Validation of the direct measurement of the soil water characteristics curve using the newly developed continuous pressurization method

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ABSTRACT

Natural disasters including earthquakes, typhoons and heavy rainfalls induce various risks such as slope failure. The soil water characteristics curve [SWCC] is a key index in unsaturated soil behavior used for estimating many unsaturated soil relations. Considering the complexity and prolonged time required for the conventional testing methods, a simple method that considers short time and high accuracy is still lacking. This paper aims at validating the newly developed continuous pressurizing method [CPM] apparatus by comparing it to the conventional axis-translation technique [Tempe cell] under drying phase. Standard soils in addition to remolded natural soils collected at earthquake and heavy rainfall induced landslides were used for validating the newly developed CPM device and investigating the CPM reliability, accuracy, repeatability and testing time in comparison to the conventional technique. It can be concluded that the newly developed CPM is an accurate with precise repeatability, reliable, direct and requires very short time SWCC obtaining method requiring 9 % to 17% of the testing time using the conventional method.

Keywords: continuous pressurization method; SWCC; landslides; axis-translation

1 INTRODUCTION

Natural disasters including earthquakes, typhoons and heavy rainfalls occur in different locations inducing various risks such as slope failure. 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 and river levees which finally leads to failure.

The soil water characteristics curve [SWCC] is a function that describes the amount of water retained in a soil at a given range of suction values. SWCC is a key index in unsaturated soil behavior used for estimating many unsaturated soil relations such as permeability, water storage and shear strength Fredlund (1996).

Many methods have been developed for measuring the SWCC such as axis – translation technique, filter paper, osmotic, centrifuge, humidity chamber and using varieties of tensiometer, psychrometer (Lu and Lukos 2004; Alowaisy et al. 2017). Among those methods, the axis-translation technique has contributed significantly in the measurement and control of suction in unsaturated soil laboratory tests. However, depending on the accuracy and amount of data points, obtaining the SWCC using the axis translation technique may require at least several weeks or even several months.

Considering the complexity and prolonged time required for the conventional testing methods, a simple method that considers short time and high accuracy is still lacking. The SWCC is a highly nonlinear function and is relatively difficult to obtain accurately. Several SWCC numerical models were developed, where Brooks and Corey (1964) and Van Genuchten (1980) are the most common. However, laboratory testing methods impose higher accuracy in determining the SWCC.

This paper aims at validating the newly developed continuous pressurizing method [CPM] apparatus Hatakeyama (2015) by comparing it to the conventional axis-translation technique [Tempe cell] under drying phase. In addition, the air pressurizing rate influence and the time required to obtain a full SWCC for standard testing soils and remolded natural soils will be discussed.

2 METHODOLOGY AND MATERIALS

2.1 Methodology and characteristics of the CPM

The newly developed CPM based testing system is fully automatic and allows for continuous measuring of the air pressure, water pressure and drained water. A picture and a schematic diagram of the newly developed CMP cell are shown in Fig. 1a and b respectively. During testing, 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 rate of pressurizing. Meanwhile, a micro-tensiometer installed at the center of the sample instantly measures the developing water pressure in response to the changing air pressure, while the ceramic disk at the bottom retains the air pressure and allows water to drain 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 matric suction (Ψ) can be calculated from the difference between the air pressure applied to the top of the specimen and the water pressure measured by the micro-tensiometer. While the water content can be deduced from the drained water in relation to the initial water content.

2.2 Materials and sampling locations

Tests were conducted using three standard soils and two natural soils. The particle size distribution curves and summary of soil properties are shown in Fig. 2 and Table 1 respectively. Kumamoto cohesive volcanic ash [VA] was collected at Aso-Ohashi, Kumamoto after Kumamoto earthquake, 2016, Fig. 3a. It has a void ration (e) = 4.701, natural water content of (w) = 181.3%, Liquid Limit (LL) = 228.8% and 48.95% organic matter. Asakura Masado soil was collected at four different locations near Masue (Otoishi river), Asakura, Fukuoka. Samples collected at locations 1, 2, 3, and 4 had different natural water contents of 10.82%, 3.76%, 5.65% and 7.54% respectively, Fig. 3b.

3 RESULTS AND DISCUSSION

3.1 Validation of the CPM

Validation of the CPM was conducted by obtaining the soil water characteristic curves under three air pressuring rates [0.05, 0.5 and 5 kPa/min.] and then comparing the results with the results obtained using the conventional method for K-4, Toyoura and K-7 soils.

Fig. 4, 5 and 6 show the SWCCs for K-4, Toyoura, and K-7 soils respectively. The black square scattered plots represent the discrete data obtained by Tempe cell. While the three other curves in each figure represent the continuous data obtained by the CPM device under 0.05, 0.5 and 5 kPa/min. air pressurizing rates as illustrated. Considering the SWCCs obtained by the CPM device, it can be observed that the same Air Entry Value [AEV] can be obtained using various air pressurizing rates. In addition, it can be observed that the AEV obtained by the newly developed CPM is in well agreement with the AEV obtained by the conventional method.

