Pore water pressure profile development through soil water characteristics curve determination utilizing the continuous pressurization method

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ABSTRACT

In order to improve the efficiency of the Soil Water Characteristics Curve (SWCC) determination and shorten the testing time, a new SWCC obtaining method utilizing the Continuous Pressure Method (CPM) was developed. The newly developed system allows continuous measuring of the suction by pressurizing the sample and continuously measuring the developing pore water pressure using a micro-tensiometer installed at the center of the sample. The suction (s) is defined as the difference between the applied air pressure and the measured pore water pressure at the center of the specimen (s = uₐ - uₐw, where uₐ = air pressure, uₐw = pore-water pressure). Both the drying and wetting (SWCC) can be obtained in 2 to 3 days. It is found that the SWCC under both the drying and the wetting phases obtained using newly developed apparatus are in well agreement with those obtained using the conventional multi-step flow method. In addition, the optimum pore-water pressure measuring point was clarified by measuring the pore water pressure at four different levels and comparing the results. Where it was found that the SWCC obtained considering the pore-water pressure being measured at different levels agree well with SWCC obtained considering the pore-water pressure being measured at the center of the specimen. Finally, it was concluded that the pore-water pressure measured at the center of the specimen can be considered as a representative point for obtaining reliable SWCC.

Keywords: SWCC, Continuous pressurization method

1 INTRODUCTION

The unsaturated soils hydrological characteristics including the Soil Water Characteristics Curve (SWCC) and the saturated and unsaturated hydraulic permeability coefficients are important parameters for proper evaluation of the total strength and stability of natural slopes and embankments during heavy rainfall events. Several laboratory and in-situ testing methods and setups have been developed, where most of them are characterized with high cost and prolonged testing time. (Fredlund et al. 2012) reported that the available experimental setups and techniques for determining the unsaturated soils properties require sophisticated advanced technology and complex operation process. Therefore, the number of cases and data where the hydrological characteristics of unsaturated grounds were determined in laboratory or in-situ are quite limited.

A new SWCC determination apparatus utilizing the Continuous Pressurization Method (CPM) was developed (Hatakeyama et al. 2015). The system reliability and capability of significantly shortening the required testing time in comparison to the conventional multi-step flow method utilizing the axis-translation technique (Tempe cells) was confirmed. The newly developed system allows continuous measuring of the suction by pressurizing the sample and continuously measuring the developing pore-water pressure using a micro-tensiometer installed at the center of the sample. Thus using the developed system, a simple, automatic SWCC determination process can be carried out.

Through this paper, the optimum pore-water pressure measuring position was investigated using four micro-tensiometers installed at different levels through the specimen. It was confirmed that the SWCC obtained considering the pore-water pressure averaged along the specimen agrees well with SWCC obtained considering the pore water pressure being measured at the center of the specimen. Thus it was concluded that the center of the specimen can be considered as a representative point for measuring the pore water

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pressure resulting in obtaining reliable SWCC.

In addition, it was found that the atmospheric pressure fluctuation during testing has significant influence on the air pressure and pore water pressure. However, it was confirmed that the suction can be accurately measured using a micro-tensiometer installed directly into the soil sample. Furthermore, the adopted pore water pressure measurement technique reliability and accuracy was discussed.

2 COMPARISON OF THE DEVELOPED CPM METHOD TO THE CONVENTIONAL MULTI-STEP FLOW METHOD

2.1 Comparison of adopted techniques

Fig. 1 illustrates the difference in the pressurization pattern and process of the newly developed CPM method in comparison to the conventional multi-step flow method.

Fig. 1. Air pressurization patterns. CPM system versus the conventional multi-step flow method.

Considering the conventional multi-step flow method, a predetermined air pressure \( p \) is supplied in steps to the specimen (JGS. 2009). The air pressure is maintained till reaching an equilibrium state where no more water flows out of the sample. Then the SWCC is obtained considering the relation between the applied air pressure and the sample water content after achieving the equilibrium state.

