Rapid concurrent measurement of the soil water characteristics curve and the hydraulic conductivity function utilizing the continuous pressurization method

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Natural disasters including earthquakes, typhoons and heavy rainfalls induce various risks such as slope failures. The conventional unsaturated soils hydrological properties mainly the Soil Water Characteristics Curve (SWCC) and the Hydraulic Conductivity Function (HCF) determination techniques are limited due to the complexity and prolonged time required. Thus a simple method that considers short time and high accuracy under the drying and the wetting phases considering remolded and undisturbed samples is lacking. Through this paper, a novel systematic testing setup utilizing the Continuous Pressurization Method (CPM) that allows rapid, concurrent, continuous, direct determination of the SWCC and the HCF considering both remolded and undisturbed samples was developed. It was found that the air pressurizing rate influence on the obtained SWCC using the developed system can be neglected. It was confirmed that remolded samples do not properly represent the in-situ conditions with significant error that should be carefully considered. It must be noted that applying low air pressurizing rate induces almost linear suction profile, however, it changes into higher order non-linear profile when applying high air pressurizing rates or achieving low degrees of saturation. A correction function based on Van Genuchten (VG) model was proposed which has finally led to obtaining accurate reliable HCFs. Finally, it was concluded that the developed system is rapid, direct, reliable, continuous with accurate repeatability that allows rapid, concurrent determination of both the SWCC and the HCF under the drying and wetting phases. Where the system allows concurrent determination of the SWCC and HCF in less than 7% of the testing time required using the conventional methods and considers testing both remolded and undisturbed soil samples.

Keywords: hydraulic conductivity function, SWCC, continuous pressurization method, hysteresis, suction profile

1 INTRODUCTION

Recently earthquakes, typhoons and heavy rainfalls induced natural Geo-disasters occur at different locations causing serious damage to life and properties. Through heavy rain periods, the water table and river water level rise causing increase in the pore water pressure resulting in total strength and stability loss through soil embankments which finally leads to failure.

The proper determination and knowledge of the unsaturated soil hydraulic properties including the Soil Water Characteristics Curve (SWCC) and the Hydraulic Conductivity Function (HCF) are key indices in analyzing the unsaturated soils hydrological properties (water and solute movement and water storage) and evaluating the unsaturated soils mechanical properties (slope stability, landslides and erosion) (Klute (1986a); Fredlund et al. (1996)).

The SWCC is a function that describes the amount of water (volumetric water content, gravimetric water content or degree of saturation) retained in a soil at a given range of suction values (the difference between the pore air pressure and the pore water pressure). While the HCF is a function that describes the ease and speed with which a fluid moves through a soil at a given range of suction values or a given range of water contents.

Several experimental setups and numerical methods were developed for directly and indirectly obtaining the SWCC and the HCF. The hanging column, tempe cells, pressure plate, tensiometers, psychrometer, chilled mirror hygrometer, filter paper, centrifuge and humidity chamber are commonly used for experimentally obtaining the SWCC (Spanner (1951); Gee et al. (1992); Fredlund and Rahardjo (1993); Japanese Geotechnical Society (2000); Lu and Likos (2004); Lu et al. (2006)). While the HCF obtaining methods can be generally categorized into three groups based on the governing flow state, steady state methods (traditional steady-state
method, centrifuge and thermal method), quasi-steady methods (multi-step method and continuous outflow method) and unsteady state methods (absorption method, sorptivity method, multi-step outflow method, one-step outflow method, instantaneous profile method and thermal method) (Klute and Dirksen (1986b); Fredlund and Rahardjo (1993); Benson and Gribb (1997); Nimmo et al. (2002); Lu and Likos (2004). Detailed reviews illustrating the advantages and disadvantages of those methods can be found in literature (Richards (1941); Fredlund and Rahardjo (1993); Benson and Gribb (1997); Lu and Likos (2004); Alowaisy et al. (2017)).

