and a large mass of material to be tested is needed. Due to large specimen size the specimen may be inhomogeneous. Also the specimen must be a disturbed specimen.

One advantage when using the modified pressure plate apparatus is that only a small specimen, thus a homogeneous specimen, is prepared. In comparison to the column testing device there is no need for local measurements of the water content. Due to the small size of the specimen, averaged water content is calculated using cumulative water flow. The application of small suction values along with small suction steps (suction control) enables a precise estimation of the shape of the SWCC and the parameters near the air-entry value, ψ_{aev}, residual suction, ψ_r, residual volumetric water content, θ_r, and water-entry value, ψ_{wev}. This is an important requirement when using the best-fit procedure on an equation. The drainage curve, imbibition curve, and scanning drainage and imbibition curves can be exactly measured (also for low suction values). The application of net stress enables the investigation of mechanical loading on an unsaturated soil. Measurements of changes in void ratio during drainage and imbibition of water to the specimen can be made. The apparatus is relatively inexpensive, small, and user-friendly. The 1 bar ceramic disk can be replaced with a 5 bar ceramic disk to investigate silt soils. Disadvantages are that only steady state tests can be performed. The testing procedure is time consuming. A permanent observation of water outflow and inflow is necessary in order to find equilibrium conditions.

Conclusions

In this study we derive SWCC including hysteresis and scanning paths from both steady state and transient state experiments. Such

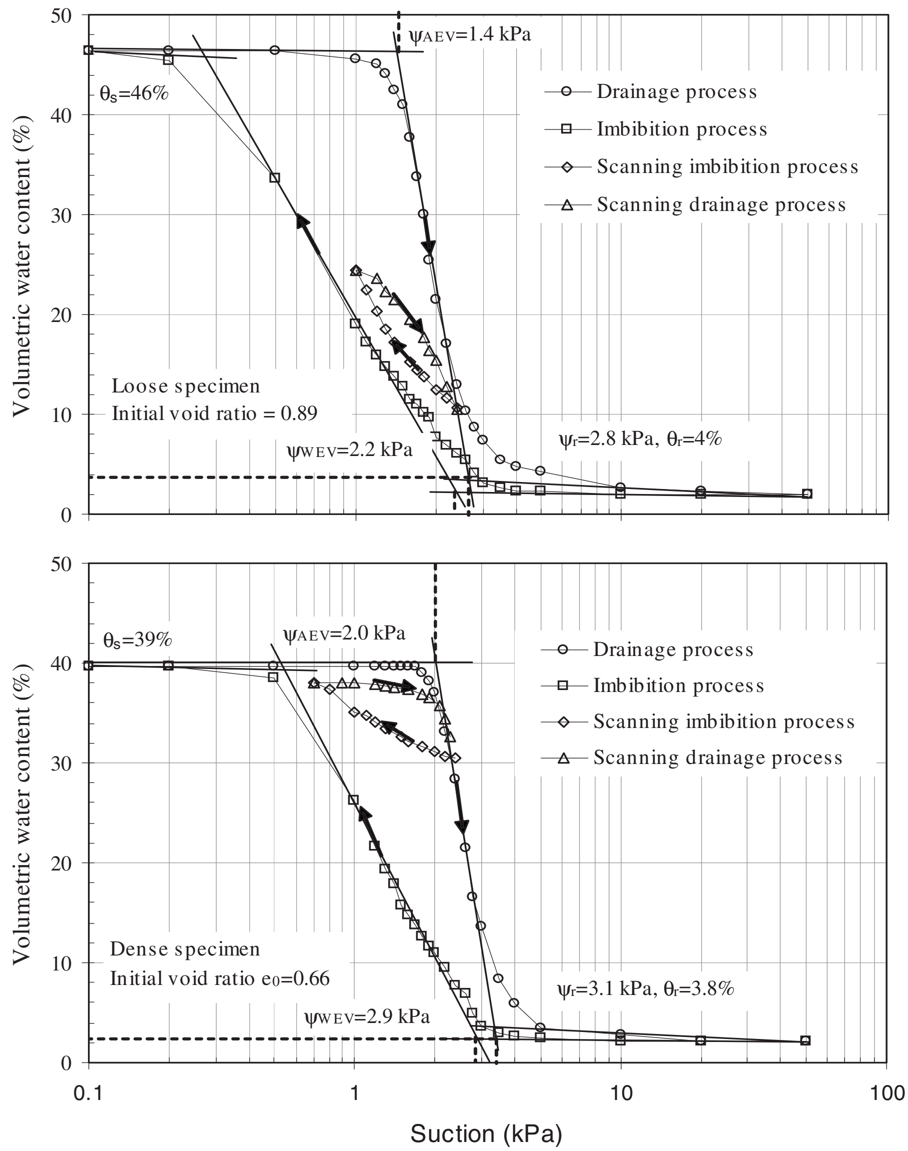

FIG. 15—*Experimental results of suction-water content relationship and scanning curves for loose and dense specimen from steady state test in modified pressure plate apparatus.*

an extensive experimental database considering initial state and different hydraulic loading pattern is very rare in literature. Even for relatively small values of applied suction, the modified pressure plate apparatus used allows for precise measurement of void ratio and water content changes by analysing fluxes at the boundary. Due to small tested volume size, averaging over samples height is acceptable. Results from modified pressure plate apparatus are then compared to those from column testing device local measurements of spatial and temporal variations in suction and water content in different sections.

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