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A rapid method for determining the soil-water characteristic curves in the full suction range

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Abstract: The traditional methods for determining the soil-water characteristic curve (SWCC) in the full suction range always takes several months. To better guide the engineering practice with the theory of unsaturated soil mechanics, the rapid determination of SWCC is particularly important. In this study, a rapid measurement method for SWCC in the wide (full) suction range was developed with the combination of pressure plate method, parallel filter paper method and dew point potentiameter method, and the proposed method was used to test two different soils. Results showed that: i) The experimental data of the parallel filter paper method and that of the serial filter paper method were in good agreement, so the parallel filter paper method can be used instead of the serial filter paper method to shorten the measurement time. ii) When the measured data meet the general shape of SWCC (or meet the requirements of engineering design), the number of tests can be reduced appropriately to improve the measurement efficiency. A complete SWCC can be determined by the proposed combined method with only 10 to 12 points. iii) The measurement method proposed in this study can shorten the measurement time of SWCC testing from several months to 7–10 days. The combined method proposed in this study achieved the rapid and accurate determination of SWCC in wide (full) suction ranges, which is expected to make the SWCC measurement become a routine geotechnical test.

Keywords: rapid determination; soil–water characteristic curve; pressure plate method; parallel filter paper method; dew point potentiameter

1 Introduction

The soil involved in the actual engineering project is mostly in an unsaturated state [1]. The primary problem of unsaturated soil study is how to obtain soil–water characteristic curve (SWCC) quickly and reasonably. SWCC is of great significance to predicting and analyzing water holding capacity, permeability, deformation, and strength of unsaturated soils. Therefore, researchers have carried out a lot of studies on its measurement methods.

At present, a large number of SWCC studies have been carried out by researchers on different types of soils, such as swelling soils, loess soils and saline soils. The acquisition of SWCC in a wide (full) suction range often requires the coordination of various test methods. There have been many studies on the measurement of SWCC in a wide (full) suction range. Stenke et al.[2] measured the SWCC of bentonite, kaolin, and kaolin–sand mixture using four different suction measurement techniques. They employed a transistor hygrometer and non-contact filter paper method to measure the total suction and a pressure plate and contact filter paper method for the matric suction. Chen et al.[3] studied the water retention characteristics and microstructure characteristics of Gaomiaozi high-pressure dense bentonite under different suction using osmotic and vapor equilibrium methods. Nam et al.[4] used six different test methods, including the filter paper method, dew point potentiameter method , vapor equilibrium method, pressure plate method, Tempe cell, and osmotic method, to measure the SWCC of four in-situ soils. Different test techniques provided various measurement ranges of suction, and the combination of different test results could yield continuous SWCC. Sun et al.[5–11] used pressure plate method, filter paper method and vapor equilibrium method to measure the SWCC of Nanyang expansive soil, Guilin lateritic clay, in-situ loess, and silt, respectively, and combined the measurement results of several test methods to obtain SWCC over the full suction range. Salager et al.[12] adopted the pressure plate method and vapor equilibrium method to measure the SWCC of clayey silt and clay in the full suction range. In order to explore a fast and effective SWCC measurement method, Rahardjo et al.[13–14] used the combination of a small centrifuge and a dew point potentiameter to quickly measure the SWCC of residual soils and compared the results obtained by the conventional Tempe cell, pressure plate, and vapor equilibrium methods to demonstrate the applicability of this method. Chen et al.[15] used the pressure plate method and vapor equilibrium method to measure the SWCC in the full suction range of mural plasters in Mogao Grottoes and fitted the test data in the full suction range using the VG model and the FX model to obtain the SWCC of mural plasters with high accuracy. Liu et al.[16] used the pressure plate method, vapor equilibrium method, and dew point potentiameter method

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to explore the SWCC in the full suction range of Qinghai silty clay (saline soil).

Although a large number of experimental results have been achieved in the study of SWCC in the wide (full) suction range, SWCC still suffers from the problem of long test cycles, and it is not easy to obtain SWCC in a short period to meet the requirements of experiments or numerical simulations. Therefore, it is particularly important to obtain SWCC in the wide (full) suction range in a short period.

