Electronic Supplementary Materials

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Measurement of a soil-water characteristic curve and unsaturated permeability using the evaporation method and the chilled-mirror method

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Theory

1 Measurement of SWCC using evaporation and chilled-mirror method

The evaporation method was carried out using HYPROP to measure SWCC up to 100 kPa while the chilled-mirror method utilizing WP4C was used to measure suctions between 500 and 5000 kPa.

1.1 HYPROP

The HYPROP test was developed from the evaporation method proposed by Wind (1966) and simplified by Schindler (1980). The working principle of HYPROP is illustrated in Fig. S1a. Fig. S1b shows the actual laboratory test setup of HYPROP apparatus. The test uses a pair of tensiometers with ceramic tips located at different depths of the specimen. One tensiometer was positioned 1/4 of the height of the specimen from the soil surface and the other at 3/4 of the height of the specimen. The tensiometers could measure suctions within the range zero to 100 kPa. The two tensiometer readings were then averaged to obtain the representative suction of the specimen at the time of measurement. The tensiometers and electronic balance were connected to the computer to record the soil suction and the mass of the specimen at regular time intervals.

The experimental work using HYPROP comprises saturation of the soil specimen, preparation of the measuring device, setting up the specimen in the device, commencement of measurement and analysis of the measured data. The height and diameter of a specimen for HYPROP tests were 5 cm and 8 cm, respectively. Two tensiometers were installed from the base of the apparatus within the soil specimen. The soil specimen was saturated prior to the test and it was ensured that there was no gap present between the specimen and the base of the HYPROP apparatus. In addition, for a short distance of 2.5 cm between the upper and lower tensiometer tips, a linear distribution of suction within the soil specimen can be assumed. The largest changes in suction during evaporation occurred a few millimeters below the surface of the specimen and not between the tensiometer tips (Song et al., 2014). The complete apparatus including the soil specimen was then placed on top of an electronic balance for real time measurement of mass change during the evaporation process. In other words, the decrease in the soil mass due to the evaporation process was measured continuously.

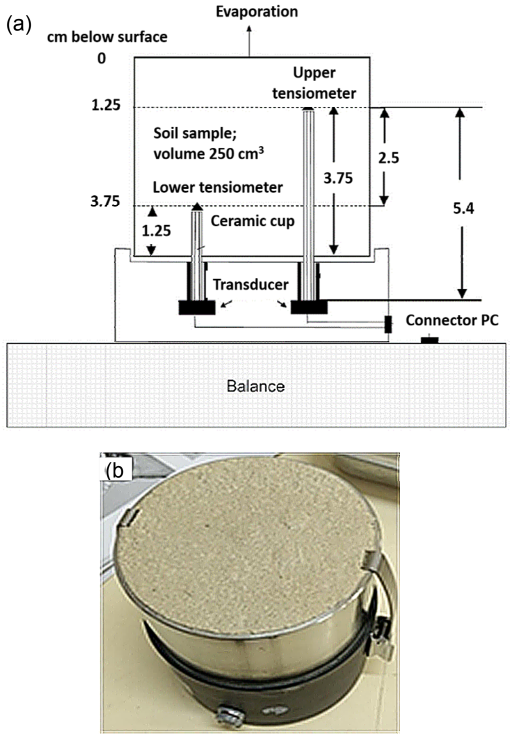

Fig. S1 Schematic diagram of HYPROP (Schindler et al., 2010b) (unit: cm) (a) and actual experimental setup of HYPROP (b)

During the test, the gravimetric water content of the soil decreased due to evaporation while the soil suction increased. The SWCC can then be obtained by plotting gravimetric water content against average soil suction, where average soil suction is calculated from the two tensiometer readings. The volumetric water content and degree of saturation of the soil specimen can be computed by measuring the volume change of the soil specimen at different suctions via an independent shrinkage test. In HYPROP, it is assumed that the water flows through a horizontal plane at midpoint between the tensiometer tips for a given interval of time. As a result, the permeability of the soil specimen at this midpoint during the water flow process can be calculated using Eq. (1). This is similar to the instantaneous profile method as presented by Krisdani et al. (2009):

$$q_i = \frac{\Delta V_i / \Delta t_i}{2A}, \tag{S1}$$

where ΔV_i is water reduction (cm^3) over the mass change, q_i is the rate of water flow (m/s), A is the cross-sectional area (cm²) of the column, Δt_i is the interval of time between two measurements.

The permeability of soil is then calculated from Darcy's equation:

$$k_i\left(h_i\right) = -\frac{q_i}{\left(\frac{\Delta h_i}{\Delta z}\right) - 1}, \tag{S2}$$

where h_i is time- and space-averaged suction, Δh_i is the difference of the two suctions measured at two measuring levels, and Δz is the height difference of the tensiometer tips.

