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Variability in the measured soil–water characteristic curve with respect to the numbers of specimens

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The soil–water characteristic curve (SWCC) defines the relationship between the amount of water in soil and soil suction. The SWCC is commonly used to estimate the hydraulic conductivity function (HCF) and the shear strength function (SSF). Therefore, an accurate determination of the SWCC is crucial for implementing the principles of unsaturated soil mechanics. The SWCC is commonly determined from a limited number of experimental data because SWCC measurements are time-consuming and costly. As a result, the minimum number of required soil specimens is crucial for a SWCC test when considering the accuracy of the determined SWCC and the experimental expenses. In this study, both engineered from sand and kaolin mixtures and residual soils from Bukit Timah Formation in Singapore are selected to prepare soil specimens for SWCC measurements. The SWCCs obtained from the specimens with engineered soil are consistent, while those from specimens with residual soil are slightly scattered. This indicates that one specimen is sufficient to determine the SWCC for engineered soil samples, while a minimum of two specimens should be prepared for the determination of SWCC for residual soil samples from Bukit Timah Formation.

Keywords Soil–water characteristic curve, Variability, Experimental measurement, Unsaturated soil

It is known that the soil–water characteristic curve (SWCC) is crucial when implementing the principles of unsaturated soil mechanics. The SWCC contains valuable information for estimating the other engineering properties of unsaturated soil, such as the hydraulic conductivity function (HCF)[1–7], shear strength function (SSF)[8–12], and tensile strength function (TSF) of unsaturated soils[13–16]. Liu et al.[17] indicated that the rate of infiltration into the slope soil is much dependent on the HCF of the soil. Zhai et al.[18] adopted the SWCC to compute the unit weight of unsaturated soil and investigate its effect on the stability of unsaturated soil slope. As a result, the accuracy of the determined SWCC can significantly affect the estimated HCF, SSF and TSF. In geotechnical analyses relating to unsaturated soils, both the SWCC and HCF are commonly used as inputs for seepage analysis, while the SSF is commonly used as an input for slope stability analysis. On the other hand, as compared with conventional geotechnical tests, the specimens prepared for the laboratory measurement are limited due to long term and costly testing process. As a result, the minimum number of specimens required for the SWCC test are crucial for geotechnical engineers in determination of SWCC in constrained timetable and with limited budget.

There are many continuous mathematical equations[3,19–28] are available for the representation of either unimodal or bimodal SWCC. Among those SWCC equations, both van Genuchten's equation[3], as illustrated in Eq. (1), and Fredlund and Xing's equation[22], as illustrated in Eq. (2), are widely used by researchers to analyze problems related to unsaturated soil.

$$\frac{S-S_r}{1-S_r}=\frac{1}{\left[1+(a_v\psi)^{n_v}\right]^{m_v}}, \tag{1}$$

where a_v, n_v and m_v are fitting parameters in van Genuchten's equation, ψ is the soil suction, S is the degree of saturation, and S_r is a rough estimation of the residual saturation. It should be noted that based on a work by Zhai

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et al.[18], it is better to consider S_r as a fitting parameter rather than the residual saturation for better performance in the best fitting.

$$S=\left[1-\frac{\ln\left(1+\frac{\psi}{C_r}\right)}{\ln\left(1+\frac{10^6}{C_r}\right)}\right]\frac{1}{\left\{\ln\left[e+\left(\frac{\psi}{a_f}\right)^{n_f}\right]\right\}^{m_f}},\tag{2}$$

where a_f, n_f and m_f are fitting parameters in Fredlund and Xing's equation[22] and C_r is an input value that is a rough estimation of the residual suction.