In this paper, three different test methods, including pressure plate method, parallel filter paper method, and dew point potentiameter method, were used to quickly measure the suction of Lanzhou silt in different ranges. The pressure plate method was used to measure the low suction range (0–50 kPa), the parallel filter paper method was used to measure the medium suction range (50–10^3 kPa), and the dew point potentiameter method was used to measure the high suction range (10^3–10^5 kPa). The combination of the three test methods can quickly determine the SWCC in the wide (full) suction range of soils, and the applicability of this method to different soils was verified by using Qinghai silty clay. This study provides a reference for the rapid determination of SWCC in a wide (full) suction range.

2 Testing materials and methods

2.1 Testing materials

The soils used in the test were silt from Lanzhou and silty clay from Qinghai. According to the *Standard for geotechnical testing methods* (GB/T 50123-2019)[17], the basic physical properties of the two kinds of soils were measured (see Table 1). In order to prevent ion exchanges between the testing water and soil from affecting the test results, the water used in this test was deionized water.

Table 1 Basic physical properties of the two soils

Soil type	Liquid limit W_L /%	Plastic limit W_P /%	Maximum dry density /(g • cm^{-3})	Optimum moisture content /%	Specific gravity G_S
Lanzhou silt	29.5	9.4	1.78	14.8	2.7
Qinghai silty clay	27.2	15.1	1.75	15.5	2.7

2.2 Testing methods

2.2.1 Pressure plate method

In this study, the SWCC in the low suction range was measured with a pressure plate instrument. The pressure plate method is an approach to measure the suction directly, and its principle is based on axial translation technology[18] to control the suction (u_a – u_w). In other words, the saturated clay plate is used to separate the pore air pressure and pore water pressure on the sample, and then the suction is controlled by applying pore air pressure. The instrument used in this test is manufactured by the American SoilMoisture Instrument Company (as shown in Fig. 1).

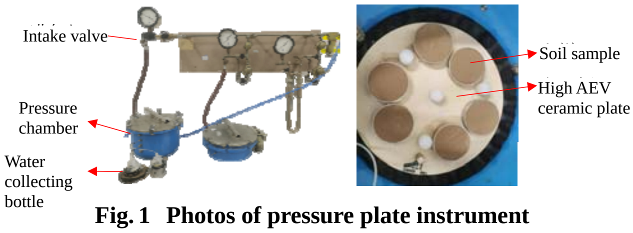


Fig. 1 Photos of pressure plate instrument

Considering the equilibrium time of axial translation (the equilibrium criterion uses the drainage volume of the soil sample within 24 h less than 0.05% of the sample volume[19–20]), in this study, the pressure plate instrument was used only when the saturation of the sample was greater than 80%, and the applied air pressure path was 4 kPa→10 kPa→20 kPa→50 kPa. According to ASTM C1699-09[21], the main steps of the test are as follows: (1) prepare the sample according to the required dry density and moisture content, and saturate the sample and the clay plate; (2) place the saturated sample on the clay plate and seal the pressure vessel; (3) apply the corresponding air pressure in a graded manner according to the air pressure path, and weigh the water collection bottle at regular intervals to determine whether equilibrium is reached at that level of air pressure; (4) after reaching equilibrium, unload the air pressure, weigh the mass of the sample and record it, then put the sample back on the clay plate and apply the next level of air pressure according to the air pressure path; (5) repeat steps (2) to (4) until the end of the test, weigh the sample mass and measure its moisture content using the drying method to calculate the mass water content under the corresponding suction.

2.2.2 Filter paper method

The SWCC in the medium suction range was measured by the filter paper method. The application of the filter paper method to measure suction is relatively mature, and the American Society for Testing and Materials (ASTM) has developed a well-established set of testing standards[22].

