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Rapid determination of the unsaturated hydraulic conductivity for sandy soils utilizing the continuous pressurization method

Détermination rapide de la conductivité hydraulique non saturée pour les sols sableux en utilisant la méthode de pressurisation continue

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ABSTRACT: Proper determination of the unsaturated soil hydrological and retention properties, including the Soil Water Characteristics Curve (SWCC) and the Hydraulic Conductivity Function (HCF), is crucial for understanding the behavior of unsaturated soil profiles. The conventional SWCC and HCF determination approaches are characterized by several limitations associated with the testing complexity, discrete measurements, and prolonged testing time. Therefore, a simple, continuous, rapid, and concurrent SWCC and HCF determination technique is in great need. Through this paper, the Continuous Pressurization Method (CPM) was extended, and a novel quasi-state model was proposed to concurrently determine the SWCC and the HCF. It was found that the proposed quasi-state model adopting the extended CPM is an accurate, reliable, and rapid method that allows for a concurrent and continuous determination of the SWCC and the HCF in less than 3% of the time required using the conventional methods. Furthermore, an indisputable hysteresis in the HCF was observed where comparing the drying and wetting phases, the unsaturated coefficient of hydraulic conductivity varies up to one order difference for the same volumetric water content (or matric suction).

RÉSUMÉ : La détermination adéquate des propriétés hydrologiques et de rétention de sols non-saturés ; notamment la Courbe de Rétention d'Eau (CRE) et la Fonction de la Conductivité Hydraulique (FCH), est cruciale pour la compréhension de leur comportement. Toutefois, les démarches conventionnelles pour la détermination de la CRE et la FCH sont généralement limitées par la complexité des essais, les mesures discrètes et la longue durée des essais. Ainsi, il devient nécessaire de développer une technique simple et rapide pour la détermination de manière simultanée et continue de la CRE et la FCH. Dans cet article, une extension de la Méthode de Pressurisation Continue (MPC) et un nouveau model quasi-statique sont proposés afin de déterminer la CRE et la FCH de manière simultanée. Ledit model comprenant la MPC modifiée s'est avéré précis, fiable et rapide, permettant la détermination de la CRE et la FCH de manière simultanée et continue en réduisant de 3% le temps nécessaire comparé aux méthodes conventionnelles. En outre, lors de la comparaison des phases de séchage et d'humidification, une hystérésis incontestable de la FCH a été observée, le coefficient non-saturé de la conductivité hydraulique varie jusqu'à un ordre de différence de un pour la même teneur en eau volumique (ou la succion matricielle).

KEYWORDS: continuous pressurization method, hydraulic conductivity function, SWCC, hysteresis, unsaturated soil.

1 INTRODUCTION

Global warming has become one of the most alarming environmental problems causing significant changes in the climate and augmenting the likelihood of more extreme rainfall and droughts. Recently, the changing patterns and intensity of rainfall induce devastating natural Geo-disasters in some areas and exacerbate the desertification issue in others.

The ability to properly determine unsaturated soils hydrological and retention properties is crucial for understanding the behavior of unsaturated soil profiles. The Soil Water Characteristics Curve (SWCC), which is a function that describes the amount of water retained in a soil at a given range of suction values, represents the retention properties of porous mediums. Furthermore, the Hydraulic Conductivity Function (HCF) describes the ease and speed at which a fluid moves and represents the hydrological properties. The SWCC and the HCF are key indices when considering unsaturated soils' hydrological and mechanical related issues such as water and solute movement, soil-atmosphere fluxes, and slope stability (Klute 1986, Fredlund et al. 1996, Alowaisy & Yasufuku 2018).

Several experimental and numerical approaches were developed for directly or indirectly determining the SWCC and the HCF. The axis-translation technique, continuous pressurization method, chilled mirror hygrometer, and centrifuge are commonly used for experimentally obtaining the SWCC. The HCF determination methods can be generally categorized based on the governing flow state into 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, and multi-step outflow method) (Klute & Dirksen 1986, Fredlund & Rahardjo 1993, JGS 2000, Lu & Likos 2004, Alowaisy et al. 2019a).

Commonly, discrete plots along the SWCC are directly determined using one of the existing techniques, followed by fitting the obtained SWCC along with the saturated coefficient of hydraulic conductivity using one of the existing models to predict the HCF.

