Effect of initial gravimetric water content and cyclic wetting-drying on soil-water characteristic curves of disintegrated carbonaceous mudstone

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Abstract

The soil-water characteristic curve (SWCC) is often used to estimate unsaturated soil properties (e.g. strength, permeability, volume change, solute and thermal diffusivity). The SWCC of soil samples is significantly affected by cyclic wetting-drying. To examine how water content and cyclic wetting-drying affect the SWCC of disintegrated carbonaceous mudstone (DCM), SWCC tests were implemented using a pressure-plate apparatus. In addition, SWCC models for DCM considering the initial gravimetric water content and cyclic wetting-drying were developed. The test results showed that the volumetric water content (θ) of the DCM first decreased rapidly and then became stable as matric suction (s) increased. The initial water content affected the SWCC by altering the pore structure of the DCM. For a given number of wetting-drying cycles, the higher the initial water content, the higher the stabilized θ. At a given s value, θ decreased as the number of wetting-drying cycles increased, which suggests that cyclic wetting-drying reduces the water-holding capacity of DCM. The Gardner model for DCM was constructed considering initial water content and cyclic wetting-drying, and was effective at describing and predicting the SWCC model for DCM.

Keywords: embankment engineering; disintegrated carbonaceous mudstone; soil-water characteristic curve; initial gravimetric water content; cyclic wetting-drying
1. Introduction

In the southwest of China, many highway embankments filled with disintegrated carbonaceous mudstone (DCM) frequently encounter instability problems [1–3]. Under the effects of climatic variation, rainwater infiltration and groundwater change, the DCM shows swelling/shrinkage and water evaporation [4–5]. The water-holding capacity and matric suction (s) of the DCM decrease significantly under the action of cyclic wetting-drying [6–7]. As a result, the shear strength of the DCM in the unsaturated zone of the embankments is reduced. Thus, the stability of the slope is reduced, which results in large deformation and even landslides.

The water-holding capacity of unsaturated soil is commonly characterized by the soil-water characteristic curve (SWCC), which intuitively describes the relationship between water content and s in the medium [8]. The unsaturated soil properties, such as strength, permeability, volume change, solute and thermal diffusivity, are dependent on the SWCC [9–12]. The SWCC of unsaturated soil is affected by many factors, such as soil type, mineral composition, soil structure, initial water content, initial void ratio, stress history and stress state of the soil [13–18]. Malaya and Sreedeep [19] reviewed the effect of many parameters (e.g. compaction state, suction measurement methodologies and procedures, stress history, additives and aging) on the SWCC. Some studies have shown the effect of initial water content of the soil and cyclic wetting-drying on the suction characteristics of unsaturated soils. Li et al. [20] stated that cracks in soils deform during a drying or wetting process, and the hydraulic conductivity and water-retention ability of cracked soil vary with changes in both crack volume and suction. Zhou and Yu [21] observed that the initial water content and stress state are more important than other factors (e.g. void ratio and high suction), but that the influence of initial water content and stress state tends to decrease when suction increases. Although there have been many studies of unsaturated soils and the SWCC, there are still few constitutive models that can describe the mechanical behaviour of soil accurately. Initial water content and cyclic wetting-drying also have an important influence on the SWCC, as has become the consensus among scholars and engineers. However, there is still a lack of SWCC models capable of taking into account the effects of initial water content and the number of wetting-drying cycles. Furthermore, DCM rapidly shows strong water sensitivity, surface detachment and strength reduction after cyclic wetting-drying, and thus the existing theories of unsaturated soils are not necessarily applicable to DCM. This highlights the need to investigate the SWCC of DCM considering the effect of initial water content and cyclic wetting-drying.

The main objective of this study was to examine the SWCC of DCM. A series of SWCC tests were carried out on DCM samples to investigate the effect of initial water content and cyclic wetting-drying on the SWCC. SWCC models considering initial water content and cyclic wetting-drying were then developed for DCM. The results will serve as a guide and reference for the slope-stability analysis of highway embankments.

2. Test design and methods

2.1 Material and sample preparation

The DCM used in this study was collected from the embankment of the Liuzhai–Hechi Expressway in Guangxi, China. Its main mineral components were chlorite, quartz and black chlorite, and its main chemical components were SiO2, Al2O3 and Fe2O3. The physical properties of the material were tested: it had a maximum dry density of 2.09 g/cm³, an optimum water content of 10.56%, a liquid limit of 32.9%, a plastic limit of 25.3% and a specific gravity of 2.66. The particle-size distribution of the DCM samples is shown in Fig. 1. The fines (particles smaller than 0.075 mm) content was 2.11%, and the proportion of the DCM with a particle size smaller than 2 mm was 50.88%.