In general, the existing laboratory techniques consider determining the SWCC and the HCF separately and are limited due to the testing complexity. In addition, most of them are applicable only under the drying phase with discrete measurements and prolonged testing time where depending on the amount of data points desired, testing may require at least several weeks or even several months. In addition, those setups consider testing remolded samples where little attention was given for obtaining undisturbed samples SWCC and HCF.

Through this paper, a novel full automatic system utilizing the Continuous Pressurization Method (CPM) that allows concurrent, continuous, direct accurate determination of the SWCC and the HCF in a very short time considering both remolded and undisturbed samples is proposed. In addition, the pore water pressure profile distribution under various air pressurizing rates and at different degrees of saturation is investigated.

2 THEORY AND TESTING SETUP

The proposed system is automatic and allows for continuous concurrent determination of the SWCC and the HCF. Fig. 1 shows the experimental setup of the proposed system. The system consists of three units: data control and acquisition unit, pressurizing unit and water collection unit. A picture of the proposed system is shown in Fig. 2. The air pressure is supplied through the inlet valve attached to the top of the cell, where a regulator connected to a computer controls the air pressurizing rate. Meanwhile, three micro-tensiometers installed at (1, 2.5 and 4 cm from the ceramic disk surface) instantly and continuously measure the developing pore water pressure in response to the changing air pressure at different levels. The ceramic disk (CD) at the bottom retains the air pressure and allows water to drain gradually through the drainage outlet. The water drains into a container that is continuously weighed using a balance with 0.001 g resolution that is directly connected to the data acquisition system. The soil sample is contained in an acrylic cylinder with 5 cm internal radius and 8.5 cm height. As shown in Fig. 1, a perforated piston hanging from the top cover using a rod is used to restrain the sample and prevent volume changes through testing.

Fig. 1. Developed system setup. (schematic).

Fig. 2. Developed system setup. (picture).

During testing, the applied air pressure, pore water pressure at three levels (micro-tensiometers) and cumulative mass of drained water are continuously recorded versus the elapsed time as shown in Fig. 3.

The SWCC can be determined utilizing the axis-translation technique, where a CD with a known Air Entry Value (AEV) is used to retain the air pressure...
while the pore water pressure is measured simultaneously. The matric suction (ψ) can be calculated by taking the difference between the applied air pressure (u_a) at the top of the sample and the averaged pore water pressure (u_{wavg}) along the soil sample. While the water content can be deduced from the drained water in relation to the initial or final water content of the tested sample.

\[ \psi = u_a - u_{wavg} \]  

(1)

The HCF determination proposed method adopts Darcy-Buckingham’s law, which states that the unsaturated hydraulic conductivity is a function of the water content or the matric potential.

\[ q_w = k_c(h) \times k_{sat} \times \frac{\Delta H}{\Delta z} \]  

(2)

where \( q_w \): flow rate; \( k_c(h) \): relative permeability defined as \( k_w/k_{sat}; \) \( k_{sat} \): is the unsaturated hydraulic conductivity; \( k_{sat} \): is the saturated hydraulic conductivity; \( \Delta H/\Delta z \): hydraulic head gradient comprised of matric head and gravitational head and \( z \): sample depth (flow direction).

A soil sample of a height \( L \) in contact with the CD, where the reference datum \( z=0 \) is set at the top of soil sample as illustrated in Fig. 4 is adopted. The following assumptions are made: (1) Water flows out of the sample can be considered as a succession of steady states where the hydraulic gradient and water flux are simply constant within each time interval. (2) 1-D water flow (downward z-direction). (3) The effective measurement range lies within the interval (\( \theta_1 \) to \( \theta_3 \)), Fig. 5. (4) Since theoretically water does not flow out of the sample for the suction values equal or less than the (AEV), the hydraulic conductivity is assumed to be equal to the saturated hydraulic conductivity obtained by the standard laboratory testing method. (5) The hydraulic conductivity equals to the residual hydraulic conductivity (\( k(\theta_1) \)) in the residual zone.

