Soils and Foundations 2012;52(2):368–380

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

Technical note

Automatic soil water retention test system with volume change measurement for sandy and silty soils

Qiang Liu, Noriyuki Yasufuku*, Kiyoshi Omine, Hemanta Hazarika

Department of Civil and Structural Engineering, Kyushu University, Nishi-ku, Fukuoka 819-0395, Japan

Available online 29 March 2012

Abstract

The determination of soil water retention curves requires the volume to be measured in order to calculate the void ratio and degree of saturation. The volume change of sample during drying and wetting cycles in soil water retention test is obvious and non-ignorable, especially for soils with deformability. The soil water retention curve is generally superimposed with the volume change of soil specimens. However, in general, many apparatus that are used for soil water retention testing cannot measure the volume change during the test process. In this study, a modified experimental system, which can measure and record volume change during test, and also can control the entire testing process via computer, is proposed to determine the soil water retention curve. The new system has several advantages over existing apparatus. Notable amongst them is that it can automatically determine both the wetting and the drying characteristics with high accuracy, and can measure volume change during test, using only one sample. This technical note presents the design detail and algorithm for control software. Water retention curves considering volume change are determined for four types of soil, ranging from sandy to silty. Then the effect of volume change on soil water retention curve is briefly discussed.

Keywords: Unsaturated soil; Soil water retention curve; Volume change (IGC: D4)

1. Introduction

Proper understanding of the soil water retention behavior is an essential precondition for a comprehensive description of unsaturated soils. The soil water retention curve (SWRC) is defined as the relationship between the water content (volumetric water content, water content or degree of saturation) and the matric suction of soil, which is the difference between pore air pressures and pore water pressure ($s = u_a - u_w$). The reliability in the determination of the soil water retention curve is of great interest in the research of unsaturated soils, as it is generally related to significant change in the unsaturated coefficient of permeability (Fredlund et al., 1996; Nishimura et al., 2006), shear strength of soils (Fredlund et al., 1996; Vanapalli et al., 1996), and particle size distribution curve (Kosugi and Hopmans, 1998). However, the soil water retention curve is not unique, and is usually referred to as hysteresis. For example, same soil may have different water contents at the same suction value in the wetting and drying process.

In laboratory and field tests, the suction and water content can be directly measured as a series of discrete data. The sample volume is required to be measured as it is used to calculate the volumetric water content or degree of saturation. There are various methods that can be used in laboratory tests for determining the soil water retention curve, such as the suction method, the pressurized method, the centrifuge method, the vapor pressure method and the

*Corresponding author. Tel.: +81 92 802 3381; fax: +81 92 802 3378.
E-mail address: yasufuku@civil.kyushu-u.ac.jp (N. Yasufuku).

Peer review under responsibility of The Japanese Geotechnical Society
doi:10.1016/j.sandf.2012.02.012

Production and hosting by Elsevier

Nomenclature

V_0	initial volume of soil specimen
V_{a0}	initial volume of air
e_0	initial void ratio
V_s	volume of soil solids
ΔV	total volume change
V_{af}	finial volume of air
e_f	finial void ratio
V_f	finial volume of soil specimen

psychrometer method (Japanese Geotechnical Society, 2000). Among them, the pressurized method is adopted most widely, since suction is easily controlled using this method: it utilizes the axis translation technique to impose suction on soil specimens. It is possible to control suction by applying air pressure to the sample. In this study this method is adopted.

Some apparatus that can obtain a soil water retention curve and hydraulic conductivity concurrently had been developed (Uno et al., 1990; Lu et al., 2006). Commercially available apparatus such as a Tempe pressure cell and the volumetric pressure plate extractor are commonly used for the laboratory measurements of the soil water retention curve. These apparatus are based on the suction method and the pressurized method, and the systems require data to be manually observed from time to time and do not consider the effect of volume change on the soil water retention curve. Likos and Lu (2003) developed a computer-automated experimental system for determining total suction characteristic curves using relative humidity control method. With further extension of the system, it can measure the axial strain at the same time (Likos, 2004; Likos and Lu, 2006).

There are various methods that can be used to measure the volume change of soil specimens (Head, 1980; Péron et al, 2007). The method in which the deformation of soil specimen is measured to obtain the volume change has been most widely adopted. A vertical load is applied to the sample to guarantee the contact between the samples and confining ring and, thus, the volume change due to suction change can be simply determined by monitoring the axial displacement of the top plate (Padilla et al., 2005). The merit is that the volume change of specimen can be measured continuously during both drying and wetting process by using only one specimen, assuming that the soil specimen is in full contact with the confining ring and that the volume change is homogeneous. In this study, this method is adopted to measure the volume change of soil specimen.

The soil water retention test is a tedious and time consuming test, and the long time required to achieve equilibrium of test tends to lead the operator to finish the test prematurely. Automating the test process using an automatic soil water retention test system can thus eliminate the artificial error. This paper focuses on the development of an automatic test system, which can be used to measure the volume change of soil specimen during drying and wetting process under one-dimensional and K_0 condition. Samples, varying from sandy to silty soils were used to verify the capability of the system. The merits and demerits of the system were discussed and the effect of volume change on soil water retention curve was briefly indicated on the basis of the obtained experimental data.

2. Automatic soil water retention test system

2.1. Components of equipment

The setup of the automatic soil water retention test system and main unit used in this study is shown in Photo 1. The automatic soil water retention test system consists of a measuring unit, which is similar to oedometer-type device, control software and an air pressure compressor. The automatic soil water retention test system is schematically shown in Fig. 1. As shown in the figure, the top plate is modified by fixing a displacement gage using a screw. The diameter of specimen is 51 mm and the height is 50 mm. A porous plastic plate was put on the top of the soil specimen that exerts an overburden pressure of 0.7 kPa on the specimen, and therefore can be neglected. The base plate is connected to a four-way connector. The other three connections are to a tube, a water supply tank and a water pressure transducer, as shown in Fig. 1. The tube is used for storing or supplying the water, which is released from or absorbed into the specimen. The water pressure transducer is used to measure water pressure in the tube. This value together with the area of tube was used to calculate the change of water content of specimen. The water supply tank is used for supplying water to the specimen during saturation process. On the top of water supply tank, there is a vacuum generator. It can produce a vacuum environment in water supply tank in order to produce non-air water using high-speed airflow method. Before starting the