DCM grains smaller than 2 mm were used in this study. Before each sample was prepared, a
predetermined amount of water was sprayed on the DCM samples using a spray device and mixed well with the soil. The wet soil was then sealed with plastic film for 24 h to ensure a homogeneous distribution of the moisture. To prepare the sample for SWCC tests, a special compaction mould with a diameter of 6.18 cm and a height of 2 cm was used. The sample was compacted in the mould in three layers with the compaction energy in accordance with the requirements of the standard Proctor compaction test [22]. The sample was then sealed with a fresh film and stored in a humidity-controlled box at 100% relative humidity.

### Test scheme and method

Initial water content and cyclic wetting-drying are the dominant factors influencing the SWCC of soil. Since the gravimetric water content of DCM is between 6% and 18% in engineering practice, four levels of initial gravimetric water content in this range (6%, 10%, 14% and 18%) were considered for the samples (Table 1). The SWCCs of the DCM samples were tested after 0, 2, 4, 6 and 8 wetting-drying cycles. The vacuum-saturation method and the oven-drying method were employed to simulate the wetting and drying processes, respectively. Based on previous experimental experience [23–25], when saturated, the sample was clamped with porous stone and filter paper and fixed with a triaxial saturator, and then vacuum-saturated in a vacuum-saturation chamber (Fig. 2). The vacuuming duration was 30 min, after which the sample was saturated with distilled water under vacuum for 24 h. Thereafter the sample was transferred into the oven and dried at 105°C for 24 h. In the process of drying, the water content of the sample was tested every 5 h. When the difference between the current water content and the initial water content was less than 5%, the water content was tested every hour. Once the difference between two water contents measured within 2 h was less than 0.5%, the process from wetting to drying was considered complete.

The SWCC tests were conducted using the 1500F1 pressure-plate apparatus (Soil Water Equipment, USA) (Fig. 3). The apparatus consisted of a pressurized system, a pressure chamber and a drainage system. It was capable of measuring the suction of soil in the range of 0–1.5 MPa. Since the suction of the embankment soil in the actual project generally does not exceed 500 kPa, only the low suction range (0–500 kPa) was tested. The detailed procedure of the SWCC test was as follows:

(i) Ceramic plate saturation. Deionized water was added to the pressure chamber of the pressure-plate apparatus until the water covered the entire ceramic plate. Air pressure of 500 kPa was then applied to the pressure chamber. When there was no further bubble discharge, the ceramic plate was deemed to be completely saturated.

(ii) SWCC test. After cyclic wetting-drying, the sample was soaked in the vacuum-saturation cylinder for a further 24 h period. The sample was then transferred to the saturated ceramic
plate. The pressure chamber was applied with air pressure from low to high, and the mass of the discharged water was measured when the water content became stable at various pressures. Based on the existing literature [26], the water content of the sample at each pressure was considered to be in equilibrium if the water content change was less than 0.1% within 24 h. Finally, the mass of each soil sample was weighed, and thus the volumetric water content of the sample was calculated.

To examine the influence of initial water content and cyclic wetting-drying on the SWCC of the DCM samples on the microscopic level, the microscopic morphology of the samples was observed using the JSM-6490LV scanning electron microscope (SEM) at the Changsha Research Institute of Mining and Metallurgy. The Image-Pro Plus software was used to process the SEM images of the DCM samples and thus identify the microscopic pore parameters, including the pore equivalent diameter, pore area and porosity. The pores of the soil were divided into micropores (<1 μm), small pores (1 μm–4 μm), mesopores (4–16 μm) and macropores (>16 μm) [27].

3. Results and discussion

3.1 SWCC of the DCM samples

Sillers et al. [28] summarized the SWCCs of different types of soils, such as clay, silt and sand, as shown in Fig. 4 (suction of 0–500 kPa). Fig. 4 also shows the measured SWCC of the DCM samples with an initial water content of 14% and 0 wetting-drying cycles. It is clear that the volumetric water content (θ) of the DCM samples decreased rapidly and then tended to become stable along with the increase in s within the suction range of 0–500 kPa. The soil samples then began to lose water at a certain rate, while the volumetric water content generally remained stable. When the suction was less than 70 kPa, the SWCC of the DCM was between that of sand and silt, and the change in the SWCC was due mainly to the discharge of water in the large pores of the DCM. When the suction was greater than 70 kPa, the SWCC of the DCM was between that of silt and clay. At this time, the change in the SWCC was due mainly to the slow discharge of water in the small pores of the DCM. This phenomenon indicates that the large-pore content of the DCM was between that of sand and silt, and the small-pore content was between that of silt and clay.