On the other hand, the direct HCF determination techniques are limited for several reasons, including the testing complexity, discrete measurements, and prolonged testing time where depending on the desired number of points, testing may require at least several weeks or even several months. Therefore, a simple, continuous, and rapid HCF determination technique is of great need.

Through this paper, the Continuous Pressurization Method (CPM) developed by (Hatakeyama et al. 2015, Alowaisy et al. 2020) was modified and extended to allow for concurrent, continuous, and rapid determination of both the SWCC and the HCF. Under transient-state testing (CPM), a novel quasi-state model was proposed, which allows for determining the drying and wetting HCFs using a single micro-tensiometer installed at the center of the sample.

2 CONTINUOUS PRESSURIZATION METHOD

The CPM system is automatic and allows for direct, rapid, continuous, and accurate determination of the SWCC (Alowaisy et al. 2020). As shown in Figure 1, the air pressure is supplied to the sample through the inlet valve attached to the top of the cell, where a regulator connected to a computer controls the air pressurizing rate. Meanwhile, a Micro-Tensiometer (MT), installed at the center of the sample, instantly and continuously measures the developing Pore Water Pressure (PWP) in response to the changing air pressure. At the bottom, the Ceramic Disk (CD) retains the air pressure and allows the accumulating PWP to dissipate by draining water out of the sample through the drainage outlet. The draining water is collected into a continuously weighed container using a balance with 0.01 g readability. The sample is 5 cm in diameter and height and is contained in an acrylic mold with a 5 cm inner diameter and 8.5 cm height. A perforated plate hanging from the top cap using a rod is used to restrain the sample and prevent volume changes through testing.

During the test, the applied air pressure (u_a), pore water pressure (u_w), and the cumulative mass of drained water are continuously measured with elapsed time, as shown in Figure 2. The matric suction (ψ) can be calculated by taking the difference between the applied air pressure (u_a) and the developing PWP (u_w) measured at the center of the sample. The corresponding water content can be deduced from the drained water and the tested sample's initial or final water content. A positive air pressurizing rate triggers an increase in the applied air pressure, consequently inducing the drying phase, while the negative rate triggers the wetting phase. The drying phase ends when achieving an equilibrium state where no water flows out of the sample, while the wetting phase ends when no more water flows into the sample. A detailed explanation of the CPM system is reported by Alowaisy et al. 2020. Figure 3 shows the SWCCs obtained using the CPM system for two standard testing silica sand (Toyoura sand and K-4 sand). The particle size distribution curves and a summary of the soil properties are given in Figure 4 and Table 1, respectively.

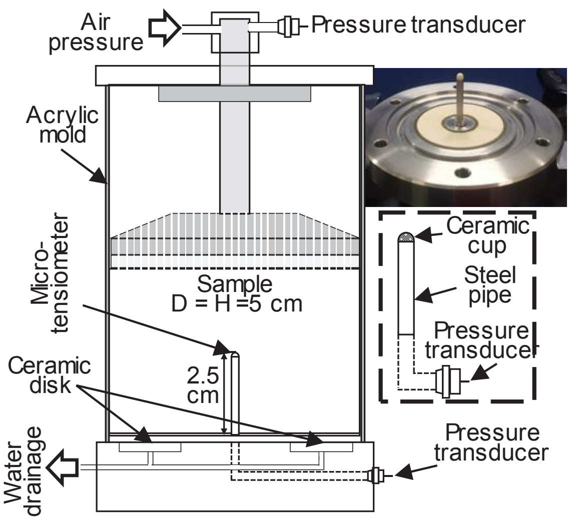

Figure 1. CPM system experimental setup.

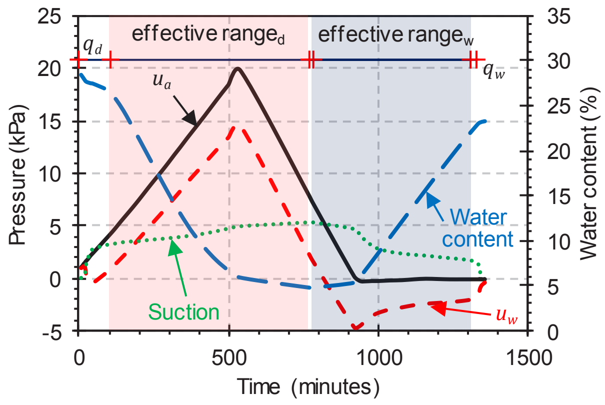

Figure 2. Measured data and calculated matric suction with time (Toyoura sand, air pressurizing rate 0.05 kPa/min).