It is observed that the measured soil properties from laboratory testing may vary for different specimens although the specimens were taken from the same soil sample. In practical engineering, more than one specimen are commonly prepared for the determination of the engineering properties of soil. Rahardjo et al.[29] and Zhai[30] reported the high variability in engineering properties of unsaturated residual soils in Singapore from the experimental data collected from the laboratory testing carried out in Nanyang Technological University. Sometimes, the engineered soil, which is artificially prepared and uniform in its property, is adopted to investigate the mechanism of soil behaviors. In this case, a question may be raised whether the measured SWCC of both residual soil and the engineered soil can be significantly affected by the number of specimens?

To investigate the effect of the number of specimens on the variability of measured SWCC, both an engineered soil (sand mixed with coarse kaolin) and a residual soil from the Bukit Timah Formation were prepared for SWCC measurements. The capabilities of the determined SWCCs, which are obtained from single specimen and more than one specimen, in representing the SWCCs for both types of soil were evaluated.

Materials and testing program

It is known that the properties of engineered soil samples are uniform because all the contents and textures are well controlled. On the other hand, there is a higher variability in the properties of residual soil than those of engineered soil because of natural deposits. Therefore, to investigate the effect of the number of specimens on the accuracy of the measured SWCC, both engineered soil and natural residual soil were utilized in this study for the SWCC measurement. The standard Graded sand (Ottawa sand) and coarse kaolin (L2) were used to prepare the engineered soil samples, while the residual soils from the Bukit Timah Formation taken from the same sampling tube at Ang Mo Kio in Singapore were selected as the residual soil samples. The grain size distributions of graded sand, coarse kaolin L2 and residual soil from the Bukit Timah Formation adopted in this study are illustrated in Fig. 1.

Figure 1 indicates that the sizes of graded sand are mainly within the range of 0.2–0.5 mm. As in the conventional pressure plate test the specimens need to be weighted at different suction level, the specimen should be prepared stiff enough so that it does not damage during the weighting procedure. To obtain a stiff specimen, coarse kaolin is mixed with graded sand. The pore size of the specimen is mainly controlled by both graded sand and coarse kaolin. Zhai[7] mixed graded sand (73%) with coarse kaolin L2 (27%) and prepared SK specimens with the same initial conditions. The RS specimens were prepared from a residual soil sample taken from the same sampling tube with diameter of 100 mm. Conventional equipment, such as the pressure plate illustrated in Fig. 2a, was used for the SWCC measurement. To ensure that all the specimens were measured under the same measurement conditions, all the specimens were placed in the same suction tank, as illustrated in Fig. 2b. The RS soil samples were illustrated in Fig. 3. The index properties of both engineered soil and the residual soil are illustrated in Table 1.

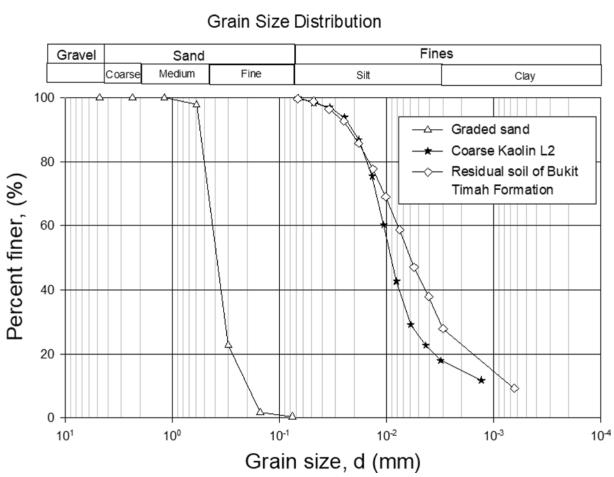

Figure 1. Illustration of grain size distribution data for the standard graded sand, coarse kaolin and residual soil of the Bukit Timah formation (modified from Zhai[7]).