The suction \( s \) at each pressure after achieving equilibrium can be calculated as follows.

\[
s = p \tag{1}
\]

where:

- \( s \) = suction
- \( p \) = air pressure applied to specimen

It must be noted that the time required to reach the equilibrium state at each air pressure step takes about 1 to 10 days for high permeable soils such as sandy soils. However, it takes longer for low permeable soils. Thus in general, it takes few weeks to few months to obtain a full SWCC under both the drying and wetting phases.

On the other hand, for the developed CPM system the air pressure \( u_a \) is continuously increased/decreased at a constant rate. During testing, the pore-water pressure \( u_w \) is continuously measured using a micro-tensiometer installed at the center of the specimen. In addition, the cumulative amount of water drained from the sample is continuously recorded.

The suction \( s \) can be calculated as follows.

\[
s = u_a - u_w \tag{2}
\]

where:

- \( u_a \) = air pressure
- \( u_w \) = pore-water pressure

2.2 Testing setup

Fig. 2 shows a picture of the developed experimental setup. The system consists of a testing unit (pressurizing cell), an electronic balance used for measuring the cumulative drained water, air pressure regulator, data control and acquisition unit and computer.

The specifications of each unit are illustrated in Table 1. Fig. 3 shows a schematic diagram of the pressurizing cell, while figure 4 shows a picture of the bottom base. An acrylic cylindrical mold with an inner diameter of 5 cm is used to contain a 5 cm in height soil sample. The air pressure is supplied to the pressurizing cell through the inlet valve attached to the top of the cell, where a regulator connected to a computer controls the rate of pressurizing. As shown in Fig. 4, a ceramic disk (CD) is installed at the bottom base of the pressurizing cell. A micro-tensiometer is installed vertically at the center of the CD.

The pressurizing cell is designed in a way where the micro-tensiometer can be replaced easily, thus a micro-tensiometer with the designated height can be installed, therefore the pore water pressure \( u_w \) at center of the sample depending on the height of the specimen can be simply carried out.

3 MATERIAL AND TEST RESULTS

3.1 Material

Tests were carried out using standard testing silica sand (Toyoura sand).

Fig. 2. Test equipment.
Fig. 3. CPM pressurizing cell (Schematic).

Fig. 4. CPM pressurizing cell bottom base (Picture).

Table 1. Specifications of each unit.

| Unit                      | Specifications                                                                 |
|---------------------------|-------------------------------------------------------------------------------|
| Pressure chamber          | Pressure capacity : 1 MPa                                                       |
|                           | Sample container : Diameter : 50 mm                                           |
|                           | height : 85 mm                                                                 |
| Air pressure,             | Pressure transducer                                                           |
| Pore-water pressure       | • Measurement range : 0 ~ 700 kPa                                             |
|                           | • Accuracy : ± 0.25 %FS                                                        |
| Water displacement        | Precision electronic balance                                                   |
|                           | • capacity up to : 2000 g                                                      |
|                           | • Minimum display : 0.01 g                                                     |
| Air pressure regulator    | Pressure regulator + Stepper motor                                            |
|                           | • Pressure ranges : 200 kPa                                                    |
|                           | • Pressurizing speed : 0.001 ~ 10 kPa/min                                      |

Fig. 5 shows the particle size distribution curve of Toyoura sand. Soil samples were prepared by directly compacting the soil to the desired density in an acrylic mold, 5 cm in diameter and 5 cm in height soil specimens were adopted for testing.

Two saturation patterns were adopted as follows.

1) Samples and the 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 condition [vacuum saturated].

2) Saturation was carried out by allowing the samples to stand in a water bath for 24 hours (capillary saturated).

Soil samples were prepared with a dry density ($\rho_d$) of 1.50 g/cm$^3$.

3.2 SWCC of the capillary saturated samples

Fig. 6 shows the air pressure ($p$) and the water content ($w$) development for time with the drying phase followed by the wetting phase using the conventional multi-step flow method. In total 11 stages were performed, 6 of the air pressure stages were adopted for the drying phase, while 5 stages for the wetting phase. Using the conventional method, it took about 44000 minutes (31 days) to obtain a full SWCC under both the drying and the wetting phases.

