Influencing factors of geometrical structure of surface shrinkage cracks in clayey soils

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ABSTRACT

In order to investigate the effects of temperature, thickness of soil layer, wetting and drying cycles and soil types on geometrical structure of surface shrinkage cracks in clayey soils, special software Crack Image Analysis System (CIAS) for analyzing shrinkage crack patterns was developed. Eight groups of soil samples were prepared and subjected to drying to crack in laboratory. The number of crack segments and intersections, average crack length, width and aggregate area, crack intensity factor (CIF), and the corresponding probability density functions (PDF) of these parameters were determined by analyzing several crack patterns derived from different experimental conditions. The results show that the soil cracking behavior and the geometrical structure of crack patterns are significantly influenced by these considered factors. There is a tendency of crack length, width, aggregate area and their most probable value (MPV) related to the PDF increases with temperature increase. With thicker soil layers, the average crack length, width, aggregate area and CIF are increased, and the main distribution ranges of crack length, width and aggregate area are increased also. When the soil is subjected to multiple wetting–drying cycles, the soil surface generates more irregular and coarse cracks. The number of short and narrow crack segments increases significantly, and the CIF decreases with an increase in wetting–drying cycles. It is also observed that the extent of cracking is directly related to the soil fines fraction and its plasticity index ($I_p$). The greatest CIF and crack width are observed in the soils with the largest fines fraction and highest $I_p$. In addition, the ratio of numbers of crack segments to intersections ranges from 1.5 to 2, and cracking mainly takes place in three stages: main-cracks initiation stage; sub-cracks initiation stage; terminal stable stage.

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1. Introduction

It is a natural phenomenon that surface cracks develop in clayey soils as they shrink when dried. These cracks create weakness zones in a soil mass causing reduction in the overall mechanical strength and increase in the compressibility. Thus, engineering properties, stabilities of buildings and structures that are constructed on clayey soils would be affected by changes in mechanical properties. Moreover, the formation of cracks often results in failure of slope. Hydraulic properties of clayey soils are controlled to a large extent by the geometries of their crack networks. Since the size (width, length and depth) and tortuosity of cracks govern the rate and the velocity at which solutes and microorganisms are transported in the soil profile, the distribution and the connectivity of these cracks determine flow pathway, and thus control dispersal of substances in soil mass. The growth of the crops can be affected by the formed cracks. The clay soil-based structures such as waste containment facilities can be compromised by the formation of shrinkage cracks, the diffusion of pollutant along the cracks may speed up and at a much greater rate than the surrounding matrix. Therefore, it is important to study this problem and a number of works have been done to examine and model the mechanisms involved in soil cracking (Morris et al., 1992; Hull, 1994). Chertkov (2002) proposed and validated a model for analyzing the initial cracking stages of shrinking saturated clay soils. It was found that the crack went through stages of delay, jump, stable growth with approximately constant velocity, and then quickly declined until it stopped. Vogel et al. (2005a,b) studied the crack dynamics in clay soil, presented a model which was based on a lattice of Hookean springs with finite strength and represented linear quasi elastic materials, for crack formation that mimics the physical processes involved. For the purpose of reconstructing the mechanics of inter-row crack formation under bidirectional lateral water flow resulting from water absorption by row-planted crops, Yoshida and Adachi (2004) proposed a model which was based on the Biot's consolidation equation, to estimate the variation in the location of the cracks resulting from changes in spatial and mechanical parameters. Yesiller et al. (2000) conducted tests to investigate desiccation cracking of compacted liner soils subjected to wetting and drying cycles. For compacted clay soils, compaction conditions affect the desiccation behavior (Holtz and Kovacs, 1981; Daniel and Wu, 1993; Albrecht, 1996).