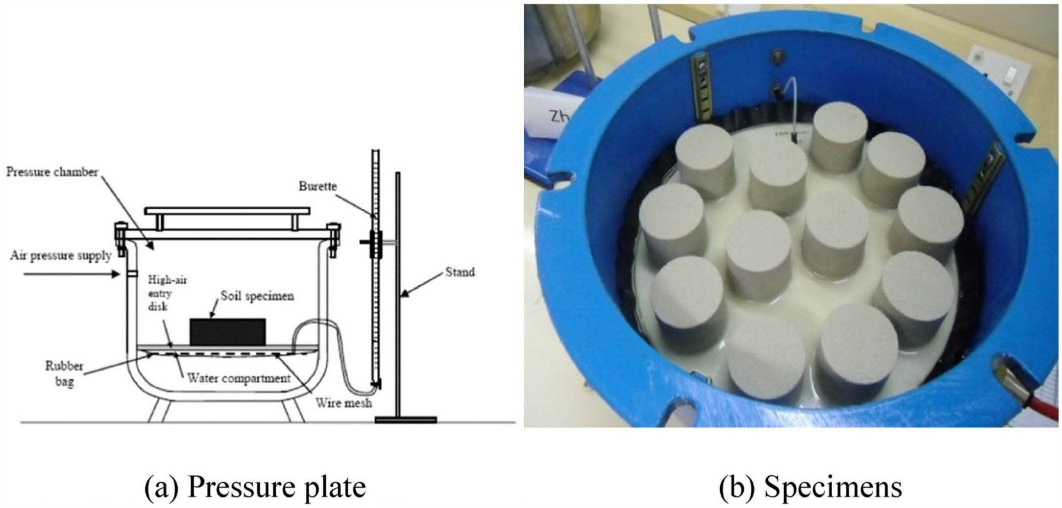

Figure 2. Illustration of the pressure plate of the soil specimens for the SWCC measurement (from Zhai[30]).

Figure 3. Illustration of RS soil samples.

Properties	Engineered soil	Residual soil
USCS classification	SM	CH
G_s	2.66	2.68
d_{60}	0.3	0.10
d_{30}	0.15	0.01
d_{10}	0.01	0.001
Dry density, ρ_d (Mg/m^3)	1.89	1.56
Initial water content w_i	7.8%	28.5%
Plastic Limit, PL	–	30%
Plastic Index, PI	–	24%

Table 1. Index properties of graded soil and residual soil.

A total of 12 specimens with diameter of 50 mm for the engineered soil, and 6 specimens with diameter of 63.5 mm for residual soil (RS) were prepared for the SWCC tests. The SWCCs for both types of soil were obtained by best fitting Fredlund and Xing's equation[22] with average measured data from all the specimens (i.e. 12 nos for the engineered soil and 6 nos for the residual soil). Subsequently, the SWCCs were determined again by best fitting the Fredlund and Xing's equation[22] with the measured data from individual specimens. Different SWCCs were obtained, and the determined SWCCs were subsequently compared with the measured data for each specimen.

Based on the GSD, as shown in Fig. 1, the SWCC of the engineered soil (SK) and the residual soil (RS) specimens can be roughly estimated from the index properties of soil[31–36]. In this paper, Fredlund et al.[31]'s method was adopted for the preliminary estimation of the SWCC for both SK and RS soil samples. The estimated results indicate that the residual suction of the SK specimen is roughly less than 300 kPa, while the residual suction of the RS specimen is roughly higher than 500 kPa. As a result, a ceramic disk with an air-entry value of 500 kPa was used for the SWCC measurement of the SK specimens. In the SWCC measurement of SK specimens, the applied suctions were controlled at 0.01 kPa, 11.17 kPa, 31.17 kPa, 51.17 kPa, 71.17 kPa, 91.17 kPa, 191.17 kPa, 291.17 kPa, and 471.17 kPa. On the other hand, a ceramic disk with an air-entry value of 1500 kPa was used for the SWCC measurement of the RS specimens. The residual soil easily collapsed when the suction decreased to zero. Therefore, in the SWCC measurement of the RS specimens, the applied suctions were controlled to be 11.17 kPa, 31.17 kPa, 51.17 kPa, 71.17 kPa, 91.17 kPa, 191.17 kPa, 291.17 kPa, 471.17 kPa, 1000.17 kPa, and 1480.17 kPa. Specimens were weighted until the equilibrium conditions were reached before increasing each step of applied suction.