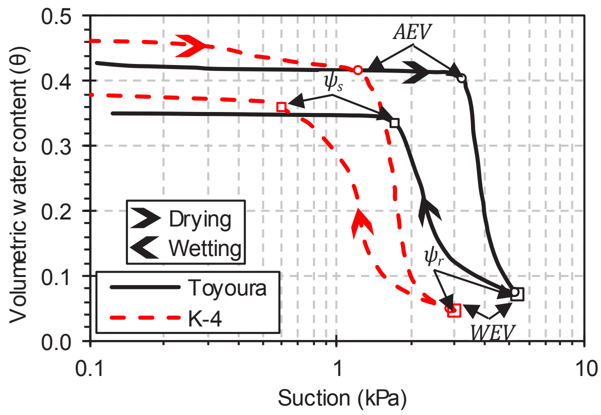

Figure 3. Standard testing silica sand SWCC (CPM extended system). Drying and wetting phases.

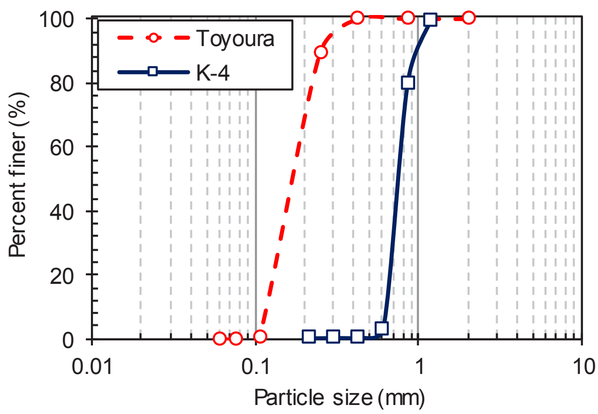

Figure 4. Particle size distribution curves.

Table 1. Summary of the soil properties.

Soil	Specific gravity	Dry density	k_s	Void ratio	D_{10}
	G_s	(g/cm^3)	(m/s)	e	(mm)
Toyoura	2.646	1.560	1.29×10^{-4}	0.693	0.116
K-4	2.640	1.551	2.07×10^{-3}	0.698	0.630

3 QUASI-STATE MODEL [HCF-CPM]

Using the same testing setup, the testing methodology developed for the SWCC determination using the CPM system (Alowaisy et al. 2020, Yasufuku et al. 2020) was extended, where an extra step of pouring 3-5 ml of deaerated water to the top of the sample before starting the test was added, as shown in Figure 5. The proposed method considers determining the HCF using only the added water and the water filling the pores of the sample. For [ψ < Air Entry Value (AEV)], the added water drains out of the sample until reaching the AEV. Followed by the drying phase where water gets lost from the pores and results in dissipating the PWP, consequently increasing the matric suction value. The drying phase ends by reaching the residual stage where no more water flows out of the sample. The wetting phase starts by decreasing the applied air pressure, consequently, the water moves back into the sample until reaching the suction value corresponding to the saturated water content of the wetting phase. However, water keeps moving into the cell and accumulating on the top of the sample due to the difference in the water levels between the cell and the water container until reaching equilibrium, as shown in Figure 5.

For each pressurization pattern, every soil exhibits unique flow rate and hydraulic gradient functions versus elapsed time (Alowaisy et al. 2019b, Hatakeyama et al. 2019). The HCF determination proposed method adopts Darcy-Buckingham's law, which states that the unsaturated hydraulic conductivity is a function of the matric potential or the volumetric water content and can be expressed as follows:

$$k(\psi) = \frac{q_m}{i} \tag{1}$$

$$k_r = \frac{k(\psi)}{k_s} \tag{2}$$

where $k(\psi)$: coefficient of hydraulic conductivity, q_m: measured flow rate; i: hydraulic gradient; k_r: relative coefficient of hydraulic conductivity; and k_s: saturated coefficient of hydraulic conductivity determined using the standard methods.