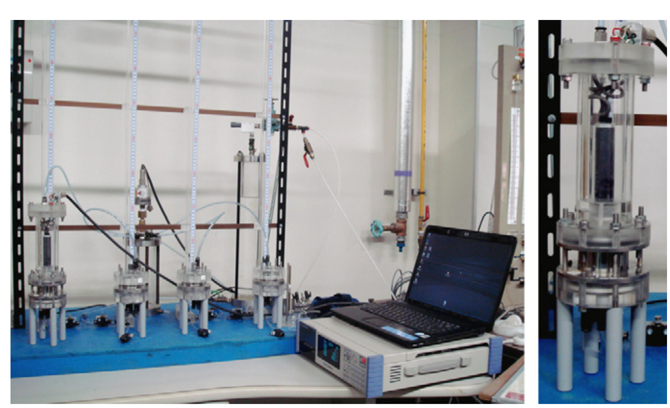
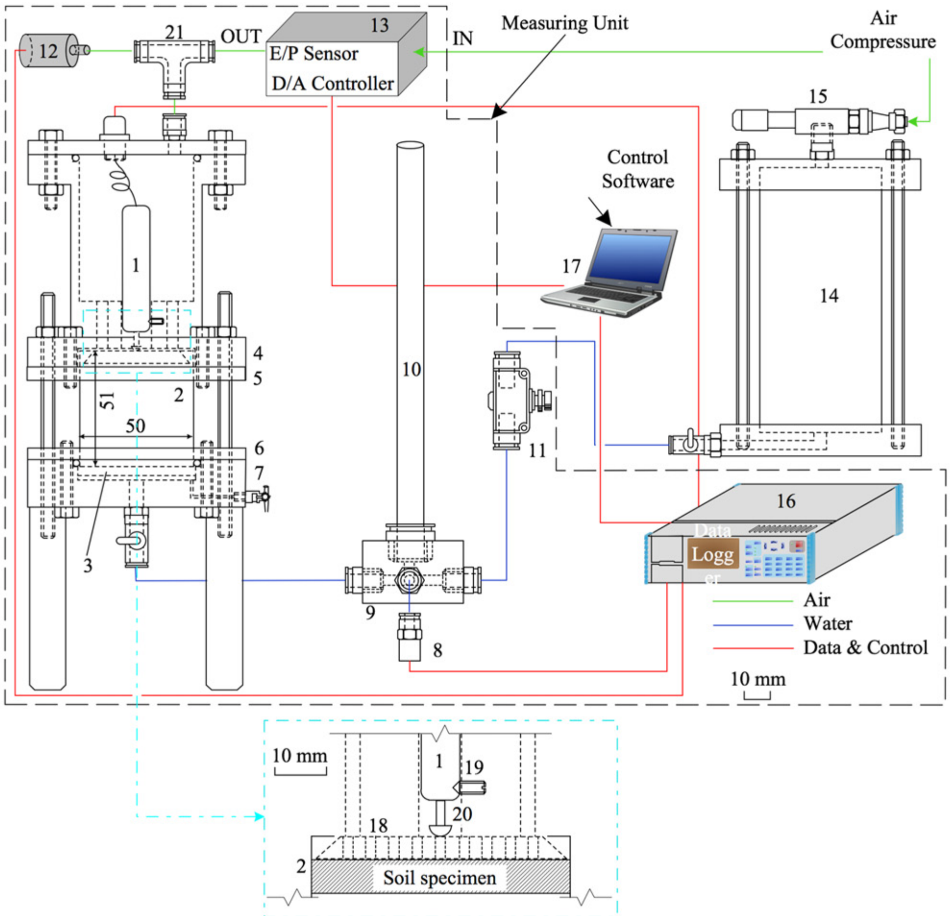


Photo 1. Set up of automatic soil water retention test system (left) and main unit (right).



No	Accessory	Functions and Remarks
1	Displacement gauge	Indicate the vertical displacement, (the accuracy is 0.001 mm)
2	Sample chamber	Place soil specimen, (the volume is 100 cm³)
3	Ceramic disk	Air entry value is 200 kPa
4	Top plate	Fix displacement gauge
5	Top metal ring	Fasten top plate and seal
6	Base metal ring	Fasten bottom plate and seal
7	Base plate	Place ceramic disk and collect water
8	Water pressure transducer	Indicate the volume change of water, (the accuracy is 0.01 kPa)
9	Four-way connector	Connect bottom plate, tube, water pressure transducer and water supply tank
10	Tube	Storing water, (inner radius is 4 mm)
11	Valve	Control water in and out from water supply tank
12	Barometer	Verificating air pressure on soil specimen, (the accuracy is 0.05 kPa)
13	Control box	Electro-pneumatic pressure (E/P) regulator, a digital to analog (D/A) converter and an air pressure regulator, generating target air pressure by using computer
14	Water supply tank	Demineralized water
15	Vacuum generator	Generate vacuum
16	Data logger	Accept command and measuring data (can be replaced by data acquisition chipset)
17	Computer	With USB or RS232 connector
18	Porous plastic plate	Weight is 7.77 g
19	Screw	Fixing displacement gauge
20	Contact point	Maximum force is 1.47 N
21	Three-way connector	Connect main unit, barometer and air compressor
	Others	Air compressor, screwdrivers etc.

Fig. 1. Schematic outline of the automatic soil water retention test device.

test, the valve of the water supply tank is closed. The top plate is connected to a three-way connector. The other two connections are with a barometer and a control box, which contains an electro-pneumatic pressure (E/P) regulator, a digital to analog (D/A) converter and an air pressure regulator. The barometer is used to measure air pressure, which is added to the specimen. The control box is used to supply steady air pressure to the specimen and this process can be controlled by signal from computer. All the three sensors are connected to a data logger, which is connected to a computer. The function of each accessory is summarized in Fig. 1.

2.2. Algorithm of control software

The control software is originally developed by authors to control the whole test procedure, which was compiled by Visual Basic language. Fig. 2 shows the flowchart of the core part of the software. The control procedure starts from inputting experiment condition (e.g. number of samples, cycle number of drying and wetting processes, target air pressure, [P], or suction, [S], in every steps. The software reads water pressure continually until a constant value is obtained. This constant value is recorded as an initial value. Then the software sends out a signal to electro-pneumatic pressure (E/P) regulator to adjust the output air pressure, P_i, which is applied to the soil specimen. After that, the program continuously loops until it is interrupted by system task. The interval of system task