In order to realize the rapid measurement of SWCC, a parallel filter paper method was proposed in this study based on the original serial filter paper method. In the unsaturated soil test, the serial test refers to a soil sample that starts the test from the initial state S_1 and then goes through S_2, S_3, ..., S_N for a total of N states. Assuming that the average time required for an unsaturated soil sample to reach a certain state equilibrium is T, the shortest time required for the serial test is NT . In the case of SWCC measurement, traditional methods (including filter paper method or axial translation method) are serial tests. One of the significant drawbacks of these methods is that they must be conducted sequentially according to a set saturation gradient from high to low (drying process) or from low to high (absorption process), which is extremely time-consuming; obtaining an SWCC often takes several months. The parallel test refers to conducting tests with N soil samples, starting from the initial state S_1 and then reaching the states S_2, S_3..., S_N, respectively. Assuming that the average time required for soil samples to reach each equilibrium state is T, the shortest time required for parallel test is T. In general, it takes a long time for unsaturated soil samples to reach the equilibrium state, the parallel test can shorten the test time to a large extent and greatly improve the test efficiency.

In this study, the parallel filter paper method was adopted instead of the traditional serial filter paper method. According to ASTM D5298–16[22], seven groups of soil samples were prepared under the optimum moisture content (as shown in Fig. 2(a)). After reaching saturation, each group of samples was air-dried to a saturation of 80%, 70%, 60%, 50%, 40%, 30%, and 20%, respectively. Three layers of filter paper were placed on each soil sample (the middle layer was Whatman filter paper, and the top and bottom layers were ordinary filter papers with diameters slightly larger than the Whatman filter paper to protect the middle filter paper), and then the sample was sealed for curing (as shown in Fig. 2(b)). The curing time was determined by the sample with low saturation and not less than 7 days. The moisture contents of the filter paper and the soil sample were measured after the sample reached equilibrium. Whatman No.42 filter paper was used in the test, and the equation of its rating curve is as follows[23]:

$$\lg\psi = -0.037\,0\omega + 3.982\,5,\ \omega < 59.5\% \qquad (1)$$

$$\lg\psi = -0.011\,2\omega + 2.442\,3,\ \omega \geqslant 59.5\% \qquad (2)$$

where ψ is the matric suction (kPa); ω is the moisture content of the filter paper after reaching equilibrium (%).

(a) Samples for filter paper method test (b) Sealed specimens

Fig. 2 Photos of specimens used in filter paper method

2.2.3 Dew point potentiameter

The SWCC in the high suction range was measured using a WP4C dew point potentiameter manufactured by the American Decagon company (as shown in Fig. 3(a)). The WP4C measures the sample water potential by balancing the liquid water of the sample with the vapor water in the space above the sample and measuring the vapor pressure in the top space[24], which is an indirect method for measuring the soil water potential. It is one of the fastest instruments for measuring soil water potential and can measure soil water potential in (3 ± 1.5) mins under the rapid measurement mode.

When the WP4C was used to measure the SWCC, only the samples with a saturation of less than 20% (i.e., 20%, 15%, 10%, and 5%) were measured. As suggested by ASTM D6836-08[25] and Xu et al.[26], the main test steps of WP4C are as follows: (1) make the samples according to the corresponding dry density and saturation (as shown in Fig. 3(b)); (2) put the prepared sample into the sample box and check whether $T_s - T_b$ (the difference between sample temperature and cavity temperature) is between –0.5 and 0 (if yes, turn the knob to the Read position; if not, take out the sample and adjust the sample temperature); (3) record the number on screen when the LED flashes; (4) After reading, take out the sample and measure its moisture content by using the drying method.