Experimental results

The measured gravimetric water contents corresponding to different suction levels for SK specimens are illustrated in Table 2 and for the RS specimens are illustrated in Table 3, respectively.

It is observed that the initial water contents of the RS specimens are inconsistent for different specimens. To be comparable, the normalized water contents, which considers that the initial water content to be equal to 1, from RS specimens are used for the best fitting process. In this study, Fredlund and Xing's equation is used as the SWCC equation to best fit the experimental data. In normal practice, the average value is usually taken when the number of specimens is more than one. As a result, the average value for the measured water contents from 12 SK specimens and 6 RS specimens are computed. Both the average values and the individual data from each specimen are used for the best fitting. Subsequently, the best fitted SWCCs are compared with the measured data for each specimen, and the coefficient of determination (R^2) for each best fitted SWCC is computed. The obtained SWCC fitting parameters and R^2 for SK specimens and RS specimens are illustrated in Tables 4 and 5, respectively.

Variability of the SWCC associated with experimental data

Tables 4 and 5 indicate that the value of R^2 for the SK soil specimens varies from 99.39 to 99.95%, while that for the RS soil specimens ranges from 96.65 to 99.94%. It is commonly believed that data from more experimental specimens give more accurate results. To verify this conclusion, the determined SWCC from the average is compared with the experimental data from each specimen, and R^2 is computed for each specimen (as shown in the second row in Tables 4 and 5). Subsequently, the SWCC is determined by using data from one set of specimens and compared with the experimental data from other specimens. The R^2 for each specimen is recalculated as

Suction (kPa)	SK1	SK2	SK3	SK4	SK5	SK6	SK7	SK8	SK9	SK10	SK11	SK12	Average
0.1	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145
11.17	0.124	0.125	0.125	0.124	0.125	0.125	0.124	0.124	0.125	0.129	0.129	0.127	0.126
31.17	0.111	0.110	0.109	0.108	0.108	0.108	0.107	0.108	0.107	0.112	0.112	0.110	0.109
51.17	0.096	0.094	0.093	0.093	0.093	0.092	0.092	0.092	0.092	0.095	0.096	0.094	0.093
71.17	0.083	0.082	0.081	0.081	0.081	0.081	0.080	0.081	0.081	0.083	0.083	0.082	0.081
91.17	0.076	0.074	0.074	0.073	0.074	0.074	0.074	0.074	0.074	0.075	0.075	0.074	0.074
191.17	0.050	0.050	0.050	0.050	0.050	0.050	0.051	0.051	0.050	0.050	0.051	0.050	0.050
291.17	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
391.17	0.033	0.033	0.033	0.033	0.033	0.033	0.034	0.034	0.034	0.033	0.034	0.034	0.033
471.17	0.030	0.030	0.030	0.030	0.029	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030

Table 2. The measured gravimetric water contents for SK specimens.

Suction (kPa)	RS1	RS2	RS3	RS4	RS5	RS6	Average
11.17	0.271	0.281	0.282	0.292	0.290	0.280	0.283
31.17	0.261	0.273	0.273	0.282	0.282	0.272	0.274
51.17	0.256	0.270	0.269	0.278	0.278	0.268	0.270
71.17	0.252	0.264	0.265	0.273	0.273	0.264	0.265
91.17	0.249	0.262	0.262	0.271	0.269	0.261	0.262
191.17	0.234	0.249	0.249	0.257	0.257	0.248	0.249
291.17	0.215	0.231	0.230	0.240	0.240	0.232	0.231
471.17	0.197	0.213	0.210	0.220	0.221	0.213	0.212
1000.17	0.173	0.182	0.179	0.190	0.188	0.181	0.182
1480.17	0.169	0.173	0.171	0.180	0.179	0.177	0.175