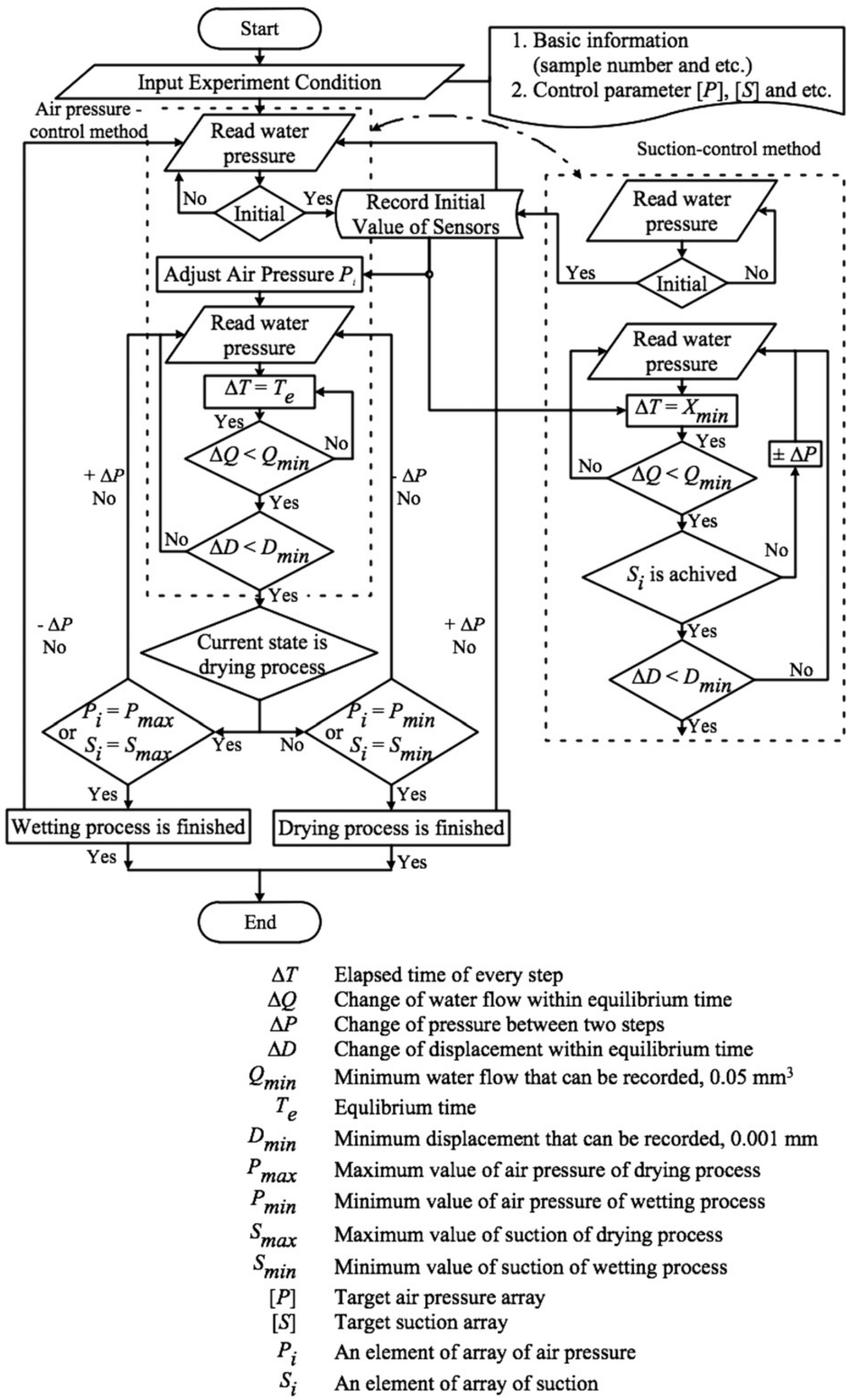


Fig. 2. Algorithm of control software.

is invoked by the timer-control at any interval (e.g. 0.2, 1, 5, 10, 20, 30, 60 s). Each system task begins by reading the water pressure, and then the program counts until the end of the elapsed time, ΔT. When the elapsed time is larger than equilibrium time, T_e (which was input before testing), the program checks whether the equilibrium states, which include both the water pressure transducer and the displacement gage, of the soil specimen are achieved or not. Essentially, the selection criterion of equilibrium time is decided by the hydraulic conductivity of soil. The mean of selected equilibrium time is to ensure that the hydraulic conductivity of soil is larger than the readable hydraulic conductivity, which is the minimum calculated value based on the equilibrium condition. When the hydraulic conductivity of soil is larger than the readable hydraulic conductivity, it means that the amount of water from drainage or absorption can be measured. Fig. 3 shows the relationship between the readable hydraulic conductivity and suction at different conditions of volumetric flow rate (different equilibrium time). According to the relationship ($J_w = -k\partial H/\partial z$) among the hydraulic conductivity, k, gradient of water potential, $\partial H/\partial z$ and volumetric flow rate, J_w. In order to get the equivalent hydraulic conductivity, it is necessary to obtain the volumetric flow rate and the gradient of water potential. According to the definition of the volumetric flow rate, $J_w = Q/At$, where, Q is the quantity of water, A is the area of cross-section of specimen, t is the equilibrium time. The volumetric flow rate can be calculated as follows.

The readable water head of the water pressure transducer used in this study was 1 mm. Therefore, the readable quantity of water flow is 0.05 cm^3, because diameter of water collection tube is 4 mm. When assuming that the equilibrium is 1 h, considering the cross-section area of soil specimen is 19.6 cm^2 and, the volumetric water flow rate, J_w, is calculated to be 7.1×10^{-7} cm/s. Thus, assuming the suction of soil specimen is 1 kPa and considering the height of the specimen is 5.1 cm, the gradient of water potential is

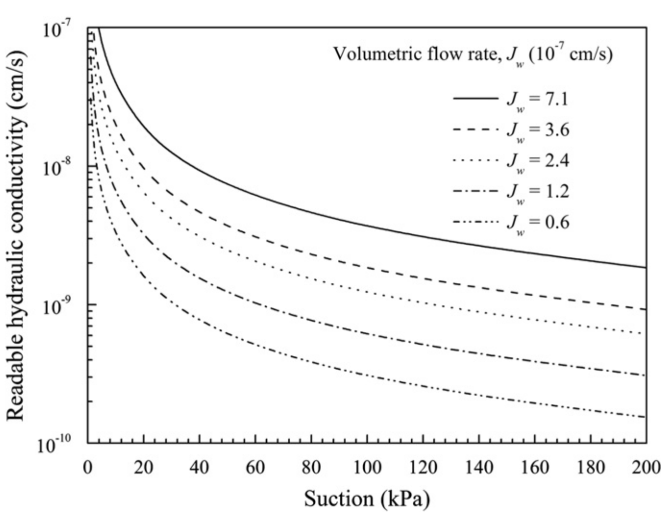


Fig. 3. Relationship between readable hydraulic conductivity and suction.

equal to 1.9. Finally, the readable hydraulic conductivity becomes around 3.7×10^{-7} cm/s. The amount of water in the tube can be used to track the water content in the specimen at any time. The equilibrium state is assumed to be attained when no more water moves out of or into the specimen which means change of water flow, ΔQ, is less than the minimum water flow, Q_{min} within equilibrium time, and no volume change occurs in the soil specimen or the speed of volume change can be neglected, which means the change of displacement, ΔD, is less than minimum displacement, D_{min} within equilibrium time. In this study, in order to judge the equilibrium condition, the conventional equation is adopted, which is described in Appendix A. In this study, the values of standard deviations of data are chosen as 0.025 and 0.0025 for the water pressure transducer and the displacement gage, respectively. These values correspond to Q_{min} and D_{min}, respectively. The whole process of judgment is done by the control software automatically.

When the equilibrium of the soil specimen is achieved, the program judges the three conditions of the test in order to decide whether the test should be terminated or not. Firstly, the program judges the first condition of test: whether the current test process is under drying process or wetting process. If the test is under drying process, then the program judges the second condition of test: whether the drying process of this cycle is finished or not by comparing current value of air pressure or suction is equal to value of maximum air pressure, P_{max}, or suction, S_{max}. If the drying process of this cycle is finished, the program judges the third condition of test: whether there are still wetting cycles that need to be executed or not. If there are no tasks left, the whole test will be terminated by closing all the sensors and returning back to the main program. Otherwise the program automatically shifts to the wetting process and the test continues.

Two methods (air pressure control method and suction-control method) are provided to the user to control the test process. The air control method will adjust the air pressure to the target value of air pressure in every step. However, the suction-control method will adjust the air pressure to fulfill the target value of suction in every step. The two doted frames shown in Fig. 2 can replace each other. The algorithm of suction-control method is briefly described in Appendix B.

3. Materials and methodology

Four kinds of soils, varying from sandy soil to silty soil, were used in this study. The four soils were: K-8, Takeda, Sasaguri and Fukuchi. K-8 is a commercially available soil. The other three soils were taken from a site where slope failure occurred. Takeda is a sampling from Takeda Town of Oita Prefecture (Japan), Sasaguri and Fukuchi were obtained from Kasuya District and Tagawa District of Fukuoka Prefecture (Japan), respectively. The grain size distribution curves of these soils are given in Fig. 4. Basic properties of soil samples are shown in Table 1. The soil sample was oven dried and passed through a 4.75 mm sieve. All samples were mixed with water at a water content of 5%. The required amount of soil is put into sample chamber and compacted to target density. Displacement is measured by using a digital displacement gage with a resolution of 0.001 mm. The tests were performed at a constant temperature of 25 ± 1 °C.