3.2 Effects of initial water content on the SWCC of the DCM

(i) Macroscopic phenomena

To study the effect of initial water content on the relationship between the volumetric water content and s of the DCM, the test results of the 0- and 8-cycle samples were analysed. The SWCCs of the DCM samples with different initial water contents are illustrated in Fig. 5. The θ of the DCM decreased along with the increase in s, and finally became stable. In addition, the rate of water-content reduction decreased along with the increase in s. This indicates that when s was low (s ≤ 50 kPa), s was sensitive to the change in θ. While s was large (s > 50 kPa), the influence of the change in θ on s was small. For a given cycle number, the higher the initial water content, the higher the stabilized θ. This was consistent with the results for unsaturated remoulded silt reported by Yi et al. [29]. Zhu et al. [30] found that suction can be divided into
three zones: a strong-adsorption zone, a water-film adsorption zone and a capillary-adsorption zone. The amount of water adsorbed in the strong-adsorption zone has a certain functional relationship with the specific surface area of the soil, the type of exchange cations and the surface-charge density of the soil particles. The initial water content affects the SWCC mainly by altering the pore structure of the soil. The DCM sample with a low initial water content had low internal cementation, large pores, and less water absorbed by the strong-adsorption zone. Therefore, the lower the initial water content, the higher the water-loss rate of the sample, and the lower the volumetric water content after stabilization.

(ii) Microscopic mechanism

The microscopic morphology of the DCM samples with different initial water contents after 8 wetting-drying cycles is shown in Fig. 6. It can be seen that the sample with an initial water content of 6% had a honeycomb structure. The sample was composed mainly of slender needle-like particles with a clear outline and a low degree of cementation. There were many pores between the particles, and the particle groups were contacted mostly in edge-to-surface and surface-to-surface forms. When the initial water content was 10%, the needle-like particles softened and gradually disappeared. The needle-like particles transformed into granular particles with a blurred outline. The particles were scattered and stacked on top of each other in an unordered arrangement, and the honeycomb structure disappeared. When the initial water content was 14% or 18%, the particles were mainly flocculent structures. The pores were significantly reduced, and the arrangement of the particles tended to be flat. The degree of cementation between the surface-to-surface contacted particles gradually increased. The scanned surface of the sample exhibited a harden feature.

The relationships between the area ratios of different pore types and initial water contents are presented in Fig. 7. It can be seen that with the increase in initial water content, the area ratio of macropores in the DCM decreased rapidly; at the same time, the ratios of micropores, small pores and mesopores gradually increased, and the increase became more significant as the initial water content increased. The area ratio of macropores (95.20%) was largest with an initial water content of 6%. When the water content was 18%, the area ratios of micropores, small pores and mesopores were at their largest, with values of 13.74%, 20.93% and 48.42%, respectively. This confirms that the higher the initial water content of the DCM, the higher the SWCC of the sample, and the better the water-holding capacity.

3.3 Effects of cyclic wetting-drying on the SWCC of the DCM

(i) Macroscopic phenomena

The SWCCs of the DCM samples with initial water contents of 10% and 14% after different numbers of wetting-drying cycles are presented in Fig. 8. Under the same conditions of initial water content and cyclic wetting-drying, the $\theta$ value of the samples in the drying process was nonlinearly, negatively correlated with $s$. Simultaneously, the decrease in $\theta$ slowed down as the $s$ value increased.
Fig. 6. Microscopic morphology of the DCM samples with different initial water contents after 8 wetting-drying cycles: (a) initial water content of 6%; (b) initial water content of 10%; (c) initial water content of 14%; (d) initial water content of 18%

Fig. 7. Relationship between area ratio and initial water content

The SWCC gradually moved downward as the cycle number increased. In other words, for a given s value, the θ value of the sample decreased as the number of cycles increased. This is because the sample porosity became larger as the number of wetting-drying cycles increased, as outlined by Sun et al. [31]. These results indicate that cyclic wetting-drying reduces the water-holding capacity of the DCM.