3.1 *Quasi-state model assumptions*

For the developed HCF determination using the CPM, the following assumptions are considered:

(1) Water flows out of/into the sample can be considered as a succession of steady states where the hydraulic gradient and flow rate are simply constant within each time interval.
(2) 1-D water flow (z-direction).
(3) The effective measurement range:
   i. Drying phase: extends from the AEV to the residual matric suction (ψ_r) [$AEV \le \psi \le \psi_r$], Figure 3.
   ii. Wetting phase: extends between the Water Entry Value (WEV) and the saturated matric suction (ψ_s) [$\psi_s \le \psi \le WEV$], Figure 3.
(4) For $\psi \le AEV$ (drying phase) and $\psi \le \psi_s$ (wetting phase), the hydraulic conductivity is assumed to be equal to the saturated hydraulic conductivity determined using the standard methods (such as the constant or falling head).
(5) For $\psi \ge \psi_r$ and $\psi \ge WEV$, the hydraulic conductivity equals the residual hydraulic conductivity ($k(\psi_r$ or $\theta_r)$) calculated using the proposed quasi-state model.
(6) Isothermal, isoelectric, and isosmotic testing conditions. Water flows out/into the sample-driven by the total hydraulic head difference comprised of the pressure (suction) and gravimetric heads.

3.2 *Drying phase*

To calculate $k(\psi)$ within the effective range, the flow rate (q_m) and the hydraulic gradient (i) should be determined. For the drying phase using the CPM, the increasing applied air pressure

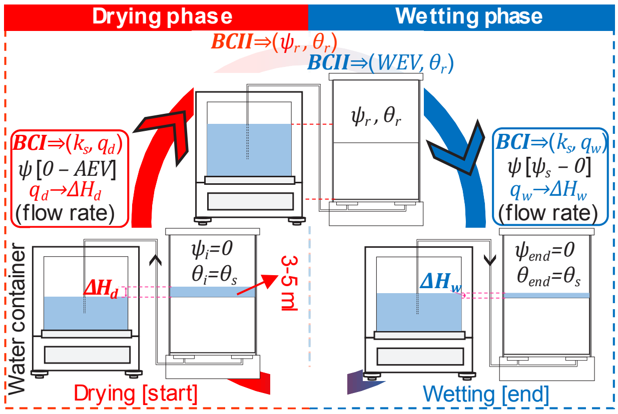

Figure 5. HCF testing conditions. Drying and wetting phases [cell-container head difference] (extended CPM).

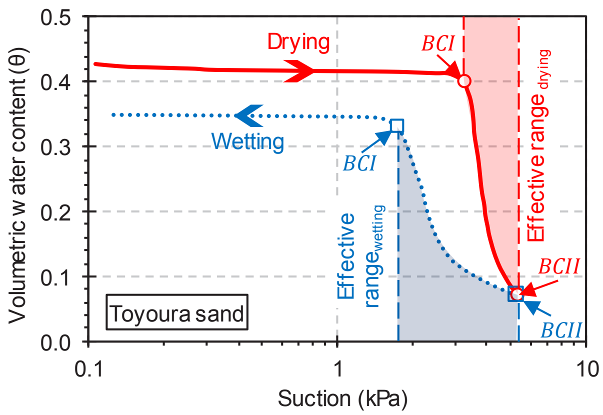

Figure 6. The HCF effective measurement range (drying and wetting) utilizing the extended CPM system.

induces an increase in the PWP associated with simultaneous drainage of the water out of the sample directly into the water container. The flow rate (q_m) can be directly calculated as follows:

$$q_m = \frac{Q}{\Delta t \times A} \tag{3}$$

where Q: volume of drained water during a time interval Δt; and A: soil sample cross-sectional area.

Meanwhile, a quasi-state model is proposed to estimate the hydraulic gradient (i_d) under transient conditions, where $i_d(\psi)$ is assumed to form a straight line as a function of the suction on a log-log scale graph and can be expressed using the general power formula as follows:

$$i_d(\psi) = a \times \psi^b \tag{4}$$

where a: hydraulic gradient corresponding to a unit suction; b: slope of the proposed power function on a log-log scale. To determine the constants a and b corresponding to a specific type of soil under a specific pressurization pattern for the drying phase, the following quasi-state points were selected, Figure 6 (drying curve):

a) BCI, for $\psi = AEV$, the hydraulic gradient can be inversely determined using Darcy's law assuming that $k = k_s$ as follows:

$$i_{AEV} = \frac{q_d}{k_s} \tag{5}$$

$$BCI \rightarrow [i_{AEV}, \text{AEV}] = [\frac{q_d}{k_s}, \text{AEV}] \tag{i}$$

where i_{AEV}: hydraulic gradient at ($\psi = AEV$); q_d: flow rate corresponding to the 3-5 ml (ΔH_d) added to the top of the sample drained out from the cell into the water container (Figure 5), and *BCI*: boundary condition I.