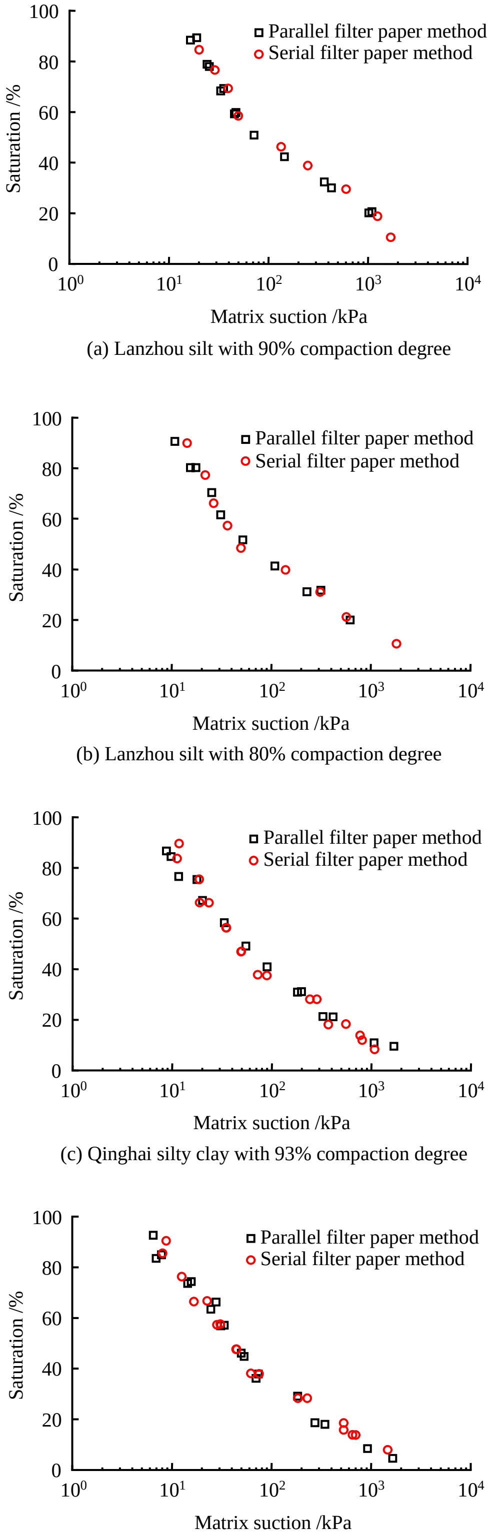
(a) Dew point potentiameter (b) Sheet specimens

Fig. 3 Dew point potentiameter and soil specimen

3 Testing results and discussion

3.1 Comparison of serial test and parallel test results

Figure 4 shows the SWCC of Lanzhou silty soil and Qinghai silty clay with different compaction degrees measured by serial and parallel filter paper methods. As can be seen from Fig. 4, the matric suction of the sample gradually decreased with the increase of saturation. The Lanzhou silt and Qinghai silty clay were selected for the drying test from high saturation to low saturation to compare the differences between the serial and parallel filter paper methods. Fig. 4 showed a good consistency between the serial and parallel test results, indicating that the parallel test could be a good substitute for the serial test, thus significantly reducing the measurement time. The parallel test could measure the SWCC of soil in about one week, which achieved fast and accurate measurement of SWCC. Each sample was operated only once, reducing the impact of repeated operations on the sample. However, the serial test sample needed to undergo multiple separations and re-contacts with the filter paper, which inevitably caused soil particles to adhere to the filter paper, thus bringing out test errors.



(a) Lanzhou silt with 90% compaction degree

(b) Lanzhou silt with 80% compaction degree

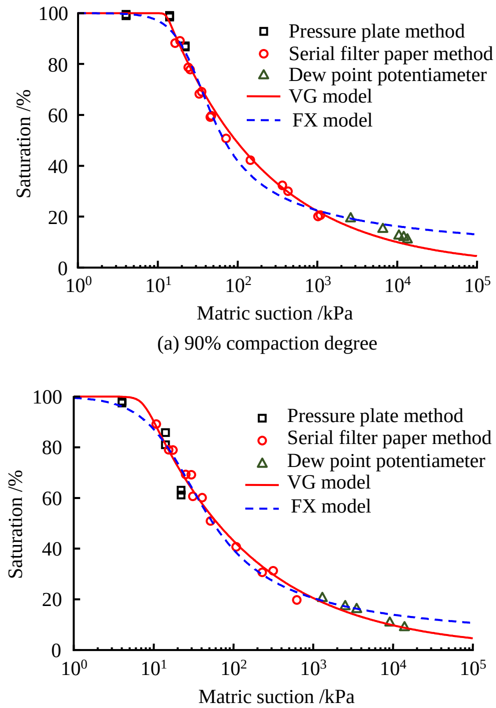
(c) Qinghai silty clay with 93% compaction degree