Under isothermal, isoelectric and isosmotic conditions the total head potential equals to the total hydraulic head in the sample which is composed of the pressure head \( h_w \) and the elevation head \( z \).

\[ H(z) = h_w(z) - z \]  

(3)

At equilibrium, the total head is assumed to be constant thus no water flows out of the sample. Therefore, using the conventional methods operated utilizing the axis-translation technique, under equilibrium state, the capillary pressure head (\( h_c \)) equals the suction (\( h_c = u_w - u_a \)) and imposes linear profile with a slope of -1. A step change in the external applied pressure is followed by an equilibrium period through which the capillary pressure profile becomes linear again (Reginato and Van Bavel (1962)).

Under transient unsaturated flow conditions, the simplest form of \( H \) that can be assumed is parabola:

\[ H(z,t) = az^2 + bz + c \]  

(4)

Where \( a, b \) and \( c \) are the parabola coefficients, which are function of time. In order to determine those coefficients, the pressure head \( h_w \) at three locations [\( z_1, z_2, z_3 \)] should be known at time \( t \). Thus the three micro-tensiometers readings at time \( t \) are considered as follows:

\[ H_1 = h_{w1} - z_1 \quad z = z_1 \]  

(4a)

\[ H_2 = h_{w2} - z_2 \quad z = z_2 \]  

(4b)

\[ H_3 = h_{w3} - z_3 \quad z = z_3 \]  

(4c)

Substituting (4a), (4b) and (4c) into (4) and solving for \( a, b \) and \( c \) gives

\[ a = \frac{(z_3^2 - z_2^2)h_{w1} - (z_3^2 - z_2^2)h_{w2} + h_{w3}}{z_3^2 - z_2^2 + z_2 - z_1} \]  

(5a)

\[ b = -a(z_1 + z_2) + \frac{h_{w2}}{z_2 - z_1} \]  

(5b)

\[ c = h_{w1} - z_1 - a(z_1^2 + z_1) \]  

(5c)
If \( q_w \) and \( \Delta H/\Delta z \) are known at a specific point, \( k_r \) can be calculated following Darcy-Buckingham’s law [eq. (2)]. The CD-soil interface \((z=L)\) is selected as a representative point, where \( q_w \) is assumed to be equal to the directly measured flow rate out of the cell (under fully saturated CD conditions).

\[
q_w = \frac{AQ}{A \times \Delta t}
\]

(8)

Where \( Q \): the cumulative water flow; \( A \) is the CD cross sectional area and \( \Delta t \): is the time interval. The hydraulic gradient can be obtained by finding the derivative of the total head potential \( H(z,t) \) at the selected CD-soil interface \((z=L)\) point.

\[
\frac{\partial H}{\partial z} \bigg|_t = 2az + b
\]

(9)

The calculated \( k_r \) is donated by the average water content of the sample or the suction value averaged along the sample over the time interval \( \Delta t \).

3 MATERIALS AND METHODOLOGY

3.1 Materials and sampling locations

Tests were conducted using two standard testing soils and natural samples collected at two Geo-disaster affected sites. After Kumamoto earthquake, Japan in April 2016, massive landslides as a result of the jolts and the following rainfall events have occurred. Samples were collected in the middle of October the same year next to a huge landslide as indicated in Fig. 6 a. A massive heavy rainfall induced landslides occurred in Fukuoka and Oita prefectures, Japan in the beginning of July 2017. One of the highly affected areas was Asakura region located in southern Fukuoka, Japan. Samples were collected in the middle of November the same year at the landslide boundaries as indicated in Fig. 6 b. Undisturbed and disturbed samples were collected at the landslide sampling locations indicated through Fig. 6. The particle size distribution curves and summary of soil physical and hydrological properties for both standard and natural soils are shown in Fig. 7 and Table 1 respectively.