Except for the initiation and mechanic behavior of shrinkage cracks, in most cases, to study the geometrical structure of the existing crack pattern is also significant. Characterizing the cracks pattern is very important for
the evaluation of geotechnical properties of soil–water system. If the real structure (size, connectivity, branching, etc.) can be determined, the soil response to wetting and drying can be predicted (Perrier, 1995; Perrier et al., 1995). Moreover, the quantitative description and measurement of crack pattern can help determine whether different soil management treatments have different effects on soil structure. They can be used together with bulk density, to calculate the volume change of the soil during drying (Ringrose-Voase and Sanidad, 1996). Other examples of crack measurement may be important as assessment of the damage to roots of crops by cracks and the preferential flow of water and pollutant down cracks into the subsoil (Wopereis et al., 1994), Zein el Aedeline and Robinson (1971) and Inoue (1993) used the number of intercepts between a transect and crack to estimate the length of cracks. Kleppe and Olsom (1985) developed a scale that ranged from 0 to 4 to describe severity of cracking. A crack severity number of 0 indicated absence of cracking, whereas, cracks with width > 20 mm and with substantial depths were described by a crack severity number of 4. An alternative is to use lengths of string to measure crack length within one square meter (Dasog and Shashidhara, 1993). Based on the intercept method, Ringrose-Voase and Sanidad (1996) described an improved method which required only simple, readily available equipment. It was a transect consisting of six linked semi-circles (1 m diameter each) which ensured that measurements were unbiased and of maximum efficiency. Mi (1995) and Miller et al. (1996) introduced the crack intensity factor (CIF) as a descriptor of the extent of surface cracking. CIF was defined as the ratio of cracks area to the total surface area of a drying soil mass. But in situ measurement, because of the irregular shape and complex geometry of cracks, it is not easy to obtain exact geometrical parameters of crack pattern. In addition, the original crack pattern is often disturbed by human activities and equipments, which results in large measurement errors. In recent years, computer aided image analysis programs were used to determine the geometrical characteristics of crack network (Miller et al., 1998; Velde, 1999; Yesiller et al., 2000; Yan et al., 2002; Vogel et al., 2005a,b). For a two-dimensional crack pattern, the area, width, length, CIF, number of intersections and angle of crack can be calculated and measured accurately by programs. To date, although a large number of methods for measuring surface cracks have been used, many significant results were obtained in this field. It was still not enough to understand the cracking behavior completely. The soils are highly complex, and conditioned by a large number of variables (temperature, thickness of soil layer, etc.), which greatly affect the formation and propagation of shrinkage cracks. However, it is usually ignored and little study emphasizes on dealing with effects of different environment variables on the geometrical structure of shrinkage cracks. Tang et al. (2007) indicated that the morphology of crack network was influenced by several factors, but only some simple data were shown. Therefore, refined and systematic research approach should be adopted to better understand the desiccation cracking behaviour.

In this paper, a quantitative description of cracks at the soil surface is proposed, which is realized by applying the software Crack Image Analysis System (CIAS) specially developed for this purpose. The factors affecting the surface crack structure in local clayey soils, including temperature, thickness of soil layer, wetting and drying cycles and soil types, are investigated. The geometric parameters, such as number of intersections and crack segments, average crack length, width and aggregate area and CIF are determined. By introducing the statistical approach, the distribution characteristics of crack length, width and aggregate area are analyzed through probability density functions.

### 2. Experiments

In order to produce crack patterns in laboratory, saturated slurry were prepared with 90% water content by using local clayey soils. The slurry was put into glass plates with a size of 16 × 16 cm, these glass plates were then placed in a dry-oven. A digital camera was installed to record the surface condition during desiccation at varying time intervals. At the beginning of drying, images of the soil surface were recorded at long intervals (about 30 min). At the end of drying, short intervals (10 min) were adopted to take images of crack pattern. The desiccation ended when the weight of samples was stabilized, namely the dehydration process was completed. In this investigation, four affecting factors were considered, including temperature, thickness of soil layer, wetting and drying cycles and soil types respectively. To study the temperature effect, 30, 40 and 50 °C were taken into account in this experiment; to study the effect of the thickness of soil layer, three variants, namely 5, 8 and 11 mm, were considered; to study the factor of wetting and drying cycles, initially, three samples were prepared with saturated slurry (90% water content) and then oven-dried, this is the first wet–dry cycle. Then, the second wetting cycle was started by adding water immediately into the glass plates, and allowed the soil and water to equilibrate for 48 h. In this process, sufficient water was provided to ensure full saturation of the soil. The glass plates were wrapped with plastic membrane to prevent evaporation of moisture. When the wetting cycle was completed, the soil was oven-dried again. The third wetting and drying cycle was similar to the second one; to study the soil type factor, three local (Nanjing area) clayey soils were used to investigate and compare the cracking behavior. The physical properties of the soils are listed in Table 1. Eight groups of experimental tests were carried out, and three samples were prepared using the same experimental methods and the same conditions for each test program. The details of experimental conditions and parameters are indicated in Table 2. The final typical crack pattern obtained after complete desiccation is shown in Fig. 1. In this figure, only the central part of 12 × 12 cm is shown. This part was almost free of boundary effects and was used for further analysis.