(d) Qinghai silty clay with 87% compaction degree

Fig. 4 SWCCs of Lanzhou silt and Qinghai silty clay (serial and parallel filter paper methods)

3.2 Combination of three test methods

Figure 5 shows the SWCCs of Lanzhou silt in the wide suction range measured by three test methods in a short time. The results showed that the curves of the three test methods in the suction range basically overlapped, indicating that the three test methods could be well combined for rapid measurement of SWCC in the wide suction range and also prove the reliability of the measurement results. From the results in Fig. 5, it can be obtained that the pressure plate method depicted the boundary effect zone of SWCC, the filter paper method depicted the transition zone of SWCC, and the dew point potentiameter method depicted the residual zone of SWCC. The three test methods could completely depict the general shape of SWCC.



(a) 90% compaction degree

(b) 80% compaction degree

Fig. 5 SWCCs in wide suction range of Lanzhou silt determined by three test methods

Among the many SWCC fitting models, two commonly used SWCC fitting models (VG model[27] and FX three-parameter model[28]) were selected to fit the test results. The fitting results are shown in Figs. 5 and 6, and the fitting parameters are given in Table 2. The model fitting effect was evaluated by the correlation coefficient R^2. It can be seen that the correlation coefficients R^2 of the two fitted models were more than 0.98, and both had a good fitting effect. By comparing the test results under different compaction degrees (such as the SWCC represented by S_r - lgψ in Fig. 6), it is found that when the saturation was the same, the matric suction of the sample with higher compaction degree was larger; when the matric suction was the same, the sample with higher compaction degree had higher saturation. This is because with the increase of compaction, the void ratio of the sample became smaller, and it was more difficult for air to enter into the sample. Therefore, the larger the corresponding air intake value of the sample was, the more difficult for water to discharge out of the soil, hence the sample had better water retention. However, with the increase of suction, the effect of compaction on SWCC became weaker and weaker.

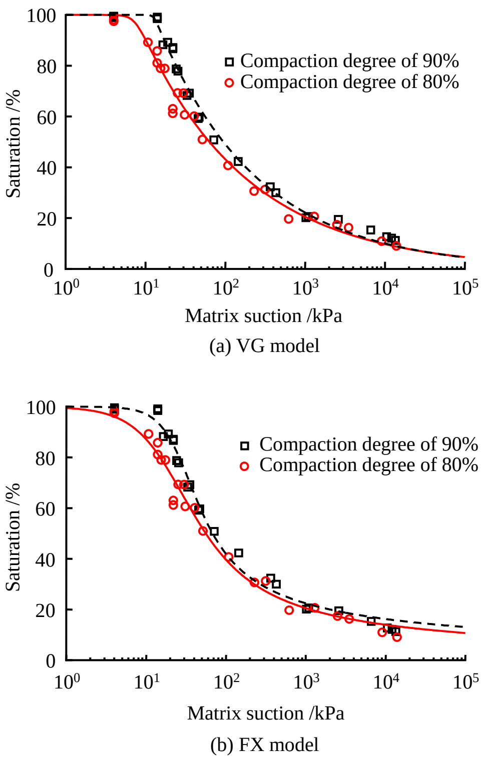


Fig. 6 Fitting curves of VG model and FX model for different compaction degrees

Table 2 Fitting parameters of SWCC models of Lanzhou silt

Fitting model	Compaction degree /%	*a* /kPa	*m*	*n*	R^2
VG model	90	12.72	0.02	20.76	0.99
FX model	90	22.34	0.68	2.43	0.99
VG model	80	7.41	0.05	7.13	0.99
FX model	80	15.92	0.87	1.47	0.98