Fig. 7 illustrates the newly developed CPM system testing results. The air pressure ($u_a$) was applied in a triangular load pattern starting from 0 kPa increasing to 50 kPa for the drying phase then decreasing again to 0 kPa for the wetting phase under an air pressurization rate of 0.1 kPa/min. for both phases. The air pressure ($u_a$), the pore-water pressure ($u_w$), the water content ($w$) and the suction ($s = u_a - u_w$), calculated from the air pressure ($u_a$) in relation to the pore-water pressure ($u_w$) over time are illustrated in Fig. 7. The pore-water pressure was measured with the micro-tensiometer installed at the center of the specimen. It can be observed that even under high air pressure values (50 kPa), the difference between the applied air pressure and the measured pore-water pressure was small, thus the suction achieved a maximum of 7 kPa. The water content has reached an equilibrium after about 300 minutes. At equilibrium the water content was about 4% which is consistent with the residual water content obtained using the conventional multi-step flow illustrated in Fig. 6. In total it took about 2700 minutes (2 days) to obtain a full SWCC under both the drying and the wetting phases using the newly CPM developed system.

Fig. 8 shows the drying and wetting phases SWCCs obtained using the newly developed CPM system indicated by the solid line, while the SWCCs obtained using the conventional multi-step flow method are indicated by the scatter plots. It must be noted that as
indicated in Fig. 8, the initial degree of saturation (Sr) at the beginning of the test using capillary saturated samples was about 80%.

Finally, it can be concluded that the SWCC obtained using the newly developed CPM system agrees very well with SWCC obtained using the conventional multi-step flow method. However, in the residual zone (Fredlund et al. 2011) where the suction exceeds 10 kPa, higher suction values were achieved using the conventional method while the CPM developed system suction was pinned at lower values.

Fig. 6. Conventional multi-step flow method obtained raw data.

Fig. 7. CPM system obtained raw data.

Fig. 8. SWCCs obtained using the CPM system and multi-step flow method (Capillary saturated sample).

Fig. 9. SWCCs obtained using the CPM system and multi-step flow method (Vacuum saturated sample).

3.3 SWCC of the vacuum saturated samples

Fig. 9 shows the SWCC obtained using the newly developed CPM system in addition to the SWCC obtained using the conventional multi-step flow method for the vacuum saturated samples. It can be observed that the SWCC obtained using the newly developed CPM system is in well agreement with SWCC obtained using the conventional multi-step flow method under both the drying and the wetting phases. Similar to the capillary saturated samples, in the residual zone where the suction exceeds 10 kPa, higher suction values were achieved using the conventional method while using the CPM developed system, the suction was pinned at lower values.

4 FACTORS AFFECTING THE SWCC DETERMINATION USING THE CPM SYSTEM

4.1 Pore-water pressure measurement position

(1) Optimization adopted method

Four pore-water pressure measurement levels 0.5, 1, 2.5 and 4 cm were adopted using four micro-tensiometers varying in length that can be attached to the pressurizing cell illustrated in Fig. 3. Fig. 10 illustrates the adopted micro-tensiometers and the corresponding pore-water pressure measurement level. The developed pressurizing cell is designed with two micro-tensiometers to be installed at the same time. Therefore, in order to measure the pore-water pressure at the designated four levels, three testing sets were adopted as illustrated in Fig. 10.

Set 1 is equipped with two micro-tensiometers installed at 4 and 2.5 cm, set 2 with two micro-tensiometers installed at 4 and 1 cm and set 3 with two micro-tensiometers installed at 4 and 0.5 cm.