Using high air pressurizing rate induces rapid increase of the pore water pressure through the sample without allowing proper dissipation of the accumulated pore water pressure by draining water to the attached container. Thus the resulting suction values remain low even under high air pressure values. However, 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 slow air pressurizing rates for all tested specimens.

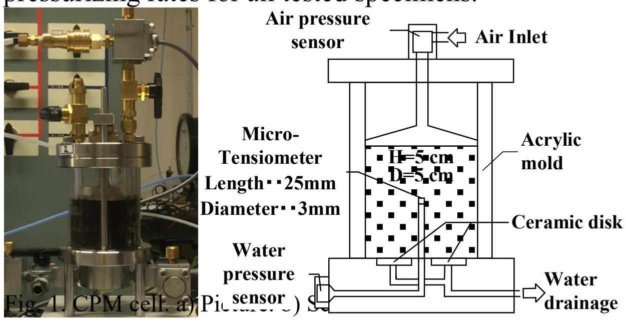


Fig. 1. CPM cell. a) Pi...) S...

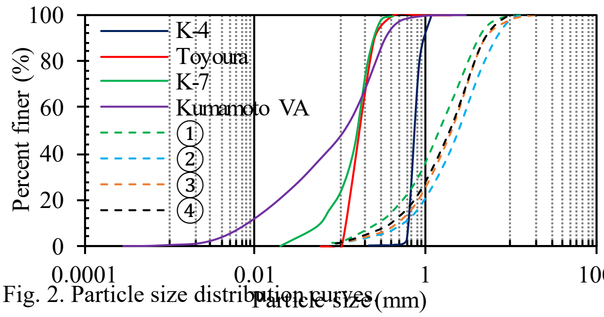


Fig. 2. Particle size distribution curves.

Table 1. Soil properties.

Soil	Specific gravity	Dry density (g/cm^3)	k_s (m/s)	Void ratio e	D_{10} (mm)
K-4	2.640	1.551	2.07x10^{-3}	0.698	0.630
Toyoura	2.646	1.560	1.29 x10^{-4}	0.693	0.116
K-7	2.642	1.618	1.14 x10^{-5}	0.629	0.059
Kumamoto VA	2.278	0.400	8.04 x10^{-8}	4.701	0.008
Asakura 1	2.701	1.425	1.08 x10^{-3}	0.850	0.285
Asakura 2	2.711	1.611	2.15 x10^{-3}	0.658	0.590
Asakura 3	2.693	1.557	2.38 x10^{-4}	0.545	0.490
Asakura 4	2.705	1.731	1.91 x10^{-3}	0.720	0.410

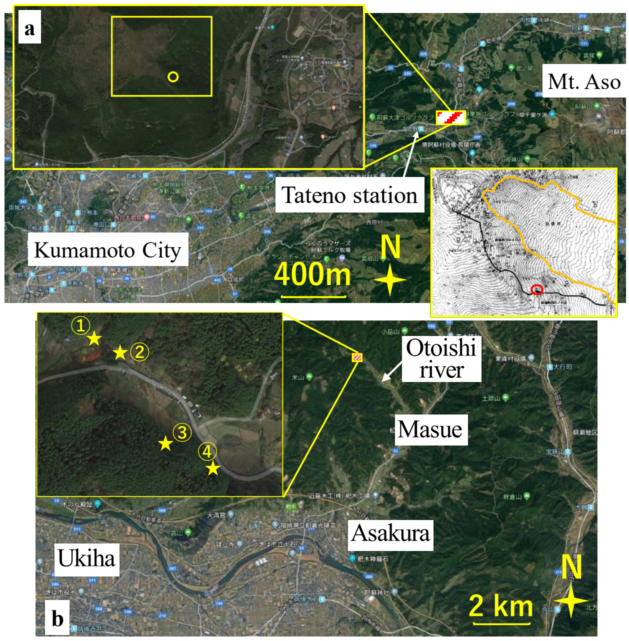


Fig. 3. Sampling location. a) Aso-Ohashi, Kumamoto.
b) Masue area (Otoishi river), Asakura, Fukuoka.

It must be noted that the slight difference between the SWCC obtained by CPM under various pressurizing rates and the SWCC obtained by the conventional method can be attributed to the difficulty in replicating identical samples with the same pore network. In addition, the surrounding boundary induces significant micro-differences on the water preferential pathways and water cohesion with the used molds. While the Tempe cell specimens were prepared in steel molds, acrylic molds were used for the newly developed CPM device. The repeatability and reliability of the newly developed CPM device was confirmed by repeating the same test at least two times for K-4, Toyoura and K-7 soils under three air pressuring rates [0.05, 0.5 and 5 kPa/min.]. The results confirmed the high repeatability and reliability of the device where almost identical SWCCs for all adopted samples were obtained.