Based on Eq. (S2), different values of the coefficient of permeability can be calculated for each average soil suction obtained from HYPROP at individual time intervals. The instantaneous value of permeability can be plotted against the corresponding soil suction to obtain the unsaturated permeability of the soil.

1.2 Chilled mirror hygrometer

The WP4C chilled mirror hygrometer was used to perform the related experiments presented in this Technical Note (Fig. S2a). Mantri and Bulut (2014) indicated that WP4C has low accuracy for measurements of SWCC at low suction. It was also stated in ASTM (2003) that the chilled mirror hygrometer method is commonly used to determine SWCC data at the drier end or the higher end of suction. Therefore, WP4C should not be used independently to establish SWCC from the low to high suction values. In this study, WP4C was used in conjunction with HYPROP to produce SWCC with a wide range of suction from low to high values. Upon completion of the SWCC tests using HYPROP, the specimen was trimmed using a cutter customized specifically for the test using WP4C. The diameter and height of specimens for the WP4C test are 37 mm and 10 mm, respectively.

WP4C measured soil suction in a soil specimen by measuring the water vapor pressure of the air in the chamber which was in equilibrium with the suction of the soil specimen. The temperature inside the chamber was set at 25 ºC throughout the experiment. A schematic diagram of the WP4C apparatus is shown in Fig. S2b.

The total suction was calculated using the Kelvin equation, which is given as (ASTM, 2003)

$$\psi = \left(\frac{RT}{M}\right)\ln(a_{\mathrm{w}}), \tag{S3}$$

where ψ is the corresponding suction of the soil specimen (kPa), R is the constant for gas, a_{w} is the water activity, M is the water molecular mass and T is the room temperature inside the chamber of the WP4C (K).

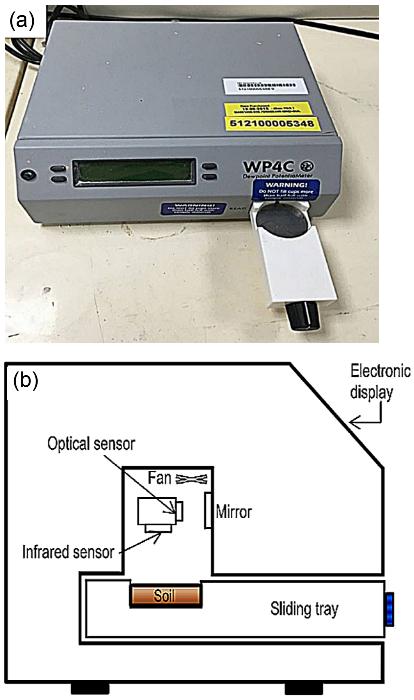

Fig. S2 Photo of WP4C (a) and schematic diagram of chilled mirror hygrometer (WP4C) (b)

2 Soil properties

The soil specimens used in this study were prepared using three different combinations of sand-kaolin mixtures as given in Table S1. Tempe and pressure plate apparatuses, HYPROP and WP4C tests were conducted on compacted specimens of these mixtures. In addition, the direct measurement of unsaturated permeability using HYPROP and the indirect measurement of unsaturated permeability from SWCC of compacted specimens of soil mixtures of 80% sand and 20% kaolin (soil name: 80S20K), 50% sand (soil name: 50S50K) and 50% kaolin (soil name: 20S80K) as well as 20% sand and 80% kaolin were also conducted. The unsaturated permeability data obtained from the direct measurements of unsaturated permeability using a modified Triaxial permeameter were taken from Priono et al. (2017) for verification purposes.

2.1 Compaction curve

The compaction curve was generated from the standard Proctor test (Fig. S3). The maximum dry densities of 80S20K, 50S50K and 20S80K soil mixtures were 1.98×10^3 kg/m^3, 1.75×10^3 kg/m^3, and 1.60×10^3 kg/m^3, respectively. The corresponding optimum water contents of these soil mixtures were 9.9%, 12.5%, and 18.9%, respectively. Soil specimens were compacted using static compaction at water content and dry density associated with the optimum water content and maximum dry density. Static compaction was selected as the compaction method in this study to generate compacted kaolin-sand specimens of uniform density.

2.2 Index properties

Index soil properties were obtained by conducting experiments in accordance with ASTM standards as stated: Atterberg limit test (ASTM, 2000b), particle size distribution (ASTM, 2017), specific gravity (ASTM, 2002), water content (ASTM, 2010), and density (ASTM, 2009). The soil specimens were then classified in accordance with the Unified Soil Classification System (USCS) (ASTM, 2000a). The grain size distribution curves of the three soil mixtures are presented in Fig. S4. Table S1 shows the index properties of all the soil mixtures used in the study.