b) *BCII*, for $\psi = \psi_r$, the total head ($H(t,z)$) comprised of the suction and gravimetric heads can be expressed as follows:

$$H(t,z) = z^{\psi^c} \quad (6)$$

$$i_r = \frac{dH}{dz} = (\psi_r)^c \times \left(\frac{H}{2}\right)^{((\psi_r)^c - 1)} \quad (7)$$

where t: time; z: depth; and c: constant.

Solving (Eq. 6) for the total head measured at the center of the sample (suction and gravimetric) when ($\psi = \psi_r$) leads to:

$$c = \log_{\psi_r}\left[\frac{\ln(H)}{\ln(\frac{L}{2})}\right] \quad (8)$$

$$BCII \rightarrow [i_r, \psi_r] = \left[(\psi_r)^c \times \left(\frac{H}{2}\right)^{((\psi_r)^c - 1)}, \psi_r\right] \quad (ii)$$

where $L/2$: gravimetric head (MT location); L: length of the sample (5 cm); and *BCII*: boundary condition II.

Solving (Eq. 4) for (Eq. i) and (Eq. ii) leads to:

$$b = \frac{\ln\left(\frac{i_{AEV}}{i_r}\right)}{\ln\left(\frac{AEV}{\psi_r}\right)} \quad (9a)$$

$$a = \frac{i_{AEV}}{(AEV)^b} \quad (9b)$$

3.3 *Wetting phase*

Similar to the drying phase, the flow rate into the sample (q_m) can be directly calculated using (Eq. 3). The quasi-state model is extended to estimate the hydraulic gradient (i_w) for the wetting phase, where it can be expressed using similar power formula as follows:

$$i_w(\psi) = c \times \psi^d \quad (10)$$

where c: hydraulic gradient corresponding to a unit suction; d: slope of the proposed power function. To determine the constants c and d corresponding to a specific type of soil under a specific pressurization pattern for the wetting phase, the following quasi-state points were selected, Figure 6 (wetting curve):

a) *BCI*, for $\psi = \psi_s$, the hydraulic gradient can be inversely determined using Darcy's law assuming $k = k_s$. At the same time, the flow rate (q_w) corresponds to the water (ΔH_w) flowing into the sample from the water container, Figure 5.

b) *BCII*, similar to the drying phase [(Eq. 6) through (Eq. ii)], but for $\psi = WEV$.

Solving (Eq. 10) for the wetting boundary conditions leads to:

$$d = \frac{\ln\left(\frac{i_{\psi_s}}{i_{WEV}}\right)}{\ln\left(\frac{\psi_s}{WEV}\right)} \quad (11a)$$

$$c = \frac{i_{\psi_s}}{(\psi_s)^d} \quad (11b)$$

4 VALIDATION OF THE PROPOSED QUASI-STATE MODEL [HCF-CPM]

The flow rate and the hydraulic gradient calculated adopting the proposed model for Toyoura sand under the drying phase are shown in Figure 7. The flow rate was calculated directly using (Eq. 3) and plotted versus the corresponding suction value

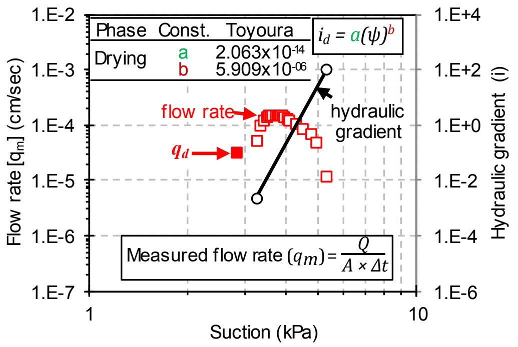

Figure 7. Flow rate and hydraulic gradient (quasi-state model). Toyoura sand (drying phase).