SWCCs obtained by the newly developed CPM under 0.05 kPa/min. air pressurizing rate in addition to the SWCCs obtained by the Tempe cell were fitted with Van Genuchten model, then alpha (α) the reciprocal of the air entry value was plotted for the CPM versus the conventional method obtained SWCCs as illustrated in Fig. 7 for three standard soils. It can be observed that alpha (α) obtained by the CPM compares very well with alpha (α) obtained by the conventional method with RMSError (root mean square error) of 0.006. Therefore, it can be concluded that the CPM method can be used to accurately obtain the SWCC in comparison with the conventional method.

3.2 Natural soils - remolded

The newly developed CPM device applicability and reliability considering natural heterogeneous soils was also investigated. After Kumamoto earthquake 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. 3a. Remolded samples having the same natural properties [dry density and water content] were prepared, then the new CPM device was used to obtain the SWCCs at various air pressuring rates [0.05, 0.5 and 5 kPa/min.]. As shown in Fig. 8a smooth identical SWCCs can be obtained with the same AEV under various air pressurizing rates. However, since the used theoretical ceramic disk AEV is 200 kPa, maximum suction value of 185 kPa was achieved by allowing longer proper dissipation of the accumulated pore water pressure.

A massive heavy rainfall induced landslides occurred in Fukuoka and Oita prefectures in the beginning of July 2017. One of the highly affected areas was Asakura region located in southern Fukuoka. Samples were collected in the middle of November the same year at the landslide boundaries as indicated in Fig. 3b. Similarly, remolded samples having the same natural properties [dry density and water content] were prepared, then the

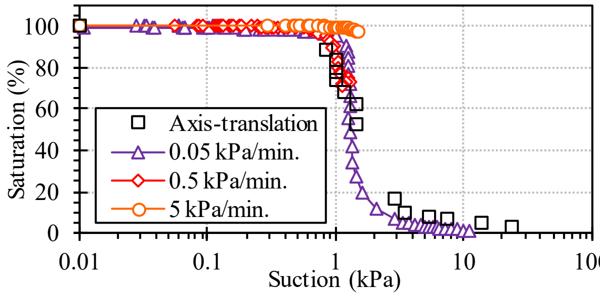


Fig. 4. K-4 sand soil water characteristics curve [SWCC].

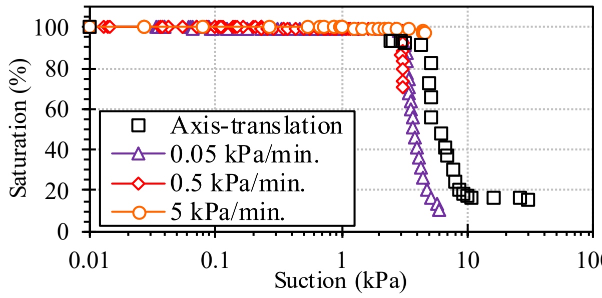


Fig. 5. Toyoura sand soil water characteristics curve [SWCC].

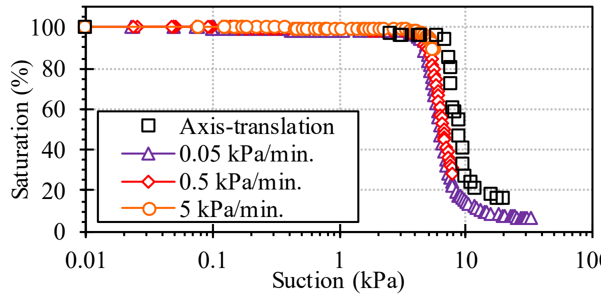


Fig. 6. K-7 sand soil water characteristics curve [SWCC].

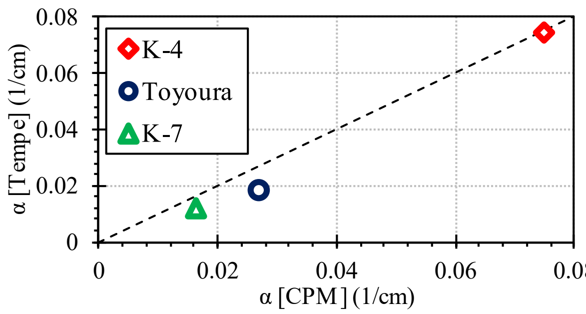
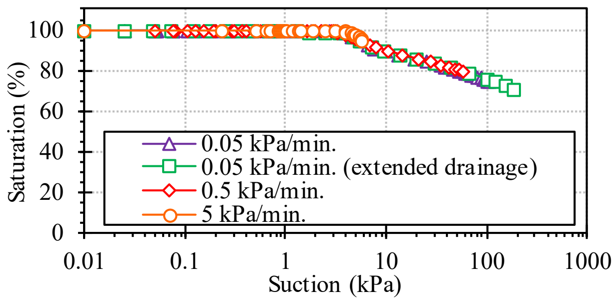