Extra water (19.6 g) was added to the top of the saturated specimen prior starting the test in order to accurately capture the pore-water pressure development in the specimen as shown in Fig. 11. Adding the extra water allows obtaining a full SWCC including the full region starting from the fully saturated region moving towards the unsaturated zone.
(2) The suction profile development under continuous air pressurization

Fig. 12 shows the normalized suction values measured at the adopted 4 positions versus the elapsed time. The saturated zone can be clearly distinguished. While draining the extra added water, the air pressure almost equals the pore-water pressure, thus the suction value remains almost zero \((s \approx 0)\). A sudden increase in the suction value can be observed, where this can be related to the onset of air ingestion into the specimen. Where this point indicates the time where all the extra water \((19.6 \text{ g})\) is drained out of the sample. This same trend was observed at the four adopted positions. Based on that, almost identical AEV was obtained at the four adopted positions.

(3) Suction profile development

Fig. 13 shows the suction profile distribution determined using the four adopted micro-tensiometers at various water contents. It can be observed that the difference in the suction values between the adopted positions is very small for water contents ranging from high \((w = 26\%)\) to low water contents \((w = 4\%)\).

Fig. 14 illustrates the normalized suction deviation in reference to the suction value measured by the micro-tensiometer installed at 4 cm. The suction deviation was confirmed to be in the range of 0.2 kPa.

(4) Comparison of the SWCC

Fig. 15 shows the SWCC obtained considering the pore-water pressure being measured at the adopted four levels. It can be observed that the SWCCs obtained considering the pore-water pressure being measured at each adopted level are in very good agreement with each other with minor differences. This phenomenon is consistent with the results reported by (Adel et al. 2018).

![Fig. 10. Adopted CPM testing setups and micro-tensiometers positions (schematic).](image)

![Fig. 11. Prior testing conditions. Extra water was added to the top of the specimen.](image)

![Fig. 12. Suction value measure at the four adopted levels versus the elapsing time.](image)

![Fig. 13. Suction profile distribution.](image)

![Fig. 14. Normalized suction profile distribution (reference value, micro-tensiometer installed at 4 cm).](image)

4.2 Influence of the initial saturation condition on the SWCC

Fig. 16 shows the SWCC obtained using the newly developed CPM system for the capillary saturated and vacuum saturated samples. It can be observed that the initial degree of saturation varies by varying the adopted saturation process. In addition, the obtained SWCC shape and AEV slightly differs considering different saturation processes.
(1) Water drainage and suction development using the conventional multi-step flow method

The cumulative water drainage versus elapsed time under the drying phase considering two pressurizing stages are shown in Fig. 17 and Fig. 18. During the air pressurizing stage ($u_a = 2 \text{kPa}$ → $4 \text{kPa}$), large amount of water was drained out of the sample as illustrated in Fig. 17. Where about 23 g of water was drained out of the sample during this stage. The equilibrium was achieved after 12000 minutes. The suction value was also converged to equilibrium after the same elapsed time.

Fig. 18 illustrates the amount of water drained versus the elapsed time for the pressurizing stage pressure ranging ($u_a = 8 \text{kPa}$ → $15 \text{kPa}$). It can be observed that only small amount of water was drained out of the sample during this stage. Although the suction achieved equilibrium in a short time, small amounts of water kept draining out of the sample. Thus, it was confirmed that under such situations, it is difficult to accurately determine the point where the water drainage achieves equilibrium point where no more water drains out of the sample.

Considering the conventional concept where the suction value is assumed to be equal to the applied air pressure at equilibrium ($s = p$), the suction is found to be 15 kPa at the end of that stage. However, considering the suction being calculated by taking the difference between the applied air pressure and the measured pore-water pressure after achieving the equilibrium ($s = u_a - u_w$), the suction is calculated with a value of 7.2 kPa.

Finally, it can be concluded that there is a significant error when considering the suction value to be equal to the applied air pressure at the equilibrium point $s = p$. Thus considering measuring the pore-water pressure when determining the SWCC is necessary.

(2) Considering the pore-water pressure using the multi-step flow method

Fig. 19 shows the SWCC under the drying phase determined using the conventional multi-step flow method. In order to cover the saturated and unsaturated zones, extra water (19.6 g) was added to the top of the sample before starting the test as illustrated Fig. 11. The SWCC shown in Fig. 19 was obtained considering calculating the suction ($s$) based on the conventional method where ($s = p$).