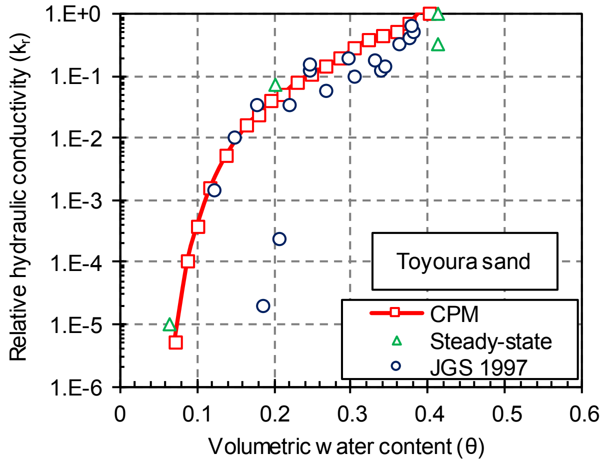

Figure 8. Toyoura sand's drying phase-HCF determined using the extended CPM system (quasi-state model).

measured at the center of the sample. The white-filled squared plots represent the effective measurement range, while the color-filled plot corresponds to the adopted boundary condition (*BCI*). It must be noted that the measured flow rate corresponds to the equivalent flow rate of the two-layered profile comprised of the soil sample and the underlying ceramic disk.

On the other hand, the hydraulic gradient was calculated using the proposed quasi-state model (Eq. 4) fitted with the aforementioned boundary conditions (Eq. i and Eq. ii). The solid line corresponds to the effective range, while the circular scatter plots represent the selected boundary conditions for solving the proposed power formula. The fitting constants (a) and (b) are indicated in the same figure.

The coefficient of hydraulic conductivity was calculated by dividing the measured flow rate by the corresponding hydraulic gradient determined using the proposed model (Eq. 1). The relative coefficient of hydraulic conductivity (Eq. 2) was plotted versus the corresponding volumetric water content, as illustrated in Figure 8. It can be observed that the drying phase HCF obtained using the proposed quasi-state model (extended CPM system) agrees well with the drying HCF obtained using the conventional steady-state method, where both HCFs compare well to the HCF reported by other researchers for the same standard testing Toyoura sand (JGS 1997). It can be concluded that the proposed quasi-state model adopting the extended CPM system is reliable and allows for simple, accurate, rapid, continuous, and concurrent determination of the SWCC and the HCF for cohesionless soils.

5 HYSTERESIS OF THE HCF

Figure 9 shows the flow rate calculated using (Eq. 3) for Toyoura sand and K-4 sand under the drying and wetting phases, respectively. Similarly, the white-filled plots represent the effective measurement range while the color-filled plots correspond to the adopted boundary conditions (*BCI* corresponding to the onset of the drying and wetting phases). It can be seen that each soil exhibits a unique flow rate function that differs for the drying and wetting phases. For both phases, the measured flow rate increases at the beginning until reaching a peak value, followed by a significant decrease in the flow rate. This pattern can be attributed to the simultaneous changes in the hydraulic gradient (function of the increasing/decreasing head) and the inter-particle water continuity. Towards the end of the drying phase, the inter-particle water discontinuity limits the water flow rate even under high driving suction gradients, while the hydraulic gradient becomes the limiting factor at the end of the wetting phase.

The hydraulic gradient calculated using the proposed quasi-state model fitted with the aforementioned boundary conditions for the drying and wetting phases are shown in Figure 10 for Toyoura sand and K-4 sand, respectively. Similarly, the lines correspond to the effective range while the scatter plots represent the selected boundary conditions for solving the proposed power formula. The fitting constants for each soil type are indicated for both phases. It was found that each soil exhibits a unique hydraulic gradient function that corresponds to a unique flow rate function within the effective measurement range and differs for the drying and wetting phases. The HCF corresponding to the drying and wetting phases calculated using the proposed quasi-state model is plotted in Figure 11 and Figure 12 for Toyoura

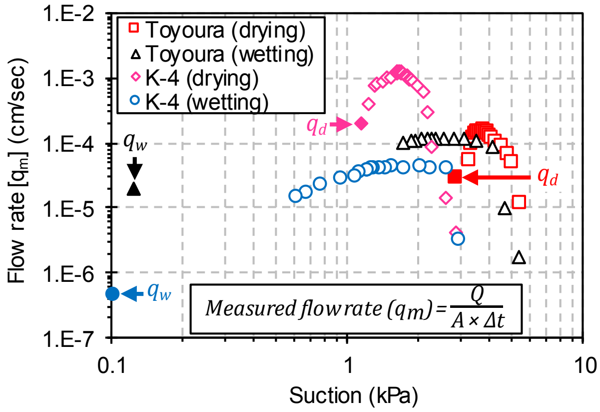

Figure 9. Directly measured flow rate (extended CPM).