Fig. 7. Comparing Van Genuchten fitting parameter alpha (α) obtained by fitting the SWCC obtained by the newly developed CPM to alpha (α) obtained by fitting the conventional axis translation technique for three standard soils.



selected sampling locations. As illustrated in Fig. 9, a smooth full SWCC with distinct AEV can be obtained regardless the heterogeneity of the origin material. Comparing the SWCCs of different sampling locations, it can be observed that despite the distance separating the sampling locations and the void ratio differences [Fig. 3b and Table 1], the samples impose similar AEV with α ranging between (0.061 – 0.082 1/cm).

3.3 SWCC obtaining time

A conventional SWCC test takes few weeks to few months depending on the soil type. The CPM shows the potential of significantly reducing the testing time. Both standard Tempe cell and the newly developed CPM requires the same time for sample preparation and saturation process. Table 2 shows the time required for obtaining a drying SWCC using the CPM device. It takes about one-day to obtain the drying phase SWCC for sandy soil using a ceramic disk with an AEV of 100 kPa and saturated hydraulic conductivity of 4.8×10^{-9} m/sec.

Fig. 10 illustrates the reduction in saturation after achieving 80 kPa air pressure versus the time required to achieve that assigned pressure for the standard soils and Kumamoto VA. It can be observed that for materials with large D_{10}, significant drop in the saturation can be achieved within short time. Therefore, a pressurizing rate in the order of 10^{-2} kPa/min. or slower is recommended for soils with large D_{10} values (sandy soils or larger) if no extended drainage time to be assigned. Comparing the scatters to the curves in Fig. 10, it can be observed that using the newly developed CPM, it took about 24 hours to obtain a full drying phase SWCC which accounts for 9.3% - 16.7% of the testing time required using the conventional method, where it took 160 – 185 hours using the conventional method for the same soil. Thus it can be concluded that the newly developed CPM device can be used for accurate obtaining of the SWCC in a very short time compared to the conventional method.

4 CONCLUSIONS

Through this paper, three distinctive standard soils in addition to remolded natural soil specimens collected at earthquake and heavy rainfall induced landslides [Kumamoto 2016 and Asakura 2017] were tested for validating the newly developed Continuous Pressurization Method [CPM] device and investigating the CPM reliability, accuracy, repeatability and testing time in comparison to the conventional axis translation technique [Tempe cell] under drying phase. It can be concluded that the CPM device is an accurate with precise repeatability, reliable, direct and requires very short time SWCC obtaining method where the results were in very good agreement with the results obtained by the conventional method. It took about 24 hours to obtain a full drying phase SWCC for sandy soils which accounts for about 9% to 17% of the time required using

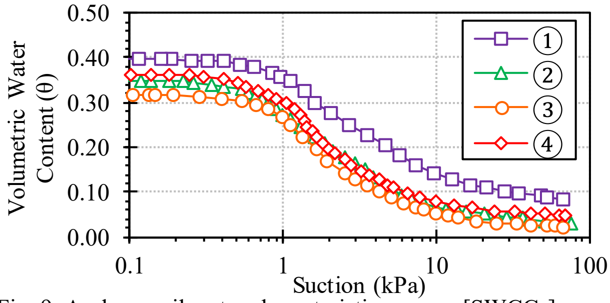


Fig. 9. Asakura soil water characteristics curves [SWCCs].

Table 2. Time required to complete a full drying SWCC [K-4 sand] using the newly developed CPM.

Step	Time (h)
1. Specimen preparation	0.5-1
2. Saturation of the system	24-48
3. Cell preparation and setup	1-2
4. Pressurizing time	26

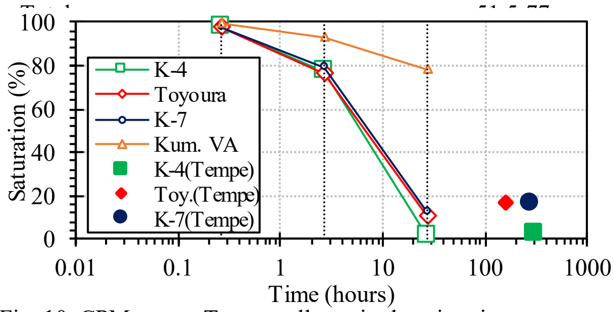


Fig. 10. CPM versus Tempe cell required testing time.

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Fig. 8. Kumamoto VA soil water characteristics curve [SWCC].