The internal microstructural change is the dominant factor affecting the SWCC for a given soil material. The dissolution of water-soluble cementing matter (e.g. kaolinite, calcite or dolomite) between soil particles can change the relative position, contact state, cementation state, pore diameter and particle shape, and is therefore the main reason for changes in the microstructure of soil samples subjected to cyclic wetting-drying [32]. When the sample is immersed in water, water molecules can easily enter the interior of sample through pores and cracks, which can increase the interlayer spacing and the thickness of the hydrated film. Moreover, the particle expansion and the dissolution of cementing matter cause relative displacement of particles, and a new stable structure is gradually formed based on the destroyed original microstructure. During the drying process, the water content of the soil gradually decreases, and the skeleton shrinkage...
disturbs the soil structure again. On the one hand, some small pores and mesopores are connected to form macropores due to the dissolution of cementing matters. On the other hand, because of the expansion and deepening of small pores in the progress of drying shrinkage, the number of mesopores and macropores between soil particles generally increases [33]. In short, under the action of cyclic wetting-drying, the cementing matter of the sample is dissolved, the structure of the soil is continuously destroyed and the increase in porosity between particles causes the SWCC of the sample to gradually move downward.

(ii) Microscopic mechanism

Fig. 9 shows the microscopic morphology of the DCM samples with an initial water content of 14% under different numbers of wetting-drying cycles. It can be seen that the soil particles showed a flocculent structure. However, as the number of cycles increased, the cementing matter between particles was gradually eroded. Thus, the outline of particles in the sample became clearer.

The area ratios of pores in the samples with different numbers of wetting-drying cycles are shown in Fig. 10. As the number of cycles increased, the area ratio of micropores, mesopores and small pores decreased gradually, while that of macropores continued increasing. These results further confirm that cyclic wetting-drying can cause the cementing matter between particles to erode, which leads to pore connection or expansion. They also explain why the samples with more cycles had a lower water-holding capacity.

4. SWCC modelling of DCM

4.1 SWCC fitting

After a careful comparative analysis, three frequently used models – the Fredlund and Xing model [34], the Gardner model [35] and the Van Genuchten model [36] – were selected to fit the SWCC data of the DCM samples. Typical expressions of the three models are as follows:

Fredlund and Xing model:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{\ln\left[\exp(1) + (s/a)^b\right]^c}$$

(1)

Gardner model:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{1 + as^b}$$

(2)

Van Genuchten model:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{1 + (s/a)^b}^{(1-1/b)}$$

(3)

where $\theta_s$ is the saturated volumetric water content (%), $\theta_r$ is the residual volumetric water content (%), and $a$, $b$, $c$ are fitting parameters.

Four fitting examples are illustrated in Fig. 11. The figure shows that these three models fitted the SWCC data of the DCM well, with the coefficients of determination higher than 94%. However, the goodness-of-fit of the Van Genuchten model was
relatively poor at a high $s$. Under the same $s$, the volumetric water content estimated by the Van Genuchten model was high. The fitting parameters of the models are summarized in Tables 2 and 3. In accordance with the existing literature [34], under the Fredlund and Xing model, $a$ refers to the suction value corresponding to the suction at the curved point of the SWCC and slightly larger than the air-entry value, $b$ is the parameter related to the slope of the curved point of the SWCC and $c$ is the fitting parameter related to the residual degree of saturation. However, the fitting parameters of the Fredlund and Xing model did not match the above physical meanings. Therefore, the Gardner model appears to have been the best for predicting the SWCC of the DCM samples.

### 4.2 SWCC of DCM considering initial water content and cyclic wetting-drying

As mentioned above, the Gardner model was best able to fit the SWCC of DCM. Table 2 shows that for the Gardner model, $a$ increased as the initial water content increased, and $b$ decreased as the initial water content increased. The relationships between the two parameters ($a$ and $b$) and the initial water content are can be expressed by two linear equations, as shown in Fig. 12. The SWCC model considering the influence of initial water content can be obtained by substituting the linear
Fig. 11. Four fitting examples for samples without cyclic wetting-drying: (a) initial water content of 6%; (b) initial water content of 10%; (c) initial water content of 14%; (d) initial water content of 18%

<table>
<thead>
<tr>
<th>Fitting model</th>
<th>Initial water content (%)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>R² (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fredlund and Xing</td>
<td>6</td>
<td>4.04 × 10^{-6}</td>
<td>0.40</td>
<td>289.22</td>
<td>99.03</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3.58 × 10^{-7}</td>
<td>0.31</td>
<td>270.30</td>
<td>98.43</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>4.48 × 10^{-9}</td>
<td>0.25</td>
<td>325.89</td>
<td>95.65</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>2.60 × 10^{-9}</td>
<td>0.25</td>
<td>327.75</td>
<td>97.83</td>
</tr>
<tr>
<td>Gardner</td>
<td>6</td>
<td>0.15</td>
<td>0.68</td>
<td>—</td>
<td>98.39</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.33</td>
<td>0.60</td>
<td>—</td>
<td>98.36</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>0.49</td>
<td>0.46</td>
<td>—</td>
<td>95.25</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>0.55</td>
<td>0.43</td>
<td>—</td>
<td>97.41</td>
</tr>
<tr>
<td>Van Genuchten</td>
<td>6</td>
<td>3.67</td>
<td>1.47</td>
<td>—</td>
<td>97.54</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.80</td>
<td>1.45</td>
<td>—</td>
<td>98.18</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>0.64</td>
<td>1.30</td>
<td>—</td>
<td>94.42</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>0.66</td>
<td>1.34</td>
<td>—</td>
<td>96.90</td>
</tr>
</tbody>
</table>

where $\theta_0$ is initial water content (%), $d = 0.034$, $e = -0.028$, $f = -0.022$ and $h = 0.81$.