### 3. Image processing

To analyze the structure of crack pattern, techniques of digital image processing are often used. The procedure of digital image processing is shown in Fig. 2. Firstly, the color photograph of the crack pattern was changed to a grey level image (Fig. 2(a)); secondly, the contrast in grey level between cracks and aggregates was sufficiently

### Table 1

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Soil 1</th>
<th>Soil 2</th>
<th>Soil 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>2.73</td>
<td>2.70</td>
<td>2.62</td>
</tr>
<tr>
<td>Consistency limit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid limit</td>
<td>36.7%</td>
<td>34.5%</td>
<td>52.6%</td>
</tr>
<tr>
<td>Plastic limit</td>
<td>18.9%</td>
<td>22.7%</td>
<td>32.9%</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>17.8</td>
<td>11.8</td>
<td>19.7</td>
</tr>
<tr>
<td>USUC classification</td>
<td>CL</td>
<td>CL</td>
<td>CL</td>
</tr>
<tr>
<td>Compaction study</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimum moisture content</td>
<td>16.0%</td>
<td>16.5%</td>
<td>16.3%</td>
</tr>
<tr>
<td>Maximum dry density</td>
<td>1.71g/cm³</td>
<td>1.70g/cm³</td>
<td>1.75g/cm³</td>
</tr>
<tr>
<td>Grain size analysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>2%</td>
<td>4%</td>
<td>2%</td>
</tr>
<tr>
<td>Silt</td>
<td>76%</td>
<td>67%</td>
<td>48%</td>
</tr>
<tr>
<td>Clay</td>
<td>22%</td>
<td>29%</td>
<td>50%</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Temperature (°C)</th>
<th>Thickness of soil layer (mm)</th>
<th>Wetting and drying cycle (times)</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>5</td>
<td>One cycle</td>
<td>Soil 1</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>5</td>
<td>One cycle</td>
<td>Soil 1</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>5</td>
<td>One cycle</td>
<td>Soil 1</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>8</td>
<td>One cycle</td>
<td>Soil 1</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>11</td>
<td>One cycle</td>
<td>Soil 1</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>5</td>
<td>Three cycles</td>
<td>Soil 1</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>5</td>
<td>One cycle</td>
<td>Soil 2</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>5</td>
<td>One cycle</td>
<td>Soil 3</td>
</tr>
</tbody>
</table>

high, so that the grey level image could be segmented into cracks and aggregates using a simple grey threshold. This process was called binarisation, resulting in binary black and white image (Fig. 2(b)). It can be seen that the black areas represent the crack networks, and the white areas represent the aggregates; Finally, in order to determine the crack intersections and lengths, schematized structure of crack network was created by skeletonising (Fig. 2(c)) (Gonzalez and Woods, 2002), the method of medial axis transformation (MAT) proposed by Blum (1967) was applied for this operation. Namely, the middle line of crack segment was extracted as the skeleton of crack network. All these processes can be operated automatically and conveniently in the software CIAS.

Sometimes, lighting angle and the resultant shadow effects from small surface irregularities on sample image result in unwanted dark spots, which do not represent crack elements as shown in the square cutout of Fig. 3(a). Moreover, some cracks were so wide that the light can reach the glass plate directly, forming some exposed zones. These zones changed to unwanted white spots after the binarisation of image. It can be seen from the circular cutout of Fig. 3(a) that these white spots do not represent the real aggregates. To avoid the related artefacts, a special tool was developed in the software CIAS. It was realized by setting an area threshold value. If the area of the isolate black and white spots was less than the set threshold value, they were eliminated automatically from the image (Fig. 3(b)).