The test procedure starts from the saturation of a ceramic disk, which has an air entry value of 200 kPa, by immersing it in to a vacuum cylinder and leaving it for at least one day. Then the base plate and corresponding tubes were connected and filled with none-air deionization water. The ceramic disk is then put into the bottom of the plate and the sample chamber and the accessory seal rubber ring is assembled and fastened to the base plate. The specimen is placed on the top of a water-saturated, high air entry value ceramic disk or a cellulose membrane, which allows the water pressure to be controlled in the soil specimen. After that, the prepared specimen is saturated by maintaining a positive water head through the base plate. During the saturating process, the water head in tube was recorded from time to time, until the constant water head is achieved, and then top plate is assembled.

The tube was vented to atmospheric pressure all the time. At the beginning, the atmospheric air pressure was maintained in the specimen until the water pressure in the tube becomes constant. The constant value was recorded as the initial value (Fig. 2). Then the air-pressure is increased through the inlet tube on the top plate to another value following a data array, which was input before the test as basic information. Water starts draining from the specimen through the porous barrier until equilibrium is reached. When the equilibrium condition is achieved, the software automatically records the corresponding air pressure and water pressure. The air pressure was then increased to another value, and this procedure was continued until the drying process was accomplished.

After completing of the drying process, the test was continued for the wetting process, if it is set in the beginning. However, when wetting process does not start from the extreme dry condition (e.g. suction is 1500 kPa), the obtained curve is not the main curve but a scanning curve. The corresponding data of the drying and wetting path is recorded and calculated by the computer. Each matric suction value is calculated from the air pressure and corresponding water pressure. When the whole test process is completed, the sample is taken out to measure the water content by oven drying. This water content, together with the previous changes in the tube, is used to back-calculate the water content corresponding to the other suction values.

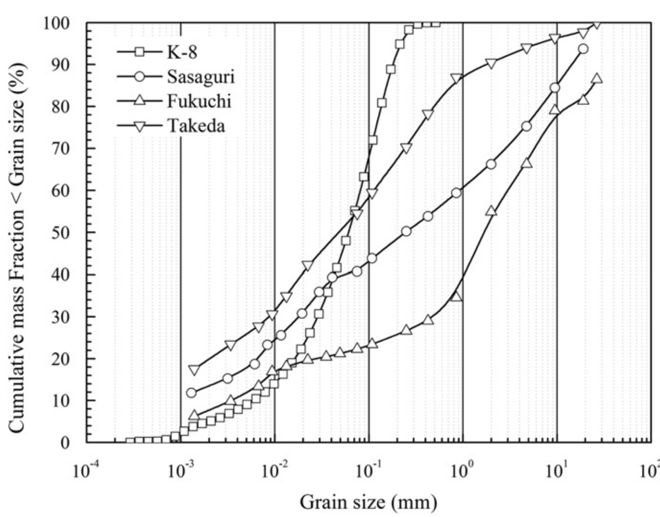


Fig. 4. Grain size distribution curve of soil samples.

4. Theoretical analysis

The soil water retention test can be considered as a form of special compression in a drained condition. The total volume change during the soil water retention test generates from the rearrangement of soil solids. A detailed analysis is described in the following section. A primary assumption of this analysis is that the process is an isothermal one.

4.1. Air phase, water phase, soil particles

Among the three phases of unsaturated soils, the air phase is most easily compressed. By using the definition of air compressibility (Eq. (1a)) and Boyle's law, the compressibility of air can be expressed as Eq. (1b)

$$C_a = -\frac{1}{V_a}\frac{dV_a}{du_a} \tag{1a}$$

$$C_a = -\frac{1}{u_a} \tag{1b}$$

Table 1
Basic properties of soil samples.

No.		Specific gravity of soil particle G_s	Liquid limit w_L (%)	Plastic limit w_P (%)	Plastic index I_P	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Uniformity coefficient U_c	Curvature coefficient U_c'
1	K-8	2.69	–	–	–	0	45.5	45.5	9	13.6	1.53
2	Takeda	2.66	62.7	29.0	0.34	10	36	29	25	–	–
3	Sasaguri	2.82	67.5	39.2	0.28	33.8	25.5	23.7	17	1000	0.324
4	Fukuchi	2.89	55.1	33.3	0.22	45.1	32.7	10.2	12	857.1	23.8

where C_a is the isothermal compressibility of air, V_a is the volume of air, dV_a/du_a is the air volume change with respect to the change of air pressure and $\bar{u}_a$ is the absolute air pressure. Eq. (1b) shows that the isothermal compressibility of air is inversely proportional to the absolute air pressure. In other words, the air has greater compressibility when the absolute air pressure is small (Fredlund and Rahardjo, 1993). However, most of the air phase is exposed to an air compressor. This part of the air has no effect on the volume change of the soil specimen. Only the other part of air, which is the enclosed air, contributes to the volume change of the soil specimen.

The compressibility of water is defined as follows:

$$C_w = -\frac{1}{V_w}\frac{dV_w}{du_w} \quad (2)$$

where C_w is the isothermal compressibility of water, V_w is the volume of water, u_w is the water pressure, dV_w/du_w is the water volume change with respect to the change of water pressure. The compressibility of water can be neglected because the real water pressure in most of the apparatus was maintained at zero. In this study, the water pressure is less than 6 kPa during the soil water retention test. Dissolved air in water produces an insignificant difference between the compressibility of air-free water and air-saturated water (Dorsey, 1940). Therefore, the compressibility of water has no significant effect on the volume change of the soil specimen. However, the volume of water changes due to the change of suction in the soil specimen. This kind of relationship is usually described mathematically and can be generalized as follows:

$$\Delta V_w = f(s_u) \quad (3)$$

where V_w is the volume change of water and S_u is the suction of soil.

Since soil particles are generally considered incompressible, the rearrangement of soil solids generates a total permanent volume change of the soil specimen.

4.2. Application of volume change assumed

The volume change of the three phases of soil during the test is shown in Fig. 5. Considering any two continuous equilibrium stages during the test, the stage before suction change is referred to as the initial condition, the stage after the equilibrium of soil specimen is referred as the final condition. As discussed before, the rearrangement of soil particles is the only source that contributes towards the total volume changes. This change can be calculated by the difference between the volume change of the air phase and the volume change of the water phase theoretically. Therefore, when considering the volume change, Eq. (3) should be substituted with Eq. (4). It means that not only suction but also the void ratio, e, has an influence on water content:

$$\Delta V_w = f(s_u, e) \quad (4)$$

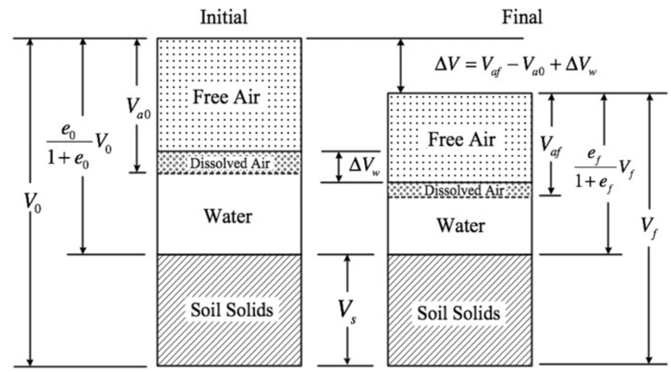


Fig. 5. Concept of volumetric composition of three phase in unsaturated soil.