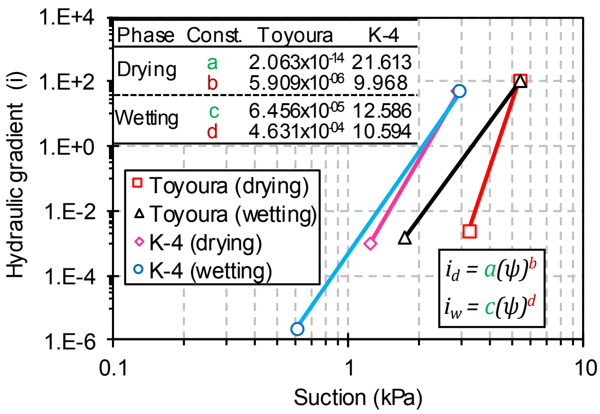

Figure 10. Calculated hydraulic gradient using the proposed quasi-state model (extended CPM).

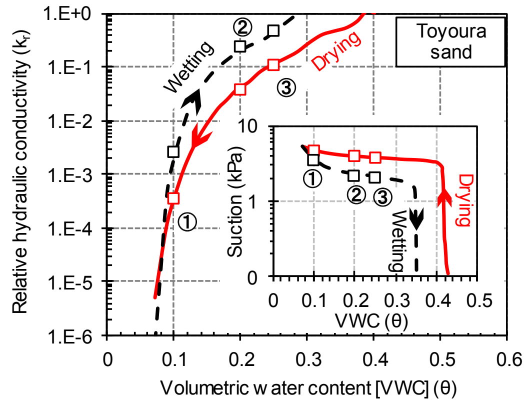

Figure 11. Toyoura sand HCF determined using the extended CPM system (quasi-state model).

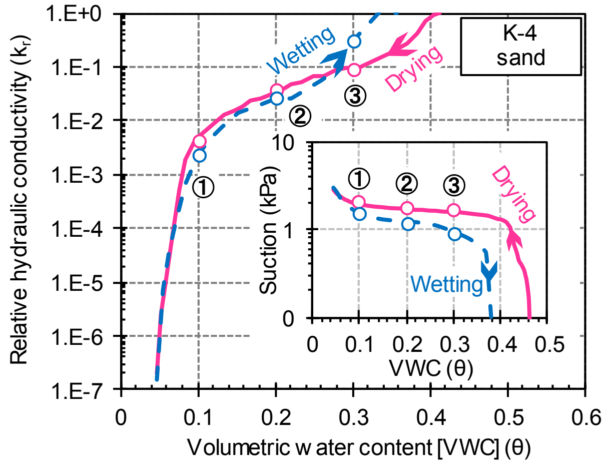

Figure 12. K-4 sand HCF determined using the extended CPM system (quasi-state model).

and K-4 sand, respectively. Similar to the SWCC, an indisputable hysteresis in the HCF was observed even when plotted versus the volumetric water content. Comparing the two phases, the unsaturated coefficient of hydraulic conductivity varies up to one order for the same volumetric water content (or matric suction). It must be noted that $k_r = 1$ corresponds to θ_s which differs for the drying and wetting phases. It was confirmed that for the drying phase $\theta_s \approx 0.41$, while it is around 0.35 for the wetting phase corresponding to a degree of saturation $S_r \approx 100\%$ and 80%, respectively. This difference is a result of the vacuum saturation adopted for the drying phase. It is assumed that the error associated with this assumption is minor (under verification). Similar to the SWCC, the HCF hysteresis becomes more significant for higher degrees of saturation (lower suction). For example, for Toyoura sand [$\theta = 0.2$], a hysteresis of [$\psi_d \approx 2\psi_w$] is opposed by approximately one order difference in the hydraulic conductivity [$k_d \approx 0.1k_w$]. The hysteresis of the HCF can be attributed to several micro-scale reasons, including:

1) The particles-fluid friction and bonding associated with the air invading into the water-filled pores during the drying phase compared to the water invading the air-filled pores in the wetting phase.
2) The resultant force in the contractile skin area (air-water interface), where for the same water content on the SWCC, the matric suction is relatively lower for the wetting phase than the drying phase.

