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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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1 Introduction

Fredlund and Rahardjo (1993) indicated that the behavior of unsaturated soil is significantly dependent on its soil-water characteristic curve (SWCC). There are many conventional methods for determining SWCC. Tempe and pressure plate apparatuses are commonly utilized in the laboratory to measure it (Zhan et al., 2007; Fredlund et al., 2012; Rahardjo et al., 2012; Cai et al., 2014). A Tempe cell is used to generate SWCC up to 100 kPa since it is provided with 1 bar (1 bar=1×10^5 Pa) high air-entry disc (Kassim et al., 2012; Rahardjo et al., 2019). A pressure plate cell (provided with a 5 or 15 bar high air-entry ceramic disc) is used to establish SWCC at suction ranges from 100 to 1500 kPa in combination with SWCC tests using the Tempe cell. These methods are known to be reliable for SWCC determination; however, they are tedious and time consuming (Fredlund, 2007).

There has been a wide interest among researchers studying unsaturated soil mechanics in exploring alternative and faster methods to evaluate SWCC for engineering practice. Merayyan and Miller (2006), Peters and Durner (2008), Schindler et al. (2010a, 2010b, 2015), and Peters et al. (2015) focused on the measurement of SWCC using only the evaporation method with HYPROP. Leong et al. (2003) and Mantri and Bulut (2014) focused on the measurement of SWCC using only the chilled-mirror method. The SWCC obtained from the dew point method was accurate for high suction ranges but was observed to have much variability at low suction ranges.

The simple evaporation method was first developed by Wind (1968) and measured the moisture content and tension in soil during the evaporation process to obtain the coefficient of permeability of the soil. Schindler (1980) modified this method to simplify the process using two tension shafts for the measurement of suctions. In this study, SWCC tests were performed based on the concept of an evaporation method using HYPROP. HYPROP was utilized for SWCC measurements up to 100 kPa soil suction.

The results are analysed using an interpolation method by taking the average suction value from measurements recorded in two tensiometers at different depths. The assumption was made that linearization errors were insignificant so that interpolation can be done accurately, as proven in previous investigations (Peters and Durner, 2008; Peters et al., 2015). One of the advantages of the HYPROP test is that it can simulate the natural evaporation process which provides the closest representation of in situ evaporation (Wind, 1968). During the experiment, the

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measurements are automatically recorded in the HYPROP-View® software at a constant interval. Direct measurements of unsaturated permeability are commonly carried out using rigid wall and flexible wall permeameters (Samingan et al., 2005; Vanapalli et al., 2007; Gallage et al., 2013; Priono et al., 2017). Direct measurements of unsaturated permeability commonly take a very long time to complete (Huang et al., 1998; Samingan et al., 2003; Zhai et al., 2017).

The object of this study was to investigate the feasibility of a combination between the evaporation method and the chilled-mirror method utilizing HYPROP and WP4C, respectively, to produce SWCC over a wide range of low to high suctions and by incorporating a shrinkage curve for volume change corrections. The SWCC data obtained from these two methods were then verified using the conventional methods of the Tempe and pressure plate apparatuses. In addition, the unsaturated permeability for suctions up to 100 kPa as measured using HYPROP was compared with (a) the unsaturated permeability values obtained from a direct measurement using a modified Triaxial permeameter (Priono et al., 2017) and (b) the unsaturated permeability function obtained from the statistical method (Fredlund and Rahardjo, 1993), in order to study the feasibility of HYPROP for direct measurement of unsaturated permeability.

The theories of HYPROP and WP4C are provided in Data S1, including all governing equations, experimental procedures, and explanations of variables. Upon completion of SWCC testing using HYPROP and WP4C, the results were generated, presented, and discussed in this section. The index properties and compaction curve of the soils investigated in this study are also provided in Data S1.

2 Results and discussion

2.1 Soil-water characteristic curve

Satyanaga et al. (2017)'s equation (Eq. (1)) was used to best fit SWCC data in this study.

$$S_\mathrm{w}=\left(1-\frac{\ln(1+\psi/\psi_\mathrm{r})}{\ln(1+10^6/\psi_\mathrm{r})}\right)\times\left\{S_\mathrm{r}+\left[(100-S_\mathrm{r})\left(1-(\beta)\mathrm{erfc}\left(\frac{\ln\left(\dfrac{\psi_\mathrm{a}-\psi}{\psi_\mathrm{a}-\psi_\mathrm{m}}\right)}{s}\right)\right)\right]\right\},\tag{1}$$

where β=1 when ψ>ψ_a; β=0 when $\psi\leq\psi_\mathrm{a}$; S_w is the calculated degree of saturation; ψ is the related soil suction (kPa); ψ_a, S_r, ψ_m, s, and ψ_r are fitting parameters representing air-entry value (kPa), residual degree of saturation (%), inflection point (kPa), standard deviation, and residual suction (kPa), respectively.