Table 3. The measured gravimetric water contents for RS specimens.

	a_f	n_f	m_f	SK1	SK2	SK3	SK4	SK5	SK6	SK7	SK8	SK9	SK10	SK11	SK12
Ave	71.825	0.929	2.061	99.70	99.89	99.92	99.85	99.91	99.93	99.86	99.86	99.91	99.78	99.76	99.93
SK1	102.46	0.877	2.522	99.79	99.83	99.80	99.67	99.77	99.76	99.66	99.69	99.73	99.83	99.83	99.86
SK2	102.45	0.859	2.564	99.75	99.87	99.89	99.82	99.88	99.88	99.82	99.83	99.86	99.75	99.73	99.89
SK3	102.45	0.847	2.588	99.70	99.86	99.90	99.87	99.91	99.91	99.88	99.88	99.90	99.66	99.64	99.87
SK4	79.98	0.873	2.257	99.56	99.81	99.89	99.91	99.92	99.94	99.94	99.91	99.95	99.54	99.51	99.84
SK5	139.99	0.794	3.123	99.63	99.79	99.85	99.86	99.88	99.88	99.87	99.87	99.87	99.52	99.50	99.79
SK6	69.68	0.914	2.053	99.60	99.85	99.91	99.90	99.93	99.50	99.93	99.90	99.95	99.64	99.61	99.89
SK7	69.68	0.893	2.074	99.50	99.79	99.88	99.90	99.91	99.94	99.94	99.91	99.95	99.51	99.47	99.82
SK8	149.9	0.769	3.234	99.56	99.74	99.82	99.85	99.85	99.86	99.88	99.88	99.87	99.41	99.39	99.73
SK9	100.01	0.83	2.568	99.60	99.81	99.88	99.90	99.91	99.92	99.92	99.91	99.93	99.53	99.50	99.82
SK10	59.226	1.058	1.726	99.67	99.76	99.70	99.49	99.63	99.64	99.47	99.48	99.58	99.94	99.93	99.84
SK11	59.227	1.058	1.719	99.67	99.74	99.68	99.45	99.61	99.61	99.44	99.45	99.56	99.94	99.93	99.82
S12	64.728	0.969	1.908	99.71	99.88	99.90	99.80	99.88	99.90	99.81	99.80	99.87	99.84	99.82	99.94

Table 4. The coefficient of determination, R^2 (%), for the determined SWCC from different SK specimens.

	a_f	n_f	m_f	RS1	RS2	RS3	RS4	RS5	RS6
Ave	147.25	1.15	0.37	97.94%	99.55	99.43	99.58	99.49	99.06
RS1	90.34	1.27	0.30	99.27	97.70	98.25	98.09	97.26	96.65
RS2	164.94	1.14	0.39	97.33	99.61	99.38	99.58	99.62	99.19
RS3	164.89	1.16	0.40	97.75	99.55	99.35	99.61	99.52	99.10
RS4	79.98	0.87	2.25	99.56	99.81	99.89	99.91	99.92	99.94
RS5	139.99	0.79	3.12	99.63	99.79	99.85	99.86	99.88	99.88
RS6	69.68	0.91	2.05	99.60	99.85	99.91	99.90	99.93	99.50

Table 5. The coefficient of determination, R^2 (%), for the determined SWCC from average values from random two RS specimens.

shown in Tables 4 and 5. Because it is believed that more data provide more reliable results, the R^2 for the SWCC obtained from the average (the data from all the specimens are considered) is taken as the reference. Subsequently, the relative error (*RE*) is computed by comparing the R^2 for SWCCs from individual specimens (the data from only one set of specimens) and the referenced R^2, as follows:

$$RE = \frac{x_i - x_{ref}}{x_{ref}} \times 100\%, \tag{3}$$

where *RE* is the relative error, x_i is the R^2 for the SWCC from individual specimens, and x_{ref} is the reference R^2, which is for the SWCC obtained from the average value. The values of *RE* are computed by using the data shown in Tables 4 and 5 and illustrated in Figs. 4 and 5, respectively.