In order to evaluate the pore-water pressure development using this conventional method, a micro-tensiometer was installed at the center of the specimen. The suction was then calculated by taking the difference between the applied air pressure and the measured pore water pressure when achieving the equilibrium state ($s = u_a - u_w$).

The obtained results are summarized in Table 2. The initial predetermined air pressure ($p$) for each pressure stage (six stages), the final air pressure ($p_f$) measured by...
the pressure transducer, the pore-water pressure \( u_{wf} \) measured at the center of the specimen, the suction \( s = (p_f - u_{wf}) \), the water content \( w \) and the difference between \( p \) and \( s \) are shown through Table 2. The difference between the predetermined initial air pressures \( (p) \) and the final measured \( p_f \) ranges between 0.4 kPa to 1.6 kPa.

For the pressurization stages 1 to 5, the change in the pore-water pressure \( (u_{wf}) \) is relatively small ranging from 0.3 to 1.4 kPa. However, for the stage number 6, a high pore-water pressure of 9.0 kPa was measured. The suction \( s = (p_f - u_{wf}) \) was found to be smaller than the suction at the end of stage number 5, which falls out of the expected trend (higher air pressure results in higher suction values). For the first and second stages, the change in water content is extremely small, where this stage represents the boundary region between the saturated state and the unsaturated states.

In addition, it can be seen that there is almost no change in the water content \( (w) \) at the end of the fifth and the sixth stages. Where increasing the air pressure induces slight decrease in the water content. Where those stages fall in the residual range. For stage 6, the difference between the initial air pressure \( (p) \) and the suction \( (s) \) in this residual zone is 8.2 kPa, which is significantly higher than the values of the other the stages \((0.7 \text{ to } 1.0 \text{ kPa})\).

Finally, the conventional suction calculation method \( s = p \) was confirmed to be not accurate, where considering the pore water pressure as zero results in significant error that cannot be neglected.

![Fig. 17. Multi-step flow method measured suction and water drainage development \( [u_a = 2 \text{ kPa} \rightarrow 4 \text{ kPa}] \).](image)

(3) **Necessity of measuring the pore water pressure**

The SWCC considering the measured pore-water pressure in the suction calculation following \( s = (p_f - u_{wf}) \) is indicated by the scatter plot in Fig. 20. It can be observed that the SWCC for the stages 1, 2, 3 and 4 is identical with the SWCC calculated following the conventional method \( (s = p) \) illustrated in Fig. 19.

![Fig. 18. Multi-step flow method measured suction and water drainage development \( [u_a = 8 \text{ kPa} \rightarrow 15 \text{ kPa}] \).](image)

![Fig. 19. Drying phase SWCC \( [suction \ (s) = p \).](image)

| Table 2. Result of measurement of pore-water pressure by multi step flow method. |
| --- |
| Pressure stage | 1 | 2 | 3 | 4 | 5 | 6 |
| Initial air pressure \( p \) (kPa) | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 |
| Final air pressure \( p_f \) (kPa) | 2.0 | 3.6 | 4.6 | 5.8 | 6.8 | 8.4 |
| Pore-water pressure \( u_{wf} \) (kPa) | 0.3 | 1.0 | 0.2 | 0.6 | 1.4 | 9.0 |
| Suction \( s \) (kPa) | 1.7 | 2.6 | 4.4 | 6.2 | 7.0 | 6.8 |
| Moisture content \( w \) (%) | 27.8 | 27.7 | 11.9 | 3.9 | 3.5 | 3.5 |
| \( p = s \) (kPa) | -0.7 | -0.6 | -0.4 | -0.2 | 1.0 | 8.2 |
| ※: \( s = p_f - u_{wf} \) |

However, for stages 5 and 6, the calculated suction values significantly differ from the conventional method calculated values shown in Fig. 19. Thus it can be concluded that during the residual stage, the conventional method assumption that the suction value equals the applied air pressure is not valid.

