Experimental study of moisture evaporation process with different soil characteristics

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ABSTRACT

Evaporation of water from soils induces soil cracking, salinization and degradation, especially in arid irrigated areas. The factors that influence water evaporation from soil includes external type, referring to atmospheric conditions and interior type, covering surficial soil characteristics and water content conditions. In spite of the numerous assessment that have been made on the influence of atmospheric conditions and soil characteristics on evaporation of moisture from soils, many aspects still require further investigation due to soil complexity. In this study, laboratory-based evaporation tests were performed on clayey soil and three kinds of quartzite sands of different particle sizes using the same environmental conditions. Three different tests were performed on slurry samples to evaluate the effects of soil characteristics on its free water evaporation process at room temperature (20-22°C) and relative humidity (50 ± 2%) conditions: soil thickness, particle size of mixing sand and mixing sands ratio. It is shown that larger soil sample thicknesses accelerate water evaporation rate and extend the constant evaporation rate stage. Higher sand mix proportions lead to larger evaporation area and soil porosity, allowing higher evaporation rate and longer duration of the first stage and the starting of the falling rate stage at lower water content. However, soil particle size was not found to have a significant impact on evaporation rate on per unit weight of added soil basis.

Keywords: evaporation, soil texture, soil drying, soil desiccations, evaporation rate, soil grain size

1 INTRODUCTION

Soil-atmosphere interactions affect soil physical, hydraulic and engineering characteristics significantly, especially in arid and semiarid areas (Cui et al., 2005; Cui and Zornberg, 2008; Saito et al., 2006). Due to the drought, evaporation leads to soil cracking, salinization, degradation and other geotechnical problems. (Shimojima et al., 1996; Corti et al., 2011; Tang et al., 2011a; Baram et al., 2013).

Abundant research work has been implemented to study the evaporation process and the corresponding soil response (Fisher et al., 1923; Wilson et al., 1994, 1997; Shimojima et al., 1996; Diaz et al., 2005; Tang et al., 2011a; Song et al., 2014). It has been stated that both exterior factors (e.g. atmospheric conditions) and interior factors (e.g. soil characteristics), influence the evaporation process (An et al., 2018; Tang et al., 2011b). Generally, the exterior factors refer to atmospheric conditions, such as solar radiation, wind speed, vapor pressure, air relative humidity and temperature. The interior factors are physical and chemical soil parameters, among which are soil permeability, composition, particle size, salinity and thickness, etc. To author’s knowledge, much research has been performed on the effects of atmospheric conditions on evaporation (An et al., 2017; Davarzani et al., 2014; Song et al., 2014; Wilson et al., 1994). However, the effect of soil nature on the evaporation process still requires further investigation due to soil complexity, in spite of the numerous assessment that have been made in terms of the influence of soil characteristics on evaporation (Diaz et al., 2005; Shahraeeni et al., 2012; Yuan et al., 2009).

With respect to mineralogical and textural composition, micro-stress state and moisture distribution, further understanding of the effects of their combinations on evaporation is still necessary. Therefore, three evaporation tests with clayey soil and quartzite sands in three types of different particle sizes under the same environmental conditions were conducted in this study, aiming to evaluate the effect of soil characteristics (soil thickness, particle size of mixing sand, and mixing sands ratio) on evaporation.
2 MATERIALS AND METHODS

2.1 Materials

The clayey soil collected from Nanjing Pukou area, China, was used in this study. After air drying, soil was crushed into powder and passed through the 2 mm sieve. Its physical and mechanical characteristics are presented in Table 1.

Table 1. The physical and mechanical properties of clayey soil

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Value</th>
<th>Soil properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.71</td>
<td>Maximum dry density (Mg/m³)</td>
<td>1.69</td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>76.2</td>
<td>Sand ratio (%)</td>
<td>24</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>29.1</td>
<td>Silt ratio (%)</td>
<td>34</td>
</tr>
<tr>
<td>USCS classification</td>
<td>CH</td>
<td>Clay ratio (%)</td>
<td>42</td>
</tr>
<tr>
<td>Optimum moisture content (%)</td>
<td>18.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2 Samples and methods

Clayey soil samples were prepared and combined with quartzite sand in three particle size ranges: 0.2-0.5 mm, 0.5-1.0 mm, and 2.0-3.0 mm.