3.2 Methodology

Disturbed and undisturbed natural soil samples were collected. Undisturbed sampling was carried out using 5 cm in diameter and 5.1 cm in height steel molds with a wall thickness of 1 mm. A guiding shaft and a hammer were used to drive the mold with the sharp edge guided to cut through the ground as illustrated in Fig. 8.

Remolded samples were compacted directly into an acrylic mold to the desired density and initial water content for standard soils and to the natural density and natural water content for natural soils. On the other hand, the undisturbed samples contained in the steel molds were installed into the acrylic mold and two O-rings [G-50 rubber rings] were used to prevent water and air from flowing between the steel and the acrylic molds surfaces. A layer of grease oil was applied to the internal surface of the acrylic mold and the external surface of the steel mold to reduce the friction and drive the steel mold smoothly into the acrylic mold, thus minimizes the disturbance.

Samples and pressurizing cell saturation process was carried out by submerging the whole mold, base (CD and its compartment) and the micro-tensiometers in a water tank and applying a negative pressure of 90 kPa for 24 hours to assure fully saturated conditions. At the end of the saturation, the micro-tensiometers are installed one by one by flushing water using syringe into the micro-
tensiometer pipe, then attaching it to the base with its pressure transducer. After that the water is flushed through the water compartment and the valve to get arid of any occluded air bubbles. Care should be taken to keep the CD and the micro-tensiometers wet during the preparations to reduce the error resulting from water loss due to evaporation. The saturation of the micro-tensiometers is tested by assembling an empty acrylic mold to the base and filling it with water, then by applying different air pressure values and monitoring the response accuracy and time required to achieve equilibrium between the applied air pressure and the measured water pressure. Slow or not accurate response indicates low saturation and requires extending or repeating the saturation process. Finally, the drainage pipe is assembled to the cell and water is flushed through the water compartment and the valve to the drainage pipe to remove any occluded air bubbles through the water compartment underlying the CD.

The sample is then prepared by removing it from the tank and excavating holes (one by one) with diameter and depth equal to the designated micro-tensiometer dimensions using a drill bit. Steel dummies are used to support the soil while making the other holes. All free water is removed from the mold then the initial weight is recorded to calculate the sample initial water content later on (final water content at the end of the test can also be used to deduce the initial water content). The sample is then carefully installed to the cell with the micro-tensiometers guided carefully through the holes to avoid disturbing the surrounding soil and assure good contact between the micro-tensiometers ceramic cups and the surrounding soil. The piston is then driven to its initial position and the top cover is assembled. O-rings are installed to the bottom and top of the acrylic mold and then tightened using screws to prevent water or air leakage during testing. The pressurizing unit is then moved to the stand and the drainage pipe is guided into the container. Using the controlling software, all the transducers and the balance are initialized (zero reading) in order to start the test. In addition, the air pressurizing rate (kPa/min.) and sampling interval in the range of 1 second to several hours are set up in the controlling software. The test is then started by manually opening the drainage valve and then clicking the start button.

4 RESULTS AND DISCUSSION

4.1 Soil Water Characteristics Curve (SWCC)

Fig. 9 illustrates the SWCCs for the standard testing soils (Toyoura and K-4 sands) obtained using the proposed system applying 0.05 kPa/min. and 0.5 kPa/min. air pressurizing rates under both the drying and the wetting phases. It can be observed that the proposed system is capable of precisely determining the SWCC under both drying and wetting phases with precise accurate capturing of the (AEV) and the residual suction value (corresponds to the residual water content).

Table 1. Standard and natural soils physical and hydrological properties.

| Physical Properties | Standard soil | Natural soil |
|---------------------|---------------|--------------|
| Dry density g/cm³   | 1.560         | 1.611        |
| Suction (kPa)       | 2.711         | 2.711        |
| L_i                 | 0.4204        | 0.4480       |
| Natural water content w_i | - | 181.3 |
| Natural degree of saturation S_i | - | 93.1 |
| Void ratio (e)      | 0.0856        | 0.1354       |
| α                   | 0.0260        | 0.0503       |
| n                   | 16.4620       | 2.8603       |
| Hydrological properties | - | - |

Fig. 8. Undisturbed sampling steel mold, shaft and methodology. (schematic).