Considering that the section area of the specimen does not change during the test, which was confirmed after the test by disassembling the apparatus, the volumetric strain can be written as follows. Here ε_i is the volumetric strain in i stage, V is the original total volume of soil specimen, V_i is the volume change in i stage (it is also equal to the summation of volume change of air and water). However, if any lateral shrinkage occurs, it indicates that the accuracy of Eq. (5) is low:

$$\varepsilon_i = \frac{\Delta V_i}{V} \times 100\% \quad (5)$$

From a microscopic point of view, the volume change during soil water retention test influences the interaction of water with soil, and hence it influences the drainage property. Therefore, it is very difficult to get a quantitative solution. From a macroscopic point of view, a volume change will influence the value of the water content, because volume is involved in calculating the volumetric water content and the degree of saturation. Considering the volume change of the soil specimen, the volumetric water content and the degree of saturation can be corrected as follows:

$$\theta'_{wi} = \frac{V_{wi}}{V - \Delta V_i} = \frac{\theta_{wi}}{1-\varepsilon_i} \quad (6a)$$

$$S'_r = \frac{V_{wi}}{(1-\varepsilon_i)V - V_s} \times 100\% \quad (6b)$$

where θ'_{wi} is the corrected volumetric water content in the i stage, V_{wi} is the volume of water in the i stage, θ_{wi} is the volumetric water content in the i stage, S'_r is the corrected degree of saturation. The correction of volumetric water content can be written in Eq. (6a). The volumetric water content is inversely proportional to the total volume. The correction for the degree of saturation can be written as in Eq. (6b). The relationship between the corrected degree of saturation and the volume of voids indicates the same tendency as Eq. (6a). The water content will not change since it is not related to the volume of soil. It is obvious that the effect of volume change depends on the definition of water content.

5. Results and discussion

5.1. Accuracy of automatic soil water retention test system

To evaluate the performance of the automatic soil water retention test system, the relationship between the output data of the water pressure transducer, barometer, displacement gage and elapsed time were carefully checked. As shown in Fig. 6, these sensors are recorded by a data logger system at intervals of 60 s. It can be seen that while air pressure stepwise increases (or decreases), water pressure and displacement increase (or decrease) gradually. This shows that all sensors correctly reflect the test process with elapsed time. The air pressure control method was adopted here.

Fig. 7 shows the test result by suction-control method. Air pressure, water pressure and matric suction, which is given as the difference between air and water pressures, are drawn as a function of the elapsed time. The tendency of output of all sensors is similar as that in Fig. 6, which is obtained by air pressure control method. In order to obtain the target suction, the water pressure was monitored from time to time. The air pressure is adjusted via the electronic pneumatic pressure regulator by bisection method, in which the air pressure was adjusted by adding air pressure in steps by taking the half of difference between the target suction and the current suction. It shows that in order to obtain a target suction value of 26 kPa, the program adjusts air pressure from initial value of 2.8–12 kPa, then to 17.5 kPa, and finally to 22.5 kPa. The corresponding value of suction achieves target suction after three adjustments.

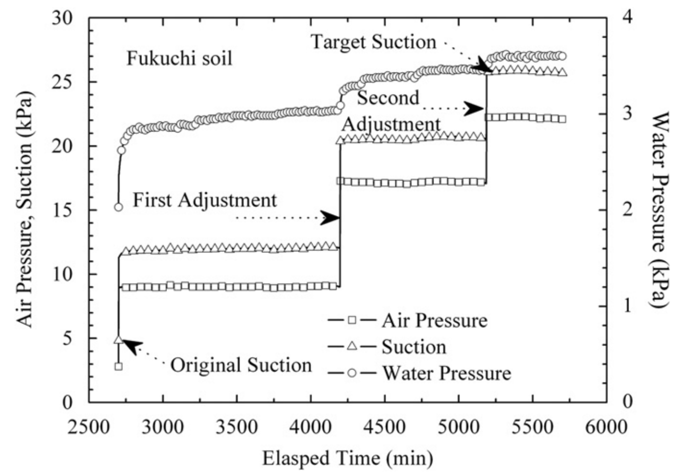


Fig. 7. Performance of suction-control method.

The accuracy of the water pressure transducer was 0.01 kPa (1 mm water head), the area of cross-section of the tube was about 0.5 cm^2, and therefore the minimum volume of water that can be observed was 0.05 cm^3. The system error was defined as the minimum obtainable value of volumetric water content, and considering the volume of soil specimen as 100 cm^3, the error was found to be less than 0.1%.

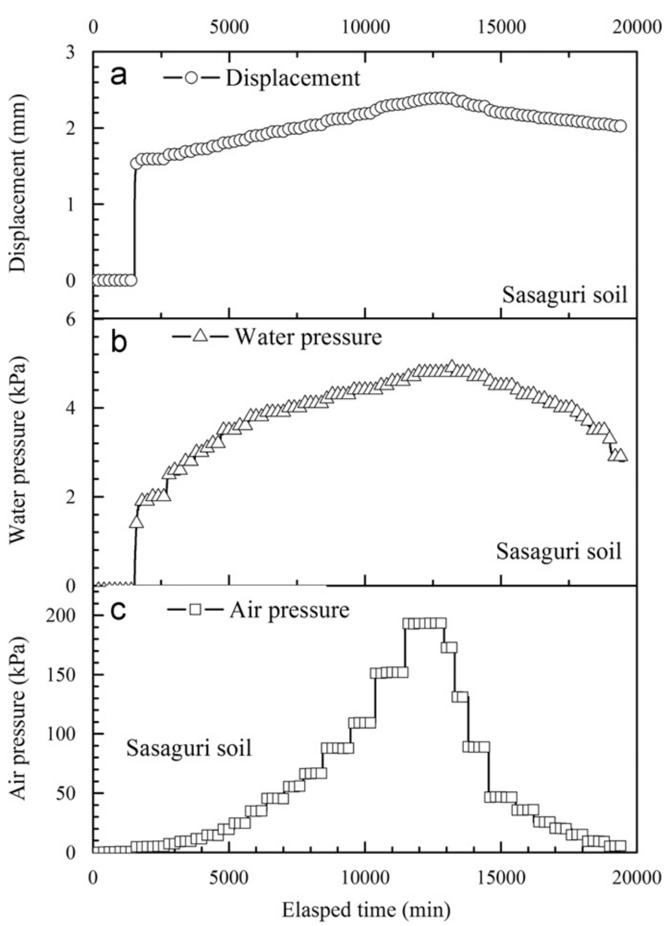


Fig. 6. Variation in displacement, negative water pressure and air pressure with respect to elapsed time. (a) Relationship between displacement and elapsed time, (b) relationship between negative water pressure and elapsed time and (c) relationship between air pressure and elapsed time.