3.3 Test number and duration

To study the effect of test number on the fitting of SWCC, during the fitting of SWCC, the test data of Lanzhou silt with a compaction of 90% were divided into four groups, in which the data from the pressure plate method and the dew point potentiameter method were separately set as a group, and the filter paper test data were divided into two groups by taking one point at an interval. The combination of the test data involved in the fitting is shown in Table 3, and Fig. 7 shows the SWCC obtained by using different numbers of test data. Fig. 7(a) shows the SWCC obtained by using three different fitting conditions A, B and C, and Fig. 7(b) shows the SWCC obtained by using four different fitting conditions C, D, E and F. Based on the results in Figs. 7 and 8 and the root mean square errors in Table 3, the SWCC fitting did not completely depend on the number of tests, but more importantly on whether the test data were within the wide suction range, whether they were representative and whether they could characterize the general shape of SWCC. These factors played an essential role in the fitting of SWCC.

The fitted data under the conditions of A, B and C can roughly represent the shape of SWCC, so the fitted curves basically coincided. However, the fitted data under the conditions of D, E and F could not describe the shape of the classic SWCC well, which was quite different from the fitted curve under the condition of C. Therefore, in the case of SWCC measurement, if the measured test data were distributed in the wide suction range and could represent the general shape of the curve, the fitted curve could have good goodness even if the test data were not too dense. This not only reduced the number of tests and improved the efficiency, but also did not affect the goodness of fitting. According to the test data and test method in this study, a complete SWCC could be determined by roughly 10–12 test points, including 3 test points for the pressure plate method, 4 test points for the filter paper method, and 3–5 test points for the dew point potentiameter method.

Table 3 Different fitting conditions and root-mean-square errors

No.	Experimental data	Root-mean-square errors
A	Pressure plate test data + Filter paper partial test data 1+ Dew point potentiameter data	0.035
B	Pressure plate test data + Filter paper partial test data 2+ Dew point potentiameter test data	0.034
C	Pressure plate test data + All filter paper test data + Dew point potentiameter test data	0.033
D	Pressure plate test data + Dew point potentiameter test data	0.069
E	Pressure plate test data + All filter paper method test data	0.045
F	Filter paper test data + Dew point potentiameter test data	0.044