Fig. 9. Standard soils (Toyoura and K-4 sands) drying and wetting phases SWCCs (0.05 and 0.5 kPa/min. air pressurizing rates).
As illustrated in Fig. 9, applying either low air pressurizing rate (0.05 kPa/min.) or high air pressurizing rate (0.5 kPa/min.) results in obtaining almost identical SWCCs with identical AEVs and residual suction values for the adopted samples. When using high air pressurizing rate is followed by rapid increase in the pore water pressure through the sample. Where without allowing proper dissipation of the accumulated pore water pressure by draining water to the attached container, results in achieving low suction values even under high air pressure values. It must be noted that the suction values are plotted in correspondence to the averaged volumetric water content of the tested sample. Allowing proper dissipation of the accumulated pore water pressure by giving longer time for draining the water from the sample results in obtaining identical SWCCs compared to the SWCCs obtained under low air pressurizing rates for all tested specimens. Where draining the water out of the sample reduces the average sample water content and dissipates the pore water pressure resulting in increasing the suction value. It must be noted that the slight difference between the SWCCs obtained by the proposed system using various pressurizing rates can be attributed to the difficulty in replicating identical samples with the same pore network and micro-structure. As illustrated in Fig. 3, the pore water pressure equals the applied air pressure through the whole sample up to the AEV indicated by the sudden reduction in the pore water pressure defining the onset of

Fig. 10. Natural undisturbed soils (Asakura and Kumamoto soil) drying and wetting phases SWCCs (0.05 kPa/min. air pressurizing rates). Remolded samples SWCCs.

![Graph showing SWCCs for different air pressurizing rates](image)

Fig. 11. Suction profile distribution for Toyoura sand under the drying and wetting phases. a) 0.05 kPa/min. air pressurizing rate. b) 0.5 kPa/min. air pressurizing rate.

![Graphs showing suction profile distribution](image)

Fig. 12. Suction profile distribution for K-4 sand under the drying and wetting phases. a) 0.05 kPa/min. air pressurizing rate. b) 0.5 kPa/min. air pressurizing rate.
draining the water from the sample where the excess water (oversaturation) is lost before this point. The residual stage starts when no more water left in the sample to drain, therefore increasing the applied air pressure increases the suction value without draining more water. The repeatability and reliability of the newly developed system was confirmed by repeating the same test at least two times for Toyoura and K-4 sands under two air pressurizing rates [0.05 and 0.5 kPa/min].

Unsaturated soils hydraulic properties including the SWCC and the HCF are functions of the micro-pore network which can be significantly affected by the sample disturbance, handling and particles rearrangement. In order to obtain a reliable representative results, samples disturbance should be minimized and natural conditions should be preserved during sampling, preparing and testing. The newly proposed undisturbed samples methodology and testing system considers minimizing the disturbance and obtaining the natural soils hydrological properties in a very short time to avoid changing the samples microstructure and properties. Fig. 10 illustrates the natural soils collected at Asakura and Kumamoto sites SWCCs obtained using the proposed system applying 0.05 kPa/min. air pressurizing rate. Both the drying and the wetting phases SWCCs of the undisturbed samples were obtained, while only the drying phase SWCCs for remolded samples were obtained. The black circled scatter plot indicates the natural water content directly measured after sampling versus the corresponding natural suction value for Asakura sampling site. In general, it can be observed that using the newly developed undisturbed samples SWCC obtaining system and sampling methodology results in obtaining smooth continuous curves with the ability to accurately capture the AEV and the residual suction value under both the drying and the wetting phases. In addition, as shown in Fig. 10 the remolded samples SWCCs are not in good agreement with the undisturbed samples SWCCs, where the AEV was shifted 2.4 kPa and 0.7 kPa for Kumamoto and Asakura soils respectively, while the saturated volumetric water content was shifted 0.008 and 0.045 for Kumamoto and Asakura soils respectively. Thus it should be noted that remolded samples do not properly represent the in-situ conditions with significant error that should be carefully considered. Finally, it can be concluded that the developed system is direct, reliable, continuous with accurate repeatability SWCC obtaining system which considers testing both remolded and undisturbed soil samples.