5.2. Applications of automatic soil water retention test system

Fig. 8 shows the relationship of the negative water pressure, air pressure and the displacement with elapsed time. These results were arbitrarily chosen from two continuous stages for both the wetting process (Fig. 8(a)) and the drying process (Fig. 8(b)). In the figures, the hollow triangular mark shows the negative water pressure, which reflect the change in the water content of the soil specimen. In addition, the hollow circle showed vertical displacement, which reflects a volume change in the soil specimen. The arrows indicate the time when the equilibrium states of adsorption or drainage of water and volume change were achieved. This equilibrium states were decided by a program automatically based on the method described in Appendix A. As shown in Fig. 8, the adsorption or drainage of water and volume change of soil specimens occur at the time when the air pressure changes. It can be seen that the process of adsorption or

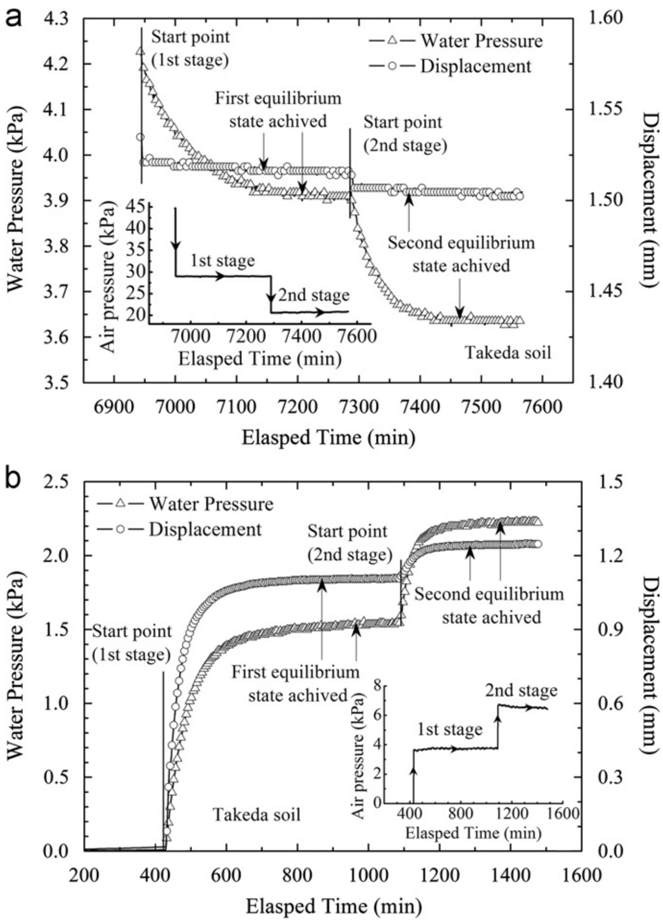


Fig. 8. Coupling of drainage and volume change of soil. (a) Wetting process an (b) drying process

drainage of water takes longer than the volume change of soil specimen in both the drying process and the wetting process. There may be two possible reasons for this. First, the volumetric change occurs due to the rebuilding of the soil structure. However, due to the drainage from the micro pore the soil structure does not rebuild. Because of viscosity of water, the drainage process is gradual. Secondly, the specimen is prepared by compaction in three layers, therefore, the anisotropy and heterogeneity of soil specimen can also result in differences between the elapsed time of drainage and the volume change.

Fig. 9 shows the effect of volume change on the soil water retention curves. The solid mark indicates the result without considering the volume change and the hollow mark is the modified result obtained from Eq. (6a). It can be observed that volume change plays an important role in determining the soil water retention curve, especially when the original volumetric water content is large. Since the volumetric water content is not directly measured, the volume change of soil specimens has a cumulative effect on the volumetric water content or the degree of saturation, which means that the effect of volume change on soil water retention curves becomes greater in the residual condition, when the slope of the soil water retention curve becomes small. Because, except for the first initial equilibrium point, all the modified data have higher water content compared with the original one, the modified curve can be obtained by rotating the original curve anticlockwise, when the first initial equivalent point is considered the rotating center.

Fig. 10 shows a series of test results showing the relationship between suction and volumetric strain. Generally, this relationship is characteristically highly non-linear. In the drying process, the volumetric strain increases as suction increases. This process can be separated into two stages. At first, the volumetric strain dramatically increases with increasing suction, and then approaches a constant value. The point which corresponds to the maximum curvature has a strong relationship with the air entry value of soil specimen. However, in the wetting process, the volumetric strain decreases linearly with decreasing suction. In this study, four types of soils were used to evaluate the effect of volume change on the soil water retention curve. For all four kinds of soils, the maximum volumetric strain was less than 3%, as shown in Table 2.

As shown in Fig. 11, an error of about 0.3% of volumetric water content occurs when the original value of the volumetric water content is 0.1 and the volumetric strain is 3%. This value is much greater than a system error. In other words, the volume change can be considered as an important factor that increases the accuracy of the soil water retention curve. In addition, this effect will be pronounced if the degree of saturation is chosen as the indicator of the moisture content. The shaded part in Fig. 11 indicates the area where the effect of volume change can be neglected. The calculated results are based on Eq. (6a).

In order to compare the effect of volume change on the soil water retention curves of each specimen, a normalized volumetric water content, M, was introduced, which is given by

$$M = \frac{\theta'_{wi} - \theta_{wi}}{\theta_{wi}} \times 100\% \tag{7}$$

where θ'_{wi} is the corrected volumetric water content in the i stage, V_{wi} is the volume of water in the i stage, θ_{wi} is the volumetric water content in the i stage, M is the normalized volumetric water content. Fig. 12 shows the effect of volume change on the soil water retention curves. The relationship between the normalized volumetric water content, M, and suction shows a nonlinear characteristic.

5.3. Limitations and further development of automatic soil water retention test system

The characteristics and advantages of a newly developed automatic soil water retention test system have been discussed, based on the experimental data. However, the system has limitations of its own. Firstly, the main unit is made of acrylic acid resin, which limits the applicable air pressure to about 300 kPa. Considering this point, the test

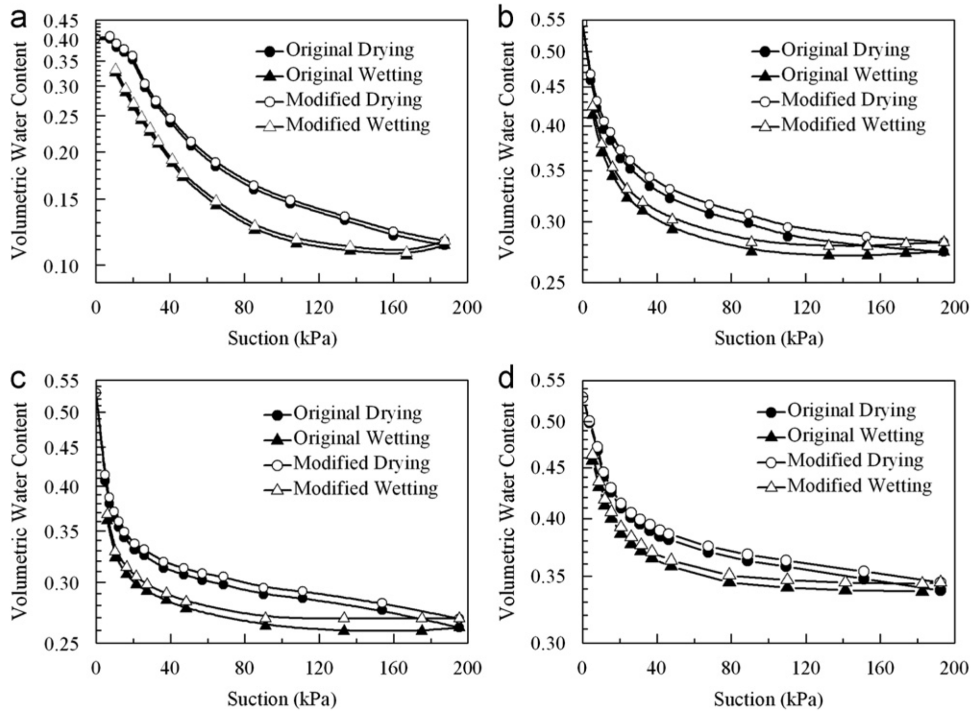


Fig. 9. Effect of volume change on soil water retention curve. (a) k-8, (b) takeda, (c) sasaguri and (d) fukuchi.