It must be noted that the degree of hysteresis might be directly related to the uniformity of the pore network of the sample.

6 SWCC AND HCF DETERMINATION TIME

The testing time required to obtain the SWCC using the conventional multi-step flow method, the HCF using the conventional steady-state method, and the concurrent SWCC and HCF determination using the developed CPM for the drying phase is illustrated in Figure 13. It must be noted that it took approximately 24 days to determine the drying phase SWCC and the HCF adopting the conventional testing methods for Toyoura sand, while it took less than half a day to concurrently determine the drying SWCC and HCF using the developed CPM system. It can be concluded that the proposed quasi-state model using the extended CPM can be used to concurrently determine the SWCC and the HCF in a remarkably short time, accounting for less than 3% of the time required using the conventional methods.

The remarkable reduction in the testing time significantly enhances the accuracy and reliability of the SWCC and HCF determination which is expected to enhance various practical aspects when dealing with unsaturated soil mechanics. Besides, the CPM system is capable of detecting the water drainage with a resolution of 0.01 g and the suction in the order of 0.1 kPa. Therefore, adopting a short time interval allows continuous determination of the SWCC and the HCF under both the drying and wetting phases. On the other hand, only discrete plots along the curves can be obtained using conventional methods.

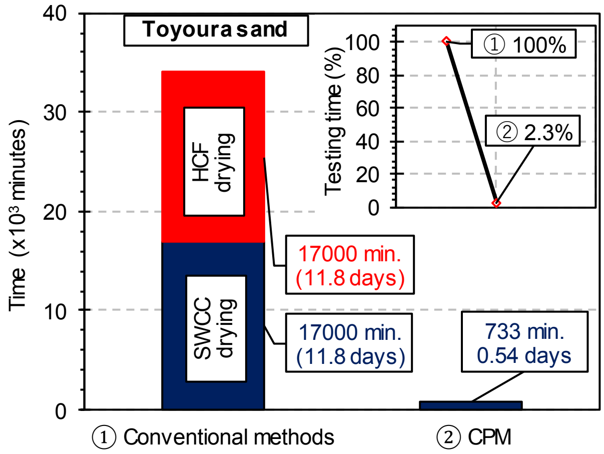

Figure 13. Testing time using the extended CPM system and the conventional methods (Drying phase).

7 CONCLUSIONS

Through this paper, the Continuous Pressurization Method (CPM) was extended to allow for concurrent, continuous, and rapid determination of the Soil Water Characteristics Curve (SWCC) and the Hydraulic Conductivity Function (HCF). The extension included proposing a novel quasi-state model to determine the drying and wetting HCFs using a single micro-tensiometer installed at the center of the sample under a transient state. The main findings of this study can be outlined as follows:

1) Each type of soil exhibits a unique hydraulic gradient function that corresponds to a unique flow rate function within the effective measurement range and differs for the drying and wetting phases. (Effective range: drying phase [$AEV \leq \psi \leq \psi_r$], wetting phase [$\psi_s \leq \psi \leq WEV$]).
2) Similar to the SWCC, an indisputable hysteresis in the HCF was observed, even as a function of the volumetric water content. Comparing the drying and wetting phases, the unsaturated coefficient of hydraulic conductivity varies up to one order for the same volumetric water content. The hysteresis can be attributed to several micro-scale reasons, while the degree of hysteresis might be directly related to the uniformity of the pore network of the sample.
3) Finally, it can be concluded that the proposed quasi-state model adopting the extended CPM is an accurate, reliable, and rapid method that allows for a concurrent determination of the SWCC and the HCF, where the drying and wetting SWCCs and HCFs can be obtained in less than 3% of the time required using the conventional methods. Furthermore, the developed method allows continuous determination of the SWCC and the HCF under the drying and wetting phases, while only discrete plots along the curves can be obtained using the conventional methods.

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