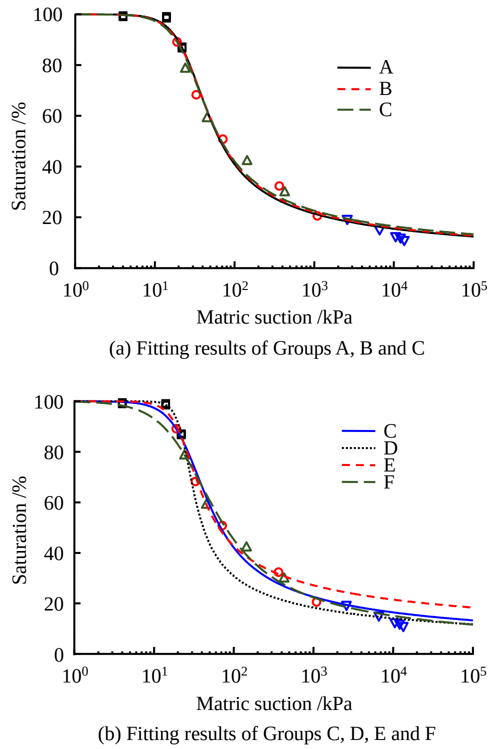


Fig. 7 Comparative analysis of fitting results for Lanzhou silt

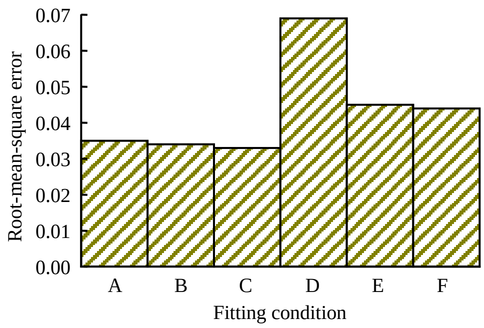


Fig. 8 RMSE values obtained under different fitting conditions

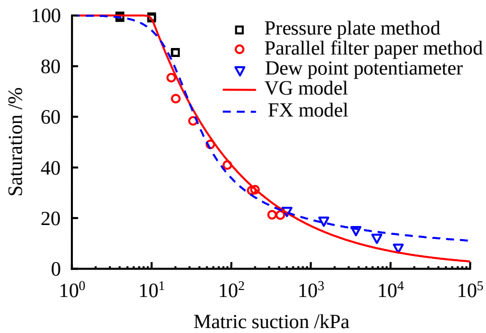
Table 4 compares the different test methods and the time required to measure the SWCC. It can be seen from Table 4 that if the serial filter paper method was used to measure the SWCC, the required time was about two months; while using the parallel filter paper method, the time required was reduced to 7–10 days, which significantly improved the test efficiency and made it possible to achieve fast and accurate SWCC measurement without reducing the measurement accuracy. The combination of three test methods required only 7–10 days to obtain a complete SWCC, which was expected to make the measurement of SWCC a conventional geotechnical test.

3.4 Method validation

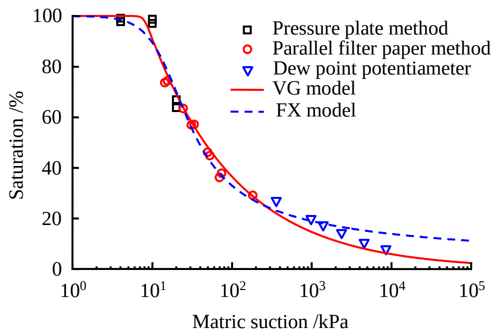
In order to verify the validity and applicability of the method proposed in this study, Qinghai silty clay was used to carry out the validation analysis. Fig. 9 shows the SWCC of Qinghai silty clay obtained by three different measurement methods. It can be seen from Fig. 9 that these three different suction measurement methods could be combined to quickly measure the SWCC of Qinghai silty clay in the wide suction range, indicating that the proposed measurement method was not only applicable to Lanzhou silt, but also to other different types of soils. This proposed method provided a reference for fast determining soil–water characteristic curves in the wide suction range.

Table 4 Time required for different test methods

Method	Saturation /%	Suction range /kPa	Standard	Time /d
Pressure plate method	80–100	0–50	The displacement of the soil sample within 24 h is less than 0.05% of the sample volume [19–20]	8.0
Parallel filter paper method	20–80, interval of 10	50–10^3	The equilibrium time of suction is at least 7 d[22]	49.0–70.0
Serial filter paper method	20–80, interval of 10	50–10^3	The equilibrium time of suction is at least 7 d[22]	7.0–10.0
Dew point potentiameter	Less than 20	10^3–10^5	In the fast measurement mode, the equilibrium time is (3±1.5) min[24]	0.5



(a) Compaction degree of 93%



(b) Compaction degree of 87%

Fig. 9 SWCCs in wide suction range of Qinghai silty clay determined by three test methods

4 Conclusions

In this paper, the pressure plate method, the filter paper method and the dew point potentiameter method were used to study the rapid test method of SWCC measurement and fit the model parameters in the wide suction range for different soils. Meanwhile, the effect of the number of tests on SWCC was also discussed. The main conclusions are as follows:

(1) The comparison tests of the serial filter paper method and the parallel filter paper method showed that the measurement results of both methods were consistent, and the parallel filter paper method could be a good substitute for the serial filter paper method. Using the parallel filter paper method could significantly shorten the time of SWCC measurement and overcome the test error caused by the frequent operation of the serial filter paper method.

(2) The combined measurement of the three different methods could better determine the SWCC in a wide suction range and shorten the time required by conventional methods from several months to 7–10 days.

(3) In the measurement of SWCC in the wide (full) suction range, the saturation level of the soil sample could be controlled at equal intervals to reduce the number of tests to improve the efficiency of the test while ensuring that the test data covered the wide suction range and could represent the general shape of SWCC. Only 10–12 points were required to measure a complete SWCC using the combined measurement method, enabling

rapid measurement of SWCC in the wide (full) suction range.

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