It can be seen that considering the pore-water pressure values when calculating the suction through
the residual stages (5 and 6) results in suction values very close to the suction value determined in stage 4 as shown in Fig. 20.

The SWCC obtained using the newly developed CPM system indicated by the solid line is also illustrated in Fig. 20. Using the conventional multi-step flow method, neglecting the pore-water pressure when calculating the suction resulted in poor agreement with the newly developed CPM system within the residual zone. For the case of Toyoura sand, the difference exceeded 10 kPa. However, considering the pore-water pressure when calculating the suction \( s = p_f - u_{wf} \) using the conventional method results in obtaining SWCC in very good agreement with the newly developed CPM system obtained SWCC for all the zones including the residual zone.

(4) Atmospheric pressure fluctuations influence on the SWCC

Fig. 21 (a) shows the measured air pressure \( (u_a) \) and pore-water pressure \( (u_w) \) under the wetting process using the newly developed CPM system. The result of changing the air pressure from 8 kPa to 4 kPa was shown. In addition, the atmospheric pressure versus time are also plotted (JMA, 2018). The air pressure was directly measured using a pressure transducer.

The measured air pressure \( (u_a) \) fluctuates around the predetermined value. In comparison to the air pressure \( (u_a) \) fluctuations, the pore-water pressure \( (u_w) \) also fluctuates following the same pattern. Comparing the air pressure and pore-water pressure fluctuations to the atmospheric pressure fluctuations, it can be confirmed that the air and pore-water pressure fluctuations result from the surrounding zone atmospheric pressure fluctuations.

When calculating the suction considering the pore-water pressure, the measured pore-water pressure fluctuations cancel the measured air pressure fluctuations. Therefore, a correction reflecting the atmospheric pressure fluctuations is not required. On the other hand, a correction is necessary when using the conventional suction calculation method where the suction is assumed to equal to the applied air pressure in order to obtain accurate SWCC.

The suction calculated considering the pore-water pressure is illustrated in Fig. 21 (b). It can be confirmed that suction \( (s) \) calculated by \( s = u_a - u_w \) is not affected by atmospheric pressure fluctuations.

6 CONCLUSIONS

The newly developed Continuous Pressurization Method (CPM) system is capable of directly obtaining the Soil Water Characteristics Curve (SWCC) under both the drying and the wetting phases in a very short time in comparison to the conventional multi-step flow method.

The main conclusions obtained through this paper are summarized below.

1) The SWCC obtained using the newly developed CPM system was confirmed to be in a very good agreement with the SWCC obtained using the conventional multi-step flow method under both the drying and the wetting phases. However, a slight difference was observed under high suction values within the residual zone. This was confirmed to be a result of the adopted suction calculation assumptions. Where considering the
pore-water pressure when calculating the suction using the conventional method results in well agreement between the two methods even within the residual stage.

2) Using the conventional multi-step flow method, since an equilibrium state should be achieved (no more water is drained out of/absorbed into the sample) before measuring the suction and the corresponding water content, the testing time is inevitably long specially for samples with low permeability. It was also confirmed that for high permeable soils such as sandy soils, it takes long time to achieve equilibrium when applying a stage where large amount of water is drained out of/absorbed into the sample. Thus, for long testing periods, the influence of the atmospheric pressure fluctuation on the suction calculation becomes significantly higher.

3) The air pressure and pore-water pressure measurements are significantly affected by the atmospheric pressure fluctuations. For the conventional multi-step method, the suction \( s \) is assumed to be equal to the applied air pressure, thus considering the atmospheric pressure fluctuations is not doable. However, by measuring the pore-water pressure and defining the suction as \( s = u_a - u_w \), the measured pore-water pressure fluctuations cancel the measured air pressure fluctuations. Therefore, a correction reflecting the atmospheric pressure fluctuations is not required.

4) The center of the sample can be considered as a representative point for measuring the pore-water pressure, which results in obtaining reliable SWCC.

From the above, it can be concluded that the newly developed CPM system is rapid, direct, reliable and accurate SWCC obtaining system.

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