Figure 4 indicates that the *RE* values for the SWCC from each SK specimen are less than 0.25%, which indicates that the SWCC from any specimen can represent the data from other specimens well. Figure 5 indicates that the *RE* values for the SWCC from each RS specimen are less than 2.5%, which is approximately ten times that for the SK specimens. This indicates that the effect of specimen number on the accuracy of the determined SWCC is more significant for the natural residual soil than for the engineered compacted sand with kaolin. To investigate the effect of the RS specimen number on the accuracy of the determined SWCC, two sets of experimental data are randomly taken, and the average value from those two sets of data is calculated and subsequently used for the best fitting. There are a total of 6 specimens, and there are a total of $C_6^2 = \frac{6\times5}{1\times2} = 15$ different combinations (the combinations are labeled CO1 to CO15). Subsequently, the data from these 15 combinations are used for the best fitting, and the obtained SWCC fitting parameters accompanied by R^2 for RS specimens are illustrated in Table 5 as follows:

The *RE* values for the SWCCs obtained from different combinations are recalculated from Table 6 and illustrated in Fig. 6.

Figures 5 and 6 indicate that *RE* can be significantly reduced (i.e. reduced from 2.5 to 1%) by adopting the experimental data from two sets of specimens. Figure 6 also indicates that the *RE* values for all SWCCs from different combinations are less than 1%, and most of them are less than 0.5%. As a result, to ensure the accuracy of the determined SWCC, one set of specimens from engineered soil and two sets of specimens from natural soil are recommended for the SWCC test.

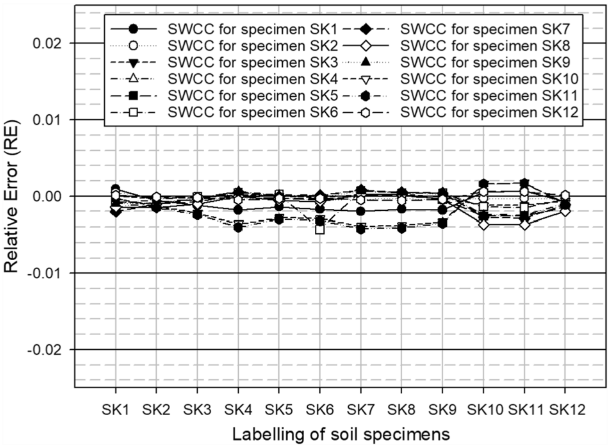

Figure 4. Illustration of *REs* for 12 specimens from the engineered soil.

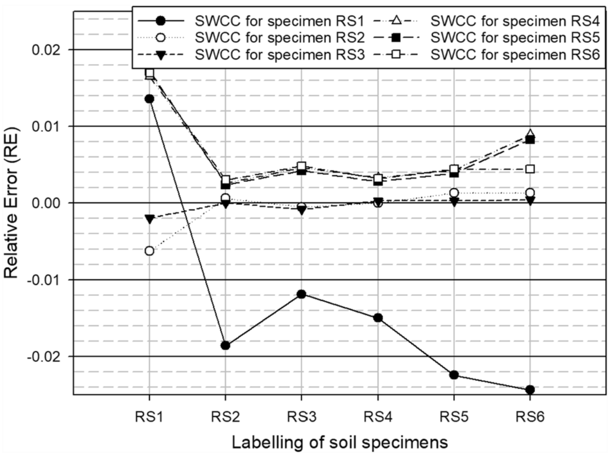

Figure 5. Illustration of *REs* for 6 specimens from the residual soil.