The SWCC data were measured using HYPROP & WP4C and Tempe and pressure plate apparatuses. The experimental procedures for Tempe and pressure plate apparatuses are given in ASTM (2002). Shrinkage tests were carried out using evaporation tests on compacted soil specimens of the three soil mixtures at a controlled room temperature of 25 °C. The details of the test procedures and the development of the shrinkage curve can be found in (Fredlund et al., 2002). The shrinkage test results were then used to correct the SWCC data for total volume changes of the soil specimen during the tests. As a result, SWCC in terms of degree of saturation was obtained.

The fitting parameters of the SWCCs for the compacted soil mixtures are summarized in Tables 1 and 2. The experimental data of the SWCC are presented in Figs. 1–3 which show that HYPROP and WP4C can be used for obtaining SWCC data for suctions up to 5000 kPa. The evaporation method using HYPROP was used to measure SWCC for suctions up to 100 kPa whereas the chilled-mirror method using WP4C was used to measure SWCC for suctions between 500 and 5000 kPa. The measurement times of 80S20K, 50S50K, and 20S80K soil specimens from HYPROP tests are 3, 5, and 7 d, respectively. There was no measurement of SWCC for suctions between 100 and 500 kPa. The SWCC data from HYPROP were obtained from real-time (continuous measurement) of suctions during the tests. As a result, a good fitting curve of the SWCC data from the HYPROP was obtained. The Fredlund and Xing (1994) equation was also used to best fit the experimental data of SWCC in Figs. 1–3. Best fitting lines from Satyanaga et al. (2017)'s equation were found to be in good agreement with those from the Fredlund and Xing (1994) equation. In addition, the parameters from Satyanaga et al. (2017) were also able to represent the variables of SWCC, such as air-entry value and residual suction.

Table 1 Fitting parameters of SWCC obtained from HYPROP and WP4C tests

Specimen	ψ_a (kPa)	ψ_m (kPa)	s	ψ_r (kPa)
80S20K	10	80	2.50	1000
50S50K	15	150	2.00	5000
20S80K	40	170	1.75	5000

Table 2 Fitting parameters of SWCC obtained from Tempe and pressure plate tests

Specimen	ψ_a (kPa)	ψ_m (kPa)	s	ψ_r (kPa)
80S20K	8	100	3.00	1000
50S50K	15	120	2.00	5000
20S80K	40	150	1.75	5000