Slurry samples were designed specifically for three tests (Tests 1, 2 and 3). They were placed in evaporation pans with diameter of 150 mm and height of 50 mm (Kondo et al., 1990; Wilson et al., 1997). The bottom of evaporation pan was covered with thin grease to avoid the appearance of crack in soil sample. All samples were left to dry at a stable room temperature of 20-22°C and relative humidity of 50 ± 2% using a controlled air-conditioner.

During the drying process, the weight of each sample was recorded by an electronic balance (accuracy of 0.01g) every two hours, allowing the estimation of actual evaporation rate (Ek). Specifically, the potential evaporation (Ep) was also measured using an evaporation pan containing pure water (Hw, Rw, and Qw in Table 2).

Test 1 was designed to evaluate the effects of soil thickness on soil moisture evaporation, four sets of soil slurry samples with different values of soil thicknesses: 7 mm (H1), 14 mm (H2), 21 mm (H3) and 28 mm (H4) were prepared (Table 2).

In Test 2, six sets of slurry samples were prepared to investigate the effects of sand mix proportion on soil evaporation. They are the mixture of clayey soil and quartzite sands in diameters ranging from 0.2 to 0.5 mm within the same thickness of 28 mm. As presented in Table 2, the mix weight proportions of quartzite sands compared with that of clayey soil (dry weight) in these six sets of slurry samples are 0% (R0), 10% (R1), 20% (R2), 30% (R3), 40% (R4), and 50% (R5), respectively.

Test 3 was designed to study the effect of the particle size distribution of mixing sand on evaporation processes. Three sets of slurry samples consist of clayey soil and quartzite sand of different particle sizes were prepared with the same thickness of 28 mm and the same sand mix proportion of 50%. Specifically, the particle size of the sand used ranges from 0.2 to 0.5 mm in Set Q1, from 0.5 to 1 mm in Set Q2; and from 2 to 3 mm in Set Q3 (Table 2).

For each set of soil tests, samples were tested concurrently and in parallel to subject them to the same environmental conditions and processes so that experimental errors could be minimized.

Table 2. The information of different sets of slurry samples

<table>
<thead>
<tr>
<th>Sets</th>
<th>Materials</th>
<th>Thickness (mm)</th>
<th>Particle size of mixing sand (mm)</th>
<th>Mixing sand (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hw/Rw/Qw</td>
<td>Pure water</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H1</td>
<td>Clayey soil</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>Clayey soil</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H3</td>
<td>Clayey soil</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H4/R0</td>
<td>Clayey soil</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>Mixed clayey soil</td>
<td>28</td>
<td>0.2-0.5</td>
<td>10</td>
</tr>
<tr>
<td>R2</td>
<td>Mixed clayey soil</td>
<td>28</td>
<td>0.2-0.5</td>
<td>20</td>
</tr>
<tr>
<td>R3</td>
<td>Mixed clayey soil</td>
<td>28</td>
<td>0.2-0.5</td>
<td>30</td>
</tr>
<tr>
<td>R4</td>
<td>Mixed clayey soil</td>
<td>28</td>
<td>0.2-0.5</td>
<td>40</td>
</tr>
<tr>
<td>R5/Q1</td>
<td>Mixed clayey soil</td>
<td>28</td>
<td>0.2-0.5</td>
<td>50</td>
</tr>
<tr>
<td>Q2</td>
<td>Mixed clayey soil</td>
<td>28</td>
<td>0.5-1.0</td>
<td>50</td>
</tr>
<tr>
<td>Q3</td>
<td>Mixed clayey soil</td>
<td>28</td>
<td>2.0-3.0</td>
<td>50</td>
</tr>
</tbody>
</table>

3 RESULTS

Due to the slight instabilities in room temperature (20-22 °C) and relative humidity (50 ± 2%) during testing, the ratio of actual to potential evaporation rate (Ea/Ep) is calculated and used to assess the significance of fluctuations in ambient conditions during the evaporation tests so that the influence of varying ambient conditions can be neglected.