4. Quantitative analysis

For the purpose of characterizing the geometrical properties of crack pattern, the following quantitative parameters were determined and calculated using the software CIAS: (1) Number of intersections \( I_n \) and crack segments \( S_n \). It can be seen from Fig. 1 that a sequence of segments which intersect other segments, and these segments define the outline of the soil crack pattern. In general, \( I_n \) and \( S_n \) can reflect the cracked degree of soil surface; (2) Average length of cracks \( l_{av} \), and average width of cracks \( w_{av} \). It should be mentioned that the crack length was determined by calculating the distance between intersections after the image was skeletonised, as shown in Fig. 2(c). The crack width was determined by calculating the shortest distance from a randomly chosen point on one boundary to the opposite boundary of crack segment. In this investigation, a total of 15,000 stochastic points were selected from each crack pattern image; (3) Average area of aggregates \( a_{av} \). Aggregate was defined as the independent closed area which is split by cracks, namely the closed white area in Fig. 2(b) and (c); (4) The crack intensity factor (CIF), which is the ratio of the surface area of cracks to the total surface area of a soil. In this study, CIF is used to quantify the amount of cracking in clayey soil; (5) Probability density function (PDF) of crack length \( f(l) \), crack width \( f(w) \) and aggregate area \( f(a) \). The binarised pattern of the crack structures shows that the crack length, width and aggregate size vary in a large range. It is obviously not enough to characterize the crack pattern quantitatively, through calculating the average values of these parameters. Moreover, it is meaningless to measure only 1 or 2 values of these parameters. Statistical method is necessary for characterizing the crack behavior and describing distribution properties of related parameters. Modeling of crack networks based on statistical approach has been considered and validated using available data for the two-dimensional case (Chertkov, 1995) and 3D case (Chertkov and Ravina, 1998; 2004; Chertkov, 2005). Therefore, the probability density function (PDF) is introduced in the present investigation to characterize the surface crack networks. Set the PDF of crack length \( f(l) \) as an example, it is a density of crack length corresponds to value \( l \) and defined as:

\[
f(l) = \frac{\Delta n}{n \cdot \Delta l}
\]

where \( n \) is the total number of crack segments, \( \Delta n \) is the number of crack segments whose length ranges between \( \Delta l \). \( f(l) \Delta l \) gives the
fraction of the crack length ranges between \( l \) and \( l + dl \). Assuming that the crack length \( l \) ranges from \( a \) to \( b \), then
\[
\int_{a}^{b} f(l)dl = \int_{0}^{a} \frac{dn}{n} - \frac{1}{n} \int_{0}^{a} dn = 1. 
\]

This means that the number of crack segments whose value fall into the interval \([a, b]\) equals the total number of crack segments, \( n \). The length related to the maximum value of \( f(l) \) is called most probable value (MPV) of crack length. It means that the probability of crack length distributed near MPV is maximal during cracking. In order to compare results obtained from different experiment conditions, the crack length selected at equally spaced intervals on the length axis and the class width \( \Delta l = 20 \) pixels was chosen as appropriate value in the present investigation. The class width \( \Delta a = 2 \) pixels and \( \Delta a = 5000 \) pixels were chosen for the PDF of \( f(w) \) and \( f(a) \) respectively.

5. Results and discussion

To investigate the affecting factors of soil cracking and quantify the geometrical structure of crack pattern, four factors were considered, six quantitative parameters and three probability density functions were analyzed.

5.1. Effect of temperature on the crack pattern

Three temperatures (30, 40 and 50 °C) were selected. Variations of crack quantitative parameters with temperature and the corresponding standard deviation (SD) are presented in Table 3. Both the number of intersections and crack segments fall down with increasing temperature. For this type of clayey soil, the ratio of \( S_{in}/S_{f} \) value falls between 1.5 and 2, since the crack network was mainly composed of quadrangles and the shapes of crack notes are general “+” and “T”, as shown in Fig. 1. The average length, width of cracks and average area of aggregates increased with increasing temperature. However, some different behaviour were observed from the results obtained by Kerneta et al. (1998) who investigated the crack patterns produced by thermal shock in ceramic tableware. The average aggregate area decreased with increasing temperature. There may be two possibilities: First, ceramic material is relatively homogeneous medium and the cracking behaviour is interpreted by brittle fracture. Crack initiation is mainly due to the rupture of atomic bonds or the breakage of crystal structures. The cracking mechanics is much different with the soft and ductile clayey soil investigated in this manuscript. Second, very high temperature (300–700 °C) was chosen to perform the water quench test in the work of Kerneta et al. (1998), while low temperature (30–50 °C) was chosen in present tests. This high difference of temperature gradient and test method would also result in different cracking behaviour. In addition, it can be seen from Table 3 that the CIF of crack pattern decreases slightly from 14.14 to 12.92% when the temperature changes from 30 to 50 °C.