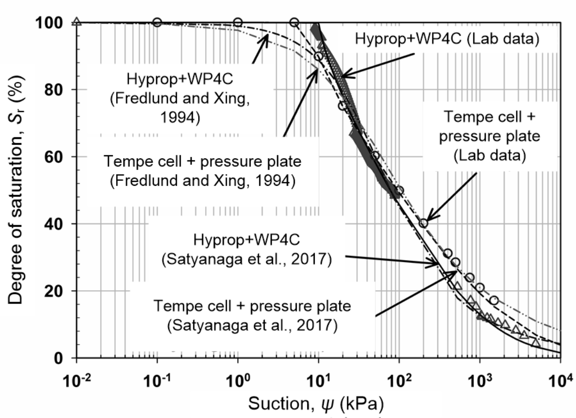

Fig. 1 SWCC of soil mixture of 80S20K

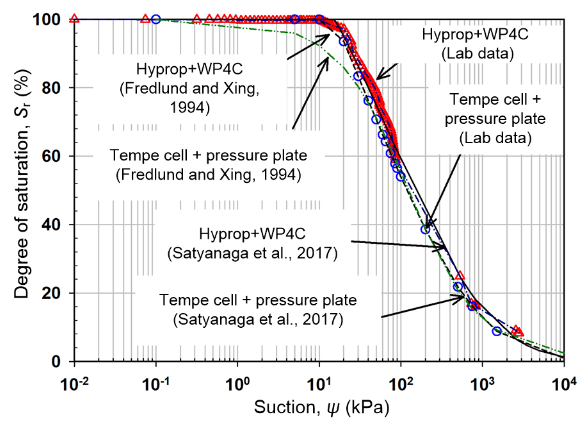

Fig. 2 SWCC of soil mixture of 50S50K

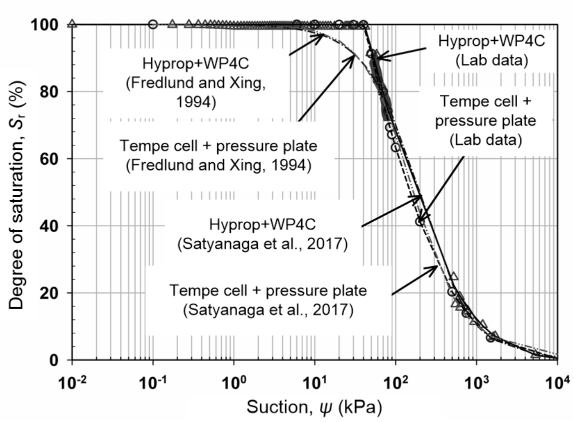

Fig. 3 SWCC of soil mixture of 20S80K

For the conventional method, the Tempe cell has a ceramic plate with an air-entry value of 1 bar which can measure suction up to 100 kPa. The pressure plate cell has a ceramic plate with an air-entry value of 15 bar which can be used to control suction up to 1500 kPa. This allows the development of SWCC for the range of suctions between 0 and 1500 kPa. However, because the ceramic disk has an air-entry value limited to 15 bar, the conventional method cannot be used to control suctions greater than 1500 kPa, and hence it has to be estimated from the best fitting SWCC.

Figs. 1–3 indicate that the shapes of SWCC of the three different soil mixtures as measured using the conventional Tempe and pressure plate apparatuses are similar to those obtained from measurements using HYPROP and WP4C. In addition, the best fitting parameters of SWCCs from the conventional Tempe and pressure plate apparatuses are of approximately the same value as those of SWCCs from HYPROP and WP4C. This indicates that the evaporation method combined with the chilled mirror hygrometer is a suitable alternative for measuring SWCC.

From Figs. 1–3, it can be observed that the two SWCCs are similar, especially in the suction range of 0–100 kPa. For suctions greater than 100 kPa, there are slight differences between the two SWCCs which may be due to the lack of data for certain suctions between those methods. The differences between the SWCC from the Tempe and pressure plate apparatuses and the SWCC from HYPROP and WP4C for specimens 80S20K are larger than the difference for other soil specimens. However, the rates of differences are still acceptable since the air-entry value (8 kPa), inflection point (100 kPa), and standard deviation (3) of the SWCC from the Tempe and pressure plate apparatuses are close to the air-entry value (10 kPa), inflection point (80 kPa), and standard deviation (2.5) of the SWCC from HYPROP and WP4C.

2.2 Unsaturated permeability

The coefficients of permeability data are plotted against the suction values for the three soil mixtures 80S20K, 50S50K, and 20S80K in Figs. 4–6, respectively. The data obtained directly from the tests using HYPROP were verified by the indirect measurement of unsaturated permeability or the statistical method (Childs and Collis-George, 1950) using the respective SWCCs of the three soil mixtures. The procedure for the determination of unsaturated permeability using the statistical method is given by Fredlund and Rahardjo (1993) and Fredlund et al. (2012). Furthermore, the unsaturated permeability values from HYPROP were compared with the permeability data obtained from the direct measurements for 50S50K by Priono et al. (2017). Priono et al. (2107) carried out the unsaturated permeability tests using a modified Triaxial permeameter.

The unsaturated permeability results obtained from HYPROP tests were compared to those determined using the statistical method (Figs. 4–6). In addition, the unsaturated coefficients of permeability of soil mixture 50S50K obtained from direct measurements using an unsaturated modified Triaxial permeameter (Priono et al., 2017) were also compared with the unsaturated permeability from HYPROP and the statistical method as demonstrated in Fig. 5. The comparison showed good agreement between the results obtained from these three methods, confirming the reasonableness of the unsaturated permeability obtained from HYPROP. As illustrated by the unsaturated permeability presented in Figs. 4–6, the data points from HYPROP measurements are located close to those determined by the statistical method. This shows that the coefficient of permeability results from HYPROP are reliable. For the 50S50K specimen, the modified Triaxial permeameter results are also located close to the HYPROP and statistical method results, further confirming the results from HYPROP and the statistical method.