3.1 Evaporation results of soil samples with different soil layer thicknesses

The variations of the ratio of actual and potential evaporation rate (Ea/Ep) versus time for four sets of soil samples with different thicknesses in Test 1 are presented in Fig.1. Generally, the evaporation process
includes three stages (Hillel, 1980; Wilson et al., 1994; Tang et al. 2010, 2011a): I constant rate stage, II falling rate stage, and III residual stage. It is observed that Sets H1, H2, H3 and H4 keep 2.13 (t1), 5.19 (t2), 7.61 (t3), 8.43 (t4) days, respectively for the constant rate stage. In addition, the ratios of $E_a/E_p$ of Sets H1, H2, H3 and H4 are 0.8, 0.85, 0.9 and 1.0 during the constant rate stage. The falling rate stage of these four sets of samples presents the similar pattern of evaporation rate decreasing as time. Finally, the residual stage of moisture evaporation was reached with a significantly diminished evaporation rate. In this test, Set H4 with the highest soil thickness of 28 mm, has the highest value of $E_a/E_p$ and the longest duration of the constant evaporation rate stage among the four studied sets.

Fig. 1b presents the water content of Set H1 with thinner soil samples, decreases more rapidly than others in the periods of their individual constant rate evaporation stages. The water contents of the four sets of soils reach the same residual value of about 6.5% when they reached the stable states.

Fig. 1c represents the variations of $E_a/E_p$ versus water content of the four sets soil in Test 1, which includes two main phases: the first and second phases which represent the variations of water content during the constant rate and falling rate evaporation stages, respectively. Because of the low value of residual evaporation rate, the water content corresponding to the residual evaporation stage varies but not significantly. Specifically, $a_1$, $a_2$, $a_3$ and $a_4$ are used to represent the water content values of Sets H1, H2, H3 and H4 at the moments (t1, t2, t3 and t4) when the falling rate stage of evaporation starts. The values of $a_1$ (H1), $a_2$ (H2) and $a_3$ (H3) are about 39.59%, 31% and 27.48%, respectively. It means that the water content levels at which the falling rate stage starts to decrease as soil thickness increases. In particular, $a_4$ is 32.52%, higher than that of samples H2 and H3. It is inferred herein, that the surface water content of soil sample H4 reaches a level that allows evaporation to shift to the falling rate stage while the soil in the deeper segment in the pan still holds relatively high water content. Overall, it can be concluded that thinner soil samples start the falling rate stage with higher water content than those of thicker soil samples.

3.2 Evaporation results of soil samples with different sand mix proportions

In Fig. 2a, it is observed that the duration of the first constant rate stage in Sets R0, R1, R2, R3, R4 and R5 are about 3.92 (t0), 4.16 (t1), 4.96 (t2), 4.29 (t3), 4.76 (t4), and 5.16 (t5) days, respectively. The ratios $E_a/E_p$ of Sets R0, R1, R2, R3, R4 and R5 keep the values of about 0.98, 1.13, 1.17, 1.21, 1.26 and 1.34 steadily during the constant rate stage. It is noticed that Set R5 holds the highest evaporation rate and longest duration of the constant rate stage among the six studied sets, reflecting the role of sand in the clayey soil in the improvement of moisture evaporation rate by 36.7%.

![Fig. 1](image-url)
residual water contents of Sets 6.5% (R0), 7.5% (R1), 6.9% (R2), 6.9% (R3), 6.0% (R4) and 5.6% (R5), respectively. It infers that the residual water content decreases with the increase of sand proportion in a sample.

Similar to the case of soil samples with different thicknesses (Fig. 1c), two phases can also be identified in Fig. 2c: the first and second phases. Similar as Test 1 (Fig. 1), the water content of sample Sets R0, R1, R2, R3, R4 and R5 at the starting moment of the second phase are then determined: 32.52% ($a_0$), 21.87% ($a_1$), 20.65% ($a_2$), 20.45% ($a_3$), 20.26% ($a_4$) and 18.34% ($a_5$), respectively. It is observed that soil samples with lower sand content generally start the second stage with higher water content.

### 3.3 Evaporation results of soil samples with different particle sizes of mixing sand

Fig. 3a shows the variations of $E_a/E_p$ versus time for soil samples with mixed sand of different grain size distributions in Test 3. In the constant rate stage, Sets Q1, Q2 and Q3 exhibit $E_a/E_p$ around the magnitude of 1. However, Set Q2 extends slightly longer of constant rate stage than others.

The variations of water content of Sets Q1, Q2 and Q3 are shown in Fig. 3b, presenting the similar curves with minor differences. Set Q1 samples hold the highest residual water content, because they comprise sand of the smallest grain size range (0.2 to 0.5 mm) when compared to the other two groups. It is thus inferred that smaller pores of this sample generated higher meniscus forces, so that more water is held to against evaporation relevant forces imposed by gradients of temperature and relative humidity.