4.2 Suction profile distribution

Figs. 11 and 12 show the suction profile distribution for Toyoura and K-4 standard testing soils under the drying and wetting phases applying high and low air pressurization rates. While Fig. 13 shows the undisturbed Asakura and Kumamoto samples suction profile distribution under the drying and wetting phases applying low air pressurization rate.

It can be observed that applying low air pressurizing rate induces higher uniformity and gentler slope of the suction profile, where the deviation of the suction value between the top, bottom and center in reference to the averaged value is significantly lower than the higher air pressurizing rate. It must be noted that under low pressurizing rate, the suction profile is almost linear, with the profile changing into higher order non-linear by increasing the air pressurizing rate or by achieving low degrees of saturation. The curvature of the suction profile is strongly related to the air pressurization rate, the soil properties and the CD hydraulic conductivity which reflects its capability of dissipating the accumulating pore water pressure. It must be noted that the top and bottom boundaries of the soil sample might not follow the shown profile measured directly by the micro-tensiometers. Where exceeding the AEV announces the onset of the drainage of water from the sample, thus exceeding this point, the top boundary layer water gets lost and the suction value is theoretically equal to the applied air pressure. Overall, it can be concluded that under such transient pressurization
situations, water gets lost non uniformly and from localized regions depending on the pressurizing rate, tortuosity of the porous medium and the CD properties. In addition, the micro-tensiometers response time could induce additional time lag which might add to the complexity.

4.3 Hydraulic Conductivity Function (HCF)

The hydraulic conductivity was calculated following Darcy – Buckingham’s law, where \( q_w \) is assumed to equal to the directly measured flow rate out of the cell (under fully saturated CD conditions) averaged over the time interval \( \Delta t \), while the hydraulic gradient is determined by taking the derivative of the total head potential \( H(z,t) \) at the selected CD-soil interface \( (z=L) \) representative point.

The directly determined SWCC was fitted with Van Genuchten model (VG) (VanGenuchten (1980)) for Toyoura, K-4 and Asakura sands, then the HCF was determined and used to validate the proposed system. In addition, data obtained from the (JGS technical report (1997)) (Fig. 14 a) circular scatter) for Toyoura sand was used for validating the proposed system.

The HCF obtained using the proposed system (triangular scatter) and the HCF obtained using VG model (solid line) are illustrated in Figs. 14 a, b and c for Toyoura sand, K-4 sand and Asakura undisturbed sample sand respectively. It can be observed that the relative hydraulic conductivity obtained using the proposed system does not agree very well with the VG relative hydraulic conductivity for Toyoura, K-4 and Asakura sands and not in well agreement with the data obtained from the (JGS technical report (1997)). Under air pressure values less than the AEV of the CD (100 kPa), the \( q_w \) at the top of the ceramic disk equals to the \( q_w \) at the bottom of the CD considering constant \( k_{sat} \). Thus the gap can be attributed to the proposed simple parabola fitted profile, where it seems to be not capable of accurately capturing the realistic hydraulic gradient at the CD-soil interface, where specially under low water contents, the boundary layers (top and bottom) experience extreme deviated head values that requires considering more complex representative head profile.