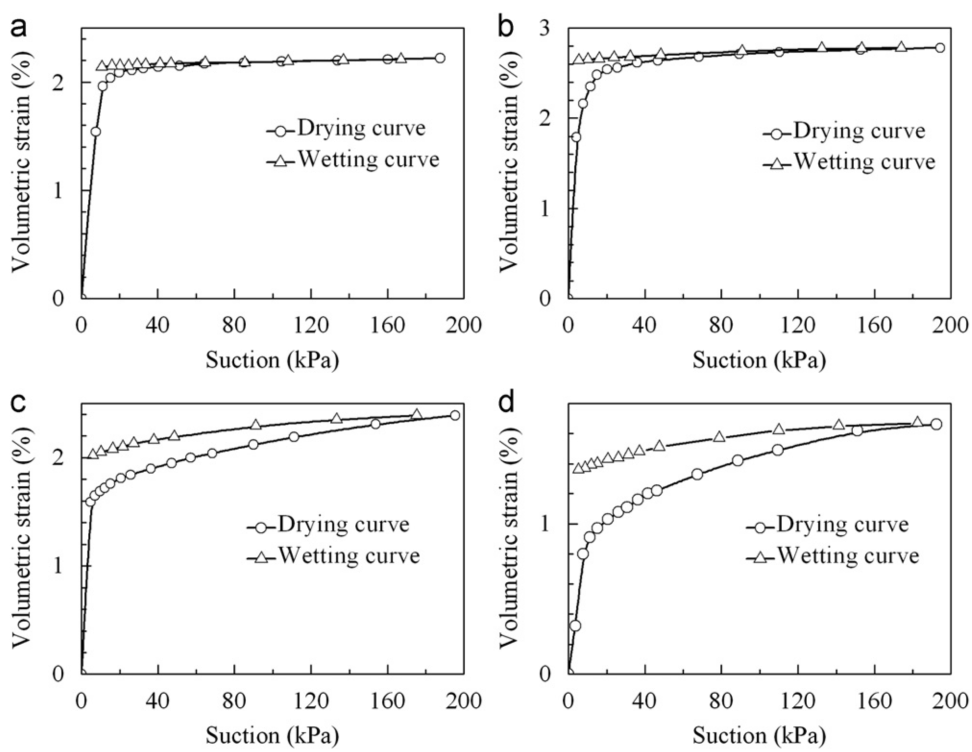


Fig. 10. Relationship between suction and volumetric strain. (a) k-8, (b) takeda, (c) sasaguri and (d) fukuchi.

system is suitable for experiment using sandy and silty soils. It is not applicable to clay soils. Secondly, since the air can diffuse through the water in the ceramic disk, the diffused air accumulates beneath the ceramic disk and introduces an error in both the water volume change measurement and in the equilibrium of soil specimen. In the typical Tempe cell, this point cannot be solved. The volumetric pressure plate apparatus can also be used as

Table 2
Test condition.

No.		Initial void ratio e_0	Initial dry density ρ_d (g/cm^3)	Applied pressure (kPa)		Maximum volumetric strain ε_{max} (%)	Elapsed time (h)	
				Maximum air pressure	Maximum water pressure		Equilibrium time	Total time
1	K-8	1.22	1.21	182.2	2.95	2.22	6	330.2
2	Takeda	1.92	0.91	190.1	5.82	2.78	3	143.2
3	Sasaguri	2.24	0.87	193.0	5.86	2.39	6	325.6
4	Fukuchi	1.70	1.07	189.7	4.45	1.67	3	247.8

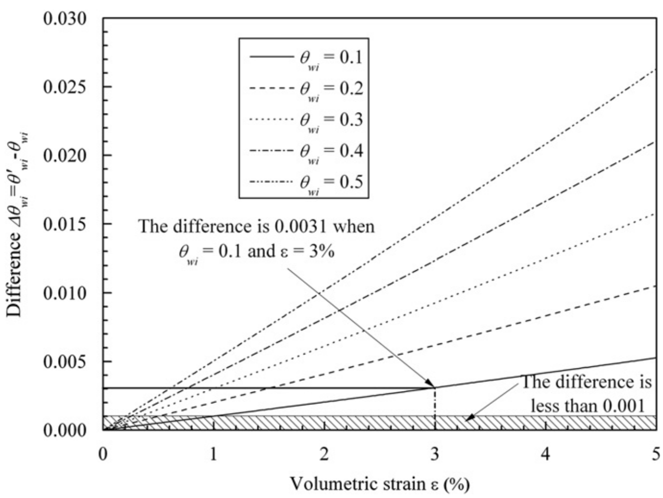


Fig. 11. Relationship between volumetric strain and difference of volumetric water content.

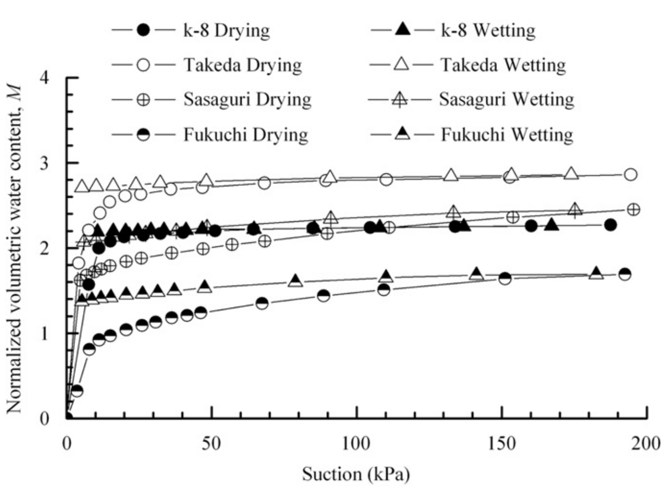


Fig. 12. Relationship between normalized volumetric water content and suction.

main unit instead of the Tempe cell. However, some accessories need to be developed to solve this problem. In addition, how these accessories collaborate with the automatic test system needs further research. Thirdly, the sample deformation induced by suction is sensitive to the displacement boundary conditions (Sibley and Williams, 1989). Therefore, as further research, the boundary effect of the soil specimen should be carefully considered.

In this study, the test results only show the general tendency of volume change and suction. Therefore, further discussions are necessary to clearly characterize the relationship of soil water retention characteristics curves with the volume change of soils during testing.

6. Conclusions

This paper focuses on the development of an automatic soil water retention system, which can measure the volume change during the drying and wetting process. Various soil samples from sandy to silty soils were used to verify the capability of the system in this study. A method is presented to evaluate the effect of volume change on the soil water retention curve. The following conclusions were able to be drawn from this research:

(1) The automatic soil water retention test apparatus provides an easy and accurate way to carry out the tests within the system error of 0.1%, which is considered acceptable for sandy and silty soils. Once the soil specimen is prepared and test condition is input, the test process is automatically executed under the control of software.
(2) Two methods, air pressure control method and suction-control method, were provided for performing soil water retention test. Based on the test results, the difference between measured data and target data of air pressure or suction is less than 0.1 kPa, when air pressure is less than 200 kPa.
(3) In both the drying and the wetting process, the elapsed time to reach the equilibrium is greater in the case of displacement than that of the water content. This provides useful information to judge whether the equilibrium of soil specimen has been achieved or not.
(4) The volume change of soil specimens should be considered as an important factor in the soil water retention curve since it produces a significant error. For example, when a volume change of 3% can occurs during the test, the volumetric water content generates an error about 0.3%, if the original volumetric water content is about 0.1. This tendency becomes larger with larger original volumetric water content.