Fig. 4 shows the PDFs of crack length, width and aggregate area at different temperatures. It can be observed that crack lengths of the three groups of samples at different temperatures mainly distribute in the range of 30 to 130 pixels (Fig. 4(a)). The peak value of \( f(l) \) was observed at crack length of 50, 70 and 110 pixels for the test performed at 30, 40 and 50 °C respectively. It indicates that the probability of initiating long cracks during desiccation increases with temperature. In general, the fraction of short crack segments (\( \leq 100 \) pixels) decreases and long crack segments (\( \geq 100 \) pixels) increases when temperature increases from 30 to 50 °C. In Fig. 4(b), it is shown that the distribution of crack width is not significantly influenced by temperature. The crack widths mainly distribute in the range of 5 to 13 pixels, and the MPV of crack widths keeps the same value (7 pixels) for the three test programs. In Fig. 4(c), the fraction of larger aggregates generally increases with the temperature, and the largest aggregate is obtained in test program at 50 °C.

By analyzing the results shown in Table 3 and Fig. 4, it can be concluded that the surface crack structure is influenced by temperature. As indicated by Morris et al. (1992), cracking in soils undergoing drying is controlled by soil suction as well as soil properties such as compression modulus, Poisson’s ratio, shear strength, tensile strength, and specific surface energy. Clayey soils are more susceptible to the

---

**Table 3**

Average values of crack network parameters and the corresponding standard deviation (SD) for soil samples at different temperature

<table>
<thead>
<tr>
<th>No.</th>
<th>Temperature (°C)</th>
<th>Number of intersections (( l_{in} ))</th>
<th>Number of crack segments (( S_{f} ))</th>
<th>SD of ( l_{in} )</th>
<th>SD of ( S_{f} )</th>
<th>Average length of cracks (( l_{av} ))</th>
<th>Average width of cracks (( w_{av} ))</th>
<th>SD of ( w_{av} )</th>
<th>Average area of aggregates (( a_{av} ))</th>
<th>SD of ( a_{av} )</th>
<th>CIF (%)</th>
<th>SD of CIF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>107</td>
<td>171</td>
<td>2.16</td>
<td>6.38</td>
<td>88.94</td>
<td>9.66</td>
<td>0.20</td>
<td>12321</td>
<td>232.79</td>
<td>14.14</td>
<td>0.17</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>92</td>
<td>148</td>
<td>2.16</td>
<td>4.12</td>
<td>94.44</td>
<td>10.17</td>
<td>0.07</td>
<td>14538</td>
<td>490.96</td>
<td>13.70</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>58</td>
<td>96</td>
<td>2.26</td>
<td>11.27</td>
<td>129.73</td>
<td>10.72</td>
<td>0.30</td>
<td>17233</td>
<td>515.19</td>
<td>12.92</td>
<td>0.11</td>
</tr>
</tbody>
</table>

---

Fig. 3. The elimination of artefacts from image. (a) Image before eliminating the artefacts, and (b) image after eliminating the artefacts.
Fig. 4. Probability density functions of crack parameters at different temperatures. (a) Probability density function of crack length $f(l)$, (b) probability density function of crack width $f(w)$, and (c) probability density function of aggregate area $f(a)$. 
development of desiccation cracks due to the presence of small pores, which allows the development of high suction (negative pore water pressure). For an open soil sample, the evaporation first occurs on the surface layer, and results in initial suction developed in this layer. If the surface tensile stress induced by an increase in soil suction exceeds the bonding strength of grains, cracks occur on soil surface. Kayyal (1995) reported that the rate of increase in the suction potential was directly related to the rate of moisture evaporation, which was controlled by the temperature and relative humidity. When soil samples are drying at higher temperature, higher tensile stress increase rate can be obtained on the surface layer. The desiccation cracking behaviour is therefore strongly connected with temperature. In addition, many other soil properties, which are directly or indirectly related to shrinkage and desiccation cracking behaviour, are also affected by temperature and heat. For example, they would affect each of the main components phases (solid, liquid, gas) separately and also their interaction with each other within the framework of the total system. The soil behavior, such as soil constants, unit weight–moisture relationship, compressibility, modulus and strength, would also be affected by temperature (Fang, 1997). Campanella and Mitchell (1968) emphasized that the role of pore water pressure changed accompanying temperature changed. Their experiment results showed several clay–water systems in which each change in temperature by 1 °F changed the pore water pressure by about 0.75 to 1.0% of the initial effective stress. Volume change and stress distribution of the clay–water system are strongly coupled with the moisture movement induced by heat (Kanno et al., 1996; Sultan et al., 2002). Tang and Cui (2005) reported the results of tests conducted on clay soil with a temperature ranging from 20 to 60 °C. They observed that an increase in temperature decreased the soil water retention capacity. However, due to the complexity of crack initiation and propagation, and there are too many factors related with desiccation cracking behaviour of clayey soils. Although a lot of works have been done on this subject in the last several decades, the changing law of crack parameters with temperature is still difficult to understand at present (Table 3 and Fig. 4). For better understanding this issue, for better understanding this issue, it should take fully coupled thermo-hydro-mechanical behaviors into account, especially the micromechanical interactions between soil and water phases. The present investigation doesn’t provide sufficient data to clarify these assertions in detail, but more works may need to be done in future investigations.