References

ASTM (American Society for Testing and Materials), 2000a. Standard Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM D2487-00, ASTM, West Conshohocken, PA, USA.

ASTM (American Society for Testing and Materials), 2000b. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM D4318-00, ASTM, West Conshohocken, PA, USA.

ASTM (American Society for Testing and Materials), 2002. Standard Test Methods for Specific Gravity of Soil Solids

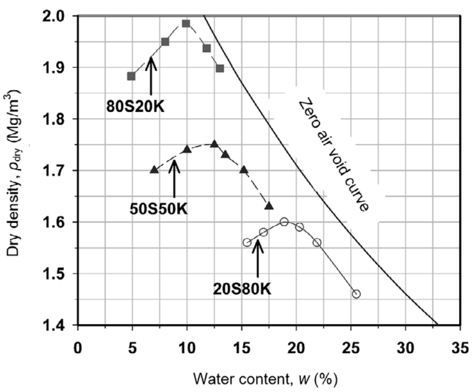

Fig. S3 Compaction curves of the three soil mixtures

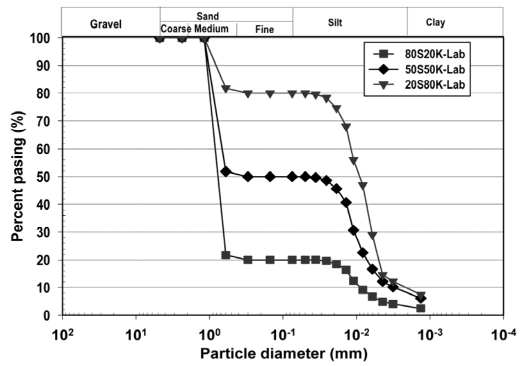

Fig. S4 Grain size distribution curves of the three soil mixtures

Table S1 Index properties of soil mixtures

Property	Maximum dry density ($\times10^3$ kg /m^3)	Optimum water content, w (%)	Specific gravity, G_s	Liquid limit, LL (%)	Plastic limit, PL (%)	Plasticityindex, PI (%)	Sand (%)	Silt (%)	Clay (%)
80S20K	1.98	9.25	2.65	17.9	13.9	4	80	15	5
50S50K	1.75	12.5	2.67	27.7	19.42	8.28	49.9	45.7	4.4
20S80K	1.6	18.9	2.67	41.18	23.89	17.29	20	72.9	7.1

by Water Pycnometer. ASTM D854-02, ASTM, West Conshohocken, PA, USA.

ASTM (American Society for Testing and Materials), 2003. Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge. ASTM D6836-02, ASTM, West Conshohocken, PA, USA

ASTM (American Society for Testing and Materials), 2009. Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens. ASTM D7263-09, ASTM, West Conshohocken, PA, USA.

ASTM (American Society for Testing and Materials), 2010. Standard Test Methods for Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM D2216-10, ASTM, West Conshohocken, PA, USA.

ASTM (American Society for Testing and Materials), 2017. Standard Test Methods for Particle-size Distribution (Gradation) of Soils Using Sieve Analysis. ASTM D6913/D6913M-17, ASTM, West Conshohocken, PA, USA.

Krisdani H, Rahardjo H, Leong EC, 2009. Use of instantaneous profile and statistical methods to determine permeability functions of unsaturated soils. *Canadian Geotechnical Journal*, 46(7):869-874. https://doi.org/10.1139/T09-027

Mantri S, Bulut R, 2014. Evaluating performance of a chilled mirror device for soil total suction measurements. Geo-Hubei 2014 International Conference on Sustainable Infrastructure: Advances in Transportation Geotechnics and Materials for Sustainable Infrastructure.

Priono, Rahardjo H, Chatterjea K, et al., 2017. Laboratory investigation on hydraulic anisotropy behavior of unsaturated soil. *Canadian Geotechnical Journal*, 54(7): 1034-1046. https://doi.org/10.1139/cgj-2016-0023

Schindler U, 1980. Ein schnellverfahren zur messung der wasserleitfähigkeit im teilgesättigten boden an stechzylinderproben. *Archiv für Acker- und Pflanzenbau und Bodenkunde*, 24(1):1-7.

Song WK, Cui YJ, Tang AM, et al., 2014. Experimental study on water evaporation from sand using environmental chamber. *Canadian Geotechnical Journal*, 51:115-128.

Wind G, 1966. Capillary conductivity data estimated by a simple method. *Water in the Unsaturated Zone*, 19-23.