As shown in Table 3, the a and b values of the Gardner model did not change significantly with
Table 3. Fitting parameters of the models for samples with an initial water content of 14%

<table>
<thead>
<tr>
<th>Fitting model</th>
<th>Number of cycles</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>( R^2 (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fredlund and Xing</td>
<td>0</td>
<td>2.02 × 10^{-9}</td>
<td>0.25</td>
<td>328.00</td>
<td>98.39</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.30 × 10^{-10}</td>
<td>0.22</td>
<td>334.59</td>
<td>97.08</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7.48 × 10^{-9}</td>
<td>0.24</td>
<td>326.84</td>
<td>97.19</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>5.99 × 10^{-9}</td>
<td>0.24</td>
<td>328.98</td>
<td>97.37</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>4.37 × 10^{-9}</td>
<td>0.24</td>
<td>329.23</td>
<td>98.01</td>
</tr>
<tr>
<td>Gardner</td>
<td>0</td>
<td>0.60</td>
<td>0.48</td>
<td>—</td>
<td>98.06</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.64</td>
<td>0.41</td>
<td>—</td>
<td>96.85</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.61</td>
<td>0.43</td>
<td>—</td>
<td>96.86</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.62</td>
<td>0.44</td>
<td>—</td>
<td>97.96</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.60</td>
<td>0.45</td>
<td>—</td>
<td>97.65</td>
</tr>
<tr>
<td>Van Genuchten</td>
<td>0</td>
<td>0.65</td>
<td>1.37</td>
<td>—</td>
<td>97.73</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.42</td>
<td>1.30</td>
<td>—</td>
<td>96.40</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.51</td>
<td>1.32</td>
<td>—</td>
<td>96.38</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.52</td>
<td>1.33</td>
<td>—</td>
<td>96.55</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.57</td>
<td>1.34</td>
<td>—</td>
<td>97.22</td>
</tr>
</tbody>
</table>

Fig. 12. Relationships between parameters \( a \) and \( b \) in the Gardner model and initial water content

...the number of wetting-drying cycles. Therefore, both \( a \) and \( b \) can be considered constant. On this basis, the SWCC model considering cyclic wetting-drying is expressed by:

\[
\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{1 + as^b}
\]  

(5)

where \( a = 0.614 \) and \( b = 0.442 \) (these are average values calculated from the fitting data listed in Table 3).

Since \( a \) and \( b \) are constants in Equation (5), the influence of the number of wetting-drying cycles does not seem to be considered by Equation (5). However, because \( \theta_s \) and \( \theta_r \) are related to the number of cycles, further analysis is necessary when using Equation (5) in practical applications.

5. Conclusions

(i) The \( \theta \) of the DCM first decreases rapidly and then becomes stable as \( s \) increases. When \( s \) is less than 70 kPa, the SWCC of the DCM is between that of sand and silt; when \( s \) is greater than 70 kPa, the SWCC of the DCM is between that of silt and clay. The large-pore content of the DCM is between that of sand and silt, and the small-pore content is between that of silt and clay.

(ii) The initial water content can affect the SWCC by altering the pore structure of the DCM. DCM with a low initial water content has low internal cementation, large pores, and less water absorbed by the strong adsorption zone. For a given number of wetting-drying cycles, the higher the initial water content, the higher the stabilized \( \theta \).

(iii) Under cyclic wetting-drying, the cementing matter of the DCM is dissolved, the structure of the soil is continuously destroyed, and the increase in porosity between particles weakens the strength of the soil. At a given \( s \) value, \( \theta \) decreases as the number of wetting-drying cycles increases, which shows that cyclic wetting-drying reduces the water-holding capacity of the DCM.

(iv) Of the Fredlund and Xing, Gardner, and Van Genuchten models, the Gardner model is the best SWCC model for DCM. Based on the Gardner model, two SWCC models have been developed for DCM considering initial water content and cyclic wetting-drying, respectively.

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Conflict of interest statement. None declared.

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