5.2. Effect of thickness on the crack pattern

Three thicknesses (5, 8 and 11 mm) were considered. Table 4 shows the value of crack quantitative parameters with thickness of soil layer. It can be seen that the number of intersections and crack segments decreases with an increase in thickness of soil layer, and the ratio of $S_{sn}/l_{sn}$ value falls between 1.5 and 2 too. However, an increase in thickness of soil layer is accompanied by increases in average length, width of cracks, average area of aggregates and CIF of crack patterns. This behaviour is consistent with the results obtained by Prat et al. (2006) who conducted similar experiments on Barcelon silty clay. Laboratory experimental data reported by Corte and Higashi (1960), Lau (1987), Nahlawi and Kodikara (2006) also showed that the average area of aggregates increased as the layer thickness of the soil increased. In addition, Corte and Higashi (1960) indicated that lower initial soil density or higher adhesion at the base tends to produce lower average aggregates area for a given thickness. Fig. 5 presents the PDFs of three crack parameters of soil samples with different thicknesses. A first look at Fig. 5(a) shows that the distribution range of crack length significantly increases with soil layer thickness. Most of the crack segments are less than 90 pixels for the specimens with 5 mm thickness. Equally, it appears that the distribution of crack width is also significantly affected by the specimen’s thickness as shown in Fig. 5(b). As the thickness of soil layer alters from 5 to 11 mm, the MPVs of crack widths increase from 7 to 25 pixels, and the distribution ranges of crack widths also increase with thickness. Fig. 5(c) shows that some very large aggregates were formed in the specimens with 11 mm thickness, and a trend of the fraction of large aggregate increase with thickness can be observed. Therefore, it can be concluded that the increase of specimen’s thickness would increase the probability of forming longer, wider cracks and bigger aggregates. This cracking behavior, probably due to the increased thickness, increased directly the normal stress of soil layer and the effective stress between particles, which eventually, lead to the changes of stress state during desiccation. As wet or moist cohesive soil system loses water, the soil particles move closer and closer. If the desiccation begins from the surface downward to interior soil mass, the dehydrated surface layer shrinks while the resistances between the upper and bottom layers prevent an adjustment to the volume decrease of the surface layer. Different total thickness of soil layer may correspond to different thickness of upper shrinkage layers during drying. This is because water flow pathways, directions and water loss rate can be affected by the thickness of soil layer, as well as the transfer of thermal energy. Nahlawi and Kodikara (2006) found that soil layers with greater thicknesses showed a slower water loss rate in general and higher water content when cracking. At the on-set of cracking, the difference of corresponding water content between the upper layer and bottom layer was generally higher in the case of thicker soil specimens indicating great difference of water loss rates. In addition, Chertkov and Ravina (1999) indicated the average spacing between cracks $d$ as a function of soil depth $z$, and there is a trend of $d$ that increases with $z$. In fact, the aggregate area strongly depends on the surface crack spacing; larger surface crack spacing corresponds to larger aggregate area. Therefore, the average aggregates area increases with an increase in thickness of soil layer.