	a_f	n_f	m_f	RS1	RS2	RS3	RS4	RS5	RS6
Ave	147.25	1.15	0.37	97.94	99.55	99.43	99.58	99.49	99.06
CO1	119.32	1.19	0.34	98.79	99.12	99.26	99.30	98.91	98.42
CO2	119.32	1.21	0.34	98.93	98.89	99.22	99.07	98.61	97.99
CO3	119.32	1.15	0.34	98.88	99.01	99.16	99.24	98.77	98.28
CO4	122.89	1.18	0.34	98.68	99.23	99.30	99.38	99.04	98.60
CO5	114.17	1.22	0.32	98.63	99.21	99.18	99.37	99.04	98.68
CO6	164.87	1.15	0.39	97.63	99.56	99.52	99.51	99.51	98.96
CO7	164.87	1.10	0.4	97.55	99.59	99.38	99.60	99.59	99.16
CO8	164.88	1.15	0.38	97.15	99.60	99.32	99.52	99.64	99.24
CO9	156.16	1.16	0.36	97.04	99.57	99.19	99.50	99.63	99.32
CO10	165.34	1.11	0.40	97.85	99.54	99.52	99.55	99.47	98.92
CO11	171.58	1.14	0.40	97.43	99.58	99.49	99.52	99.56	99.03
CO12	156.38	1.17	0.37	97.44	99.61	99.41	99.55	99.60	99.18
CO13	172.75	1.09	0.41	97.32	99.60	99.33	99.58	99.62	99.21
CO14	155.95	1.12	0.37	97.28	99.56	99.19	99.55	99.60	99.30
CO15	162.33	1.15	0.37	96.79	99.54	99.10	99.45	99.63	99.34

Table 6. The coefficient of determination, R^2 (%), for the determined SWCC from average values from random two RS specimens.

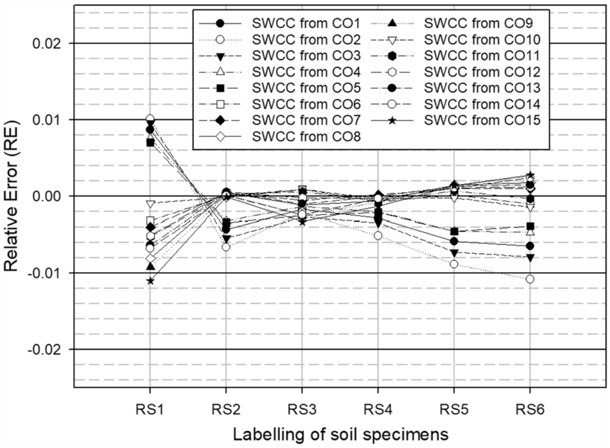

Figure 6. Illustration of *REs* for 15 combinations from the residual soil.

Conclusions and recommendations

Both engineered soil (consisting of graded sand and coarse kaolin) and residual soil from the Bukit Timah Formation in Singapore were prepared for SWCC tests. The SWCCs for both engineered soil and residual soil were first determined from average values from those specimens (12 for the engineered soil and 6 for the residual soil) and compared with experimental data from individual specimens. Subsequently, the SWCCs for both engineered soil and residual soil were determined again by using the experimental data from one set of specimens and compared with measured data from other specimens. Based on the best fitted SWCCs in this study, it was observed that the SWCC from any single specimen is consistent with that obtained from other single specimen and also consistent with that determined from 12 specimens for the engineered soil. This indicates that one specimen is sufficient for the determination of the SWCC for the engineered soil. On the other hand, it is observed that high deviations may result from one set of specimens of residual soil compared with the data from other specimens. The variability of the determined SWCC for the residual soil can be significantly reduced using the data from two sets of specimens. It should be noted that the texture and fabric of natural soil can vary much at different zones and further research works may be needed for the natural soils from different formations rather than in Singapore.

Data availability

Data is provided within the manuscript or Supplementary Information files.

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Author contributions

Wang H and Gao ZW prepare the main manuscript. Ma RC help to prepare the figures Satyanaga A and Zhai Q do the conceptual comments. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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