As a trial to quantify the influence of the CD on the head profile distribution, the hydraulic gradient determined by the proposed method considering a parabola function representing the hydraulic head profile was plotted versus the hydraulic gradient determined inversely using VG model corresponding to the measured \( q_w \) for Toyoura, K-4 and Asakura sands respectively as shown in Figs. 15 a and b. It can be observed that there is a significant gap up to four orders difference. Thus leads to the conclusion that the total hydraulic head acting on the CD-soil interface which drives the water from the sample through the CD into the drainage tank is not well determined. However, a correction coefficient is proposed by taking the ratio of the hydraulic gradient inversely calculated using VG model to the hydraulic gradient determined following the adopted parabola profile \( (\text{VG}/\text{Parabola}) \). The correction factor was plotted versus the average suction using a semi – log scale graph for Toyoura, K-4 and Asakura soils as illustrated in Figs. 16 a and b. A perfect power trend line using the power regression model was obtained with coefficient of determination \( R^2 \) of 0.88 for both Toyoura and Asakura sands and 0.9 for K-4 sand.
This leads to the conclusion that a calibration function can be systematically developed which can be used for quantifying the impedance of the CD on the hydraulic gradient at the CD-soil interface. The fitting trend line equation was then used as a correction coefficient to calibrate the hydraulic gradient. The HCFs for Toyoura sand, K-4 sand and Asakura natural soil were then recalculated following Darcy-Buckingham’s law using the modified hydraulic gradient and then plotted versus the corresponding Volumetric Water Content (VWC) (black square scatters) as illustrated in Figs. 14 a,b and c respectively. It can be observed that the HCF calculated using the corrected hydraulic gradient (black square scatters) agrees very well with the data obtained from the (JGS technical report (1997)) for Toyoura sand, and also in well agreement with HCF obtained using VG model for Toyoura sand, K-4 sand and Asakura natural soil. Finally, it can be concluded that applying a proper correction coefficient to consider the CD impedance on the total and localized hydraulic gradient results in obtaining a reliable accurate HCF in the region falling between \( \theta_a \) to \( \theta_b \).

### 4.4 SWCC and HCF concurrent obtaining time

Using the conventional SWCC and HCF obtaining methods, it takes few weeks to few months to obtain a full SWCC for both the drying and the wetting phases depending on the soil type. Similar time or even a little longer is needed to obtain the HCF using the conventional testing methods depending on the soil type. Table 2 shows the time required to concurrently obtain a full SWCC and full HCF under both the drying and wetting phases for Toyoura sand, K-4 sand and Asakura natural soil using the newly developed system. As indicated in Table 2, it takes less than 5 days to concurrently obtain the drying and wetting phases SWCC and HCF for sandy soils using a CD with an AEV of 100 kPa and saturated hydraulic conductivity of \( 8.6 \times 10^{-8} \) m/sec. Assuming that in average it takes about 4 weeks to get the SWCC for sandy soils using the conventional testing methods, and another four week to determine the HCF, thus using the newly developed system allows concurrent determination of the SWCC and HCF in less than 7% of the testing time required using the conventional testing methods. It must be noted that the system provides continuous curves in comparison to the discrete plots obtained using the conventional methods. Finally, it can be concluded that the newly developed system is an accurate with precise repeatability, reliable, direct and requires very short time concurrent SWCC and HCF obtaining system. However, a proper evaluation of the CD impedance on the driving hydraulic gradient is necessary. The system is capable of testing not only remolded but also undisturbed samples and considers minimizing the degree of disturbance to accurately evaluate the realistic in-situ properties.
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Finally, it can be concluded that the developed system is

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wetting phases. Where the system allows concurrent
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the testing time required using the conventional testing

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undisturbed soil samples.

5 CONCLUSIONS

Through this paper, a novel systematic testing setup

and methodology utilizing the Continuous

Pressurization Method (CPM) that allows rapid,

concurrent, continuous, direct determination of the Soil

Water Characteristics Curve (SWCC) and the Hydraulic

Conductivity Function (HCF) considering both

remolded and undisturbed samples was developed. It

was found that the air pressurizing rate influence on the

obtained SWCC using the developed system can be

neglected, where almost identical SWCCs were obtained

using high and low air pressurizing rates. It was

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ACKNOWLEDGEMENTS

The authors express their gratitude to Mr. Nakashima

Michio (Kyushu university) for his great support.

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