Only limited soil samples were used in this research. More detailed research work is needed to clarify the general effect of volume change on the soil water retention curve.

Acknowledgments

This research was supported in part by joint project between Kyushu University, Fukuoka and Genkai town, Saga prefecture, on the cultivation of medicinal plants in arid ground, and a Grant-in Aid for scientific research (A) No. 22246064, from Japan Society for the Promotion of Science (JSPS). The authors acknowledge the support. The authors also would like to express their sincere gratitude to Prof. Ryosuke Kitamura of Kagoshima University for his valuable advice in improving the content of this manuscript. The first author also acknowledges the scholarship, provided by the Ministry of Education, Culture, Sports, Science and Technology, for pursuing his doctorate at Kyushu University.

Appendix A

The data of water pressure transducer and displacement gage is volatile with elapsed time. It was assumed that these data obey the following normal distribution:

$$f(x)=\frac{1}{\sqrt{2\pi\sigma^2}}e^{-((x-\mu)^2)/2\sigma^2}$$

where parameter μ is mean of x, σ is standard deviation of x, e is Euler's constant, x is data of water pressure or displacement. According to normal distribution theory, about 68% of values drawn from a normal distribution are within one standard deviation σ away from the mean μ; about 95% of the values lie within two standard deviations. Therefore two standard deviations, 2σ or four standard deviations, 4σ are considered as threshold of the stability of observed data. This means that when 2σ or 4σ are less than the accuracy of the water pressure transducer and displacement gage during a period, the equilibrium condition of test is considered to be attained (Fig. A1).

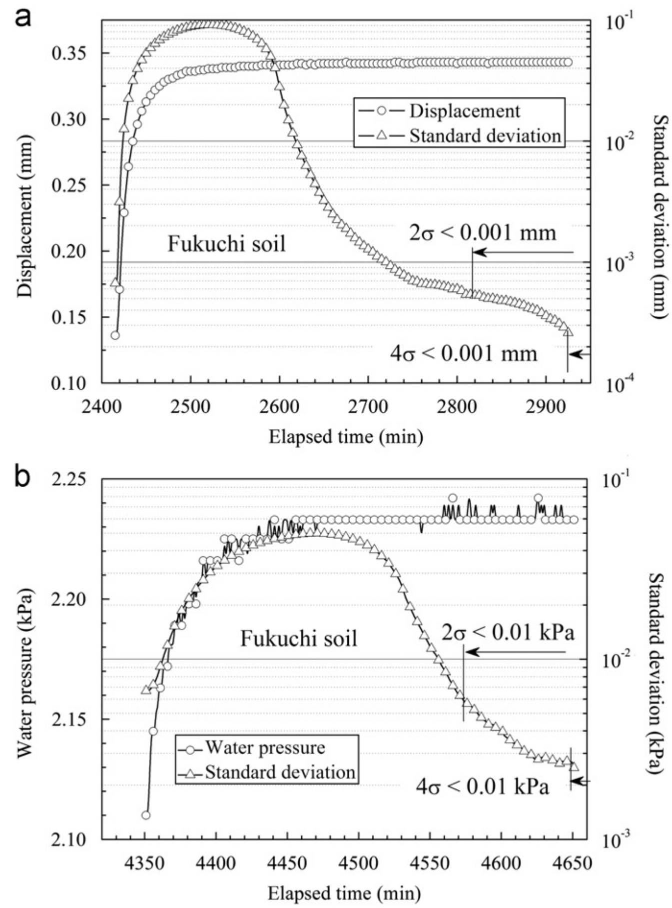


Fig. A-1. Equilibrium conditions of the soil specimen.

Appendix B

If time interval is fulfilled then 'wait for a time period'
  If $4\sigma_d \leq 0.001$ mm and $4\sigma_p \leq 0.1$ kPa then 'check whether the water pressure transducer is stable or not'
    If $|S_{it}-S_i| \geq 0.1$ kPa then 'to judge current suction is equal to target suction or not'
      $P_{i+1}=P_i+0.5|S_{i+1}-S_i|$ 'adjust current air pressure to next step'
      Else $P_i=P_i+0.5|S_i-S_{it}|$ 'adjust current air presssure to more close to tagret suction'
    Else wait until next time interval 'wait water pressure transducer becomes stable'
Else exit

Where S_{it} is current suction value, σ_d is standard deviation of displacement, σ_p is standard deviation of water pressure.

References

Dorsey, N.E., 1940. Properties of Ordinary Water-Substances, American Chemist Society. Reinhold, New York.

Fredlund, D.G., Rahardjo, H., 1993. Soil Mechanics for Unsaturated Soils. Wiley-Interscience, New York.

Fredlund, D.G., Xing, A., Huang, S., 1994. Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. Canadian Geotechnical Journal 31 (4), 533–546.

Head, K.H., 1980. Manual of Soil Laboratory Test, Volume 1: Soil Classification and Compaction Test. Pentech Press, London, pp. 119–122.

Japanese Geotechnical Society, Method and explanation of geotechnical test-the first revised edition-1, 2000.

Kosugi, K., Hopmans, J.W., 1998. Scaling water retention curves for soils with lognormal pore-size distribution. Soil Science Society of America Journal 62, 1496–1505.

Likos, W.J., Lu, N., 2003. Automated humidity system for measuring total suction characteristics of clay. Geotechnical Testing Journal 26 (2), 1–12.

Likos, W.J., 2004. Measurement of crystalline swelling in expensive clay. Geotechnical Testing Journal 27 (6), 540–546.

Likos, W.J., Lu, N., 2006. Pore-scale analysis of bulk volume change from crystalline interlayer swelling in Na^{+}- and Ca^{2+}-smectite. Clays and Clay Minerals 54 (4), 516–529.

Lu, N., Wayllace, A., Carrera, J., Likos, W.J., 2006. Constant flow method for cocurrently measuring soil-water characteristic curve and hydraulic conductivity function. Geotechnical Testing Journal 29 (3), 230–241.

Nishimura T., Murasawa, Y., Okami, T., 2006. Estimating air–water hydraulic conductivity using soil-water characteristic curve. In: Proceedings of the Fourth International Conference on Unsaturated Soils, UNSAT 2006, Arizona, pp. 1595–1606.

Padilla, J.M., Perera, Y.Y., Houston, W.N., Fredlund, D.G., 2005. A new soil-water characteristic curve device. In: Proceedings of the International Symposium Advanced Experimental Unsaturated Soil Mechanics, Experus 2005, pp. 15–22.

Péron, H., Hueckel, T., Laloui, L., 2007. An improved volume measurement for determining soil water retention curves. Geotechnical Testing Journal 30 (1), 1–8.

Sibley, J.W., Williams, D.J., 1989. A procedure for determining volumetric shrinkage of an unsaturated soil. Geotechnical Testing Journal 12 (3), 181–187.

Uno, T., Sato, T., Sugii, T., Tsuge, H., 1990. Method of test for permeability of unsaturated sandy soil with controlled air pressure. In: Proceedings of Japan Society of Civil Engineering C, 418, III-13, pp. 115–124 (in Japanese).

Vanapalli, S., Fredlund, D.G., Pufahl, D.E., Clifton, A.W., 1996. Model for the prediction of shear strength with respect to soil suction. Canadian Geotechnical Journal 33 (3), 379–392.