Similar to the case of Test 1, two phases can also be identified in Fig. 3c. Three sets have similar value of $E_a/E_p$ in the first phase of drying. Afterwards, in the second phase, evaporation ratios $E_a/E_p$ decrease significantly with decreasing water content during the falling rate stage. Specifically, the water contents held by Sets Q1, Q2, and Q3 are about 18.35% ($a_1$), 17.29% ($a_2$), and 17.07% ($a_3$), respectively. Overall, it indicates that the particle size of the sand fraction of soil affects water evaporation but not significantly.

### 4 DISCUSSION

Based on the experimental results obtained in this research, the three stages of evaporation are further discussed as followed. The value of evaporation rate in the first stage is not only affected by atmosphere conditions, but also by soil surface characteristics as well. In Test 1, soil samples with different thicknesses correspond to different soil surface conditions. For the thicker samples among four sets of soil samples, the annular space above the samples is short, so that the moisture was transferred in vapor phase much more

![Diagram](image_url)

Fig. 2. For six sets of samples R0, R1, R2, R3, R4 and R5 with different mixing sand ratio in Test2, variations of (a) the ratio of actual and potential evaporation ($E_a/E_p$) versus time; (b) water content with time; and (c) the ratio of actual and potential evaporation ($E_a/E_p$) versus water content.

Water contents of the six sets are approximately the same (60%) at the beginning of tests (Fig. 2b). Due to the high evaporation rates in the constant rate stage, the water content of Set R5 (50% sand) samples decreases more quickly than others. After a short falling rate stage, all samples reach the residual stage, keeping the
samples. In addition, it is observed that Set R5 with the highest sand mix proportion in Test 2, shows both the largest values of evaporation rate and the longest durations of the first stage (Fig. 2a). Mixing sand into soil samples increases the roughness of sample surfaces as well as the actual evaporation area, allowing more water to evaporate within a given time period. As a result, the actual evaporation rate increases when more sand is added in a soil sample. The three soil samples with different particle sizes of admixed sand in Test 3 exhibit similar evaporation rates in the first stage of evaporation, reflecting that grain size distribution has negligible effects on soil surface conditions and the actual evaporation rate of the first stage.

In the second stage of evaporation, the starting value of evaporation rate is controlled by its intensity during its first stage, and the ending value is determined by the soil water holding capacity in the third stage. As stated by Bittelli et al. (2008), evaporation during the second stage is limited by soil hydraulic properties that determine the transfer of liquid and vaporized water to the surface at which evaporation occurs. Specifically, the results of Test 2 present that the incorporated sand changes soil texture, thus improving soil permeability and higher evaporation decreasing rate. The differences observed among the designed soil samples in Tests 1 and 3 are not obvious.

In the third stage of evaporation, the evaporation rate of water from each soil sample approaches zero while the residual water content varies, depending on soil characteristics. The residual water content is related intimately with soil water-holding capacity which is determined by soil texture (Adamu and Aliyu, 2012; Easton and Bock, 2016). Four soil sets in Test 1 have the same soil texture and thus, holding the similar residual water content. With higher sand mix proportion in Test 2, soil water holding capacity is lower, leading to the lower residual water content. Only minor differences can be observed in three soil samples with different sand grain size fractions in Test 3.

5 CONCLUSIONS

Through three different evaporation tests, the effects of interior factors including soil thickness, mixing sand ratio, and the particle size of mixing sand on the evaporation process are studied respectively. Complete evaporation of water from a soil surface occurs normally in three stages: constant rate stage, falling rate stage, and residual stage. As soil thickness increases, evaporation rate and the duration of the first stage of evaporation both increase. Higher sand mix proportions lead to larger evaporation area and soil porosity, allowing higher evaporation rate and longer duration of the first stage. Moreover, residual water content of soil with higher mixing sand ratio is lower because of its lower water holding capability. The grain size of mixed sand is observed to influence the evaporation process,
Evaporation continues at a stable rate which is influenced by both atmospheric conditions and soil surface characteristics for the first stage. The duration of the first stage is governed by both the initial evaporation rate and the water content of the soil sample. However, the duration of the second stage is mainly decided by soil permeability. In the last stage of evaporation, evaporation rate approaches to zero while the residual water content of soil sample may differ depending on soil texture.

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