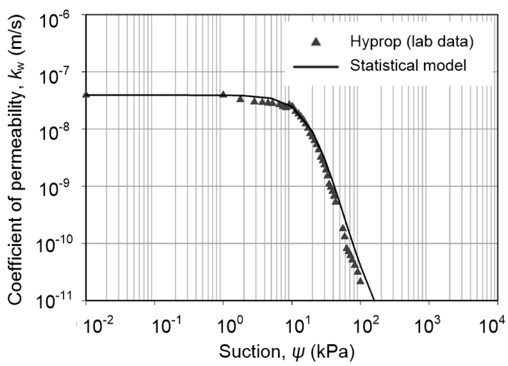

Fig. 4 Unsaturated permeability of the soil mixture of 80S20K

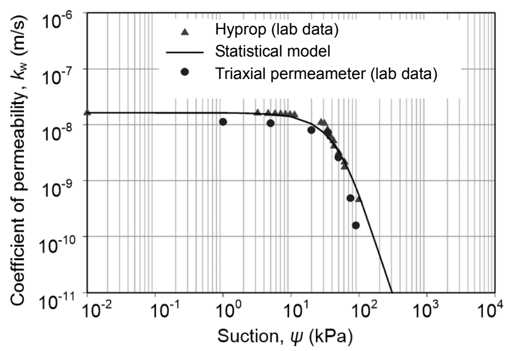

Fig. 5 Unsaturated permeability of the soil mixture of 50S50K

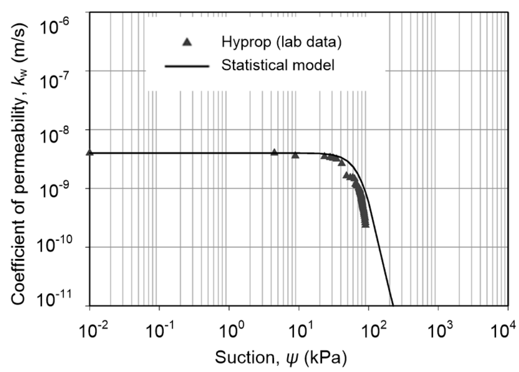

Fig. 6 Unsaturated permeability of the soil mixture of 20S80K

3 Conclusions

1. The SWCC data from the conventional methods (Tempe and pressure plate apparatuses) and the alternative methods (HYPROP and WP4C) were fitted using the equation of Satyanaga et al. (2017). The fitting parameters related to air-entry value, inflection point, and standard deviation from both curves, agreed well and indicated that the combined SWCC data from the evaporation and chilled-mirror methods can be used to obtain SWCC with a wider range of suction.

2. The unsaturated permeability data obtained from HYPROP agreed with the data from direct measurement using a modified Triaxial permeameter and the data from the statistical method. Hence, HYPROP can be used to expedite the measurement of unsaturated permeability of soil for suctions up to 100 kPa.

3. The combination of SWCC tests using HYPROP and WP4C offers a shorter experimental duration compared with the conventional method. However, this method is applicable only for soils with air-entry values less than 100 kPa or higher than 500 kPa.

4. Further works are required to investigate the applicability of this alternative method on different soil conditions, especially on soils with significant volume change.

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List of electronic supplementary materials

Data S1 Theory

中文概要

题　目：综合蒸发法和冷镜露点法测量水-土特征曲线和非饱和渗透系数

目　的： 综合使用 HYPROP 和 WP4C 两种仪器，探索采用蒸发法和冷镜露点法测量大吸力范围的水-土特征曲线，并采用收缩曲线对土体变形进行修正。

方　法： 1. 采用 HYPROP 仪器，在 0~100 kPa 吸力范围内测量土体的水-土特征曲线。2. 当吸力大于 600 kPa 时，采用 WP4C 仪器，测量土体的水-土特征曲线。3. 采用传统张力仪吸力板仪器，在 0~500 kPa 吸力范围内测量土体的水-土特征曲线。4. 采用 Satyanaga et al. (2017)公式，对实验数据进行拟合。5. 采用 HYPROP 仪器直接测量土体的非饱和渗透系数。6. 采用蒸发法，获取干缩曲线。

结　论： 1. 采用 Satyanaga et al. (2017)公式，对实验数据进

行拟合，拟合参数直接关联到进气值、拐点及方差。拟合结果显示，不同仪器所收集的水-土特征曲线的数据相互吻合，为水-土特征曲线的实验测量提供了更大的吸力范围。2. 采用 HYPROP 仪器测量的非饱和渗透系数和采用传统改装的非饱和三轴实验数据基本吻合，因此，HYPROP 可以作为在低吸力范围内（<100 kPa）测量非饱和渗透系数的有效仪器。3. 当进气值小于 100 kPa 或者大于 500 kPa 时，综合采用 HYPROP 和 WP4C 可以有效缩短实验周期。

关键词： 蒸发法；露点法；水-土特征曲线；非饱和渗透系数