5.3. Effect of wetting and drying cycles on the crack pattern

In order to investigate the effect of wetting and drying cycles on geometrical structure of desiccation crack pattern, a group of three soil samples were subject to three wetting–drying cycles, and several quantitative parameters of surficial crack pattern were recorded and calculated. Table 5 shows the values of parameters after each wetting–drying cycle and the corresponding standard deviation (SD). Different tendencies can be observed from Table 5 by comparing with the effects of temperature and thickness of soil layer, the number of intersections and crack segments increase with an increase in wet–dry cycles. Nevertheless the ratio of $S_{sn}/l_{sn}$ value still falls between 1.5 and 2 after each wetting–drying cycle. The average length, width of cracks, average area of aggregates and CIF of crack

### Table 4

<table>
<thead>
<tr>
<th>No.</th>
<th>Thickness (mm)</th>
<th>Number of intersections ($l_{sn}$)</th>
<th>$SD$ of $l_{sn}$</th>
<th>Number of crack segments ($S_{sn}$)</th>
<th>$SD$ of $S_{sn}$</th>
<th>Average length of cracks ($l_{av}$)</th>
<th>$SD$ of $l_{av}$</th>
<th>Average width of cracks ($w_{av}$)</th>
<th>$SD$ of $w_{av}$</th>
<th>Average area of aggregates ($a_{av}$)</th>
<th>$SD$ of $a_{av}$</th>
<th>CIF (a)</th>
<th>$SD$ of CIF (a)</th>
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</thead>
<tbody>
<tr>
<td>2</td>
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<td>92</td>
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<td>148</td>
<td>4.12</td>
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<td>10.17</td>
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<td>45152</td>
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</table>

Fig. 5. Probability density functions of crack parameters of soil samples with different thicknesses. (a) Probability density function of crack length $f(l)$, (b) probability density function of crack width $f(w)$, and (c) probability density function of aggregate area $f(a)$. 
patterns all decrease with increasing wetting–drying cycles. However, Yeşiller et al. (2000) observed that the CIF is increased after the first wet–dry cycle. This could be due to the effects of compaction conditions, since compacted soil was used in their investigation, while saturated slurry was adopted here.

The PDFs of crack length, width and aggregate area for soils due to each wetting and drying cycle are presented in Fig. 6. It can be seen that the distribution characteristics of these parameters are significantly influenced by wetting–drying cycles. The MPVs of crack lengths and widths decrease with wetting–drying cycles increasing. In Fig. 6(a), the MPV of crack lengths is 90 pixels after the first wetting–drying cycle, and decreases to about 40 pixels after the third wetting–drying cycle. In Fig. 6(b), the increase of wetting–drying cycles results in an increased fraction of thin cracks (width $<$ 5 mm) and decreased fraction of wide cracks (width $>$ 9 mm). From Fig. 6(c) it can be seen that the probability of small aggregates (area $<$ 7500 pixels) is increased with wetting–drying cycles, but reverse phenomenon is observed for the distribution characteristics of large aggregates (area $>$ 22500 pixels).

By analyzing the results shown in Table 5 and Fig. 6, that the soil surface became more fragmented with the increase of wetting–drying cycles, and short crack segments also increased, as shown in Fig. 7. Cracks appeared at the same locations as the first drying period in the second and third drying cycles, this phenomenon is similar to the observations of Yeşiller et al. (2000). It is mainly because some particle bonds were broken during the former drying cycle to initiate cracks. Upon wetting, the broken bonds may attract water and become preferential weak zones in soil. Subsequent drying will again cause shrinkage and cracking will occur at the weakest locations of the soil structure where it associate with the earlier cracks.

It can also be seen from Fig. 7 that the cracks become more irregular and coarse after undergoing the second and third cycles, and the crack pattern in Fig. 7(b) is similar to that in Fig. 7(c). This may be due to the multiple wetting–drying cycles that resulted in decreasing the extent of the homogeneity of the sample. Yong and Warkentin (1975) indicated that the shrinkage during drying cycle in a clay soil may cause some irreversible fabric changes. Upon subsequent wetting cycle, the soil fabric and structure were impossible to return to the initial state (deposited from homogenous slurry), and the initial relatively homogenous distribution of bond strengths between soil particles was therefore changed. Especially desiccation cracks were initiated after first drying, and these cracks acted as preferential weak zones in soil and greatly weakened the sample integrity. In addition, some pore air was entrapped in soil mass during subsequent wetting cycle (this phenomenon will be discussed later). The existence and moving of these air bubbles in soil mass would also result in weak zones. As a result, surface tensile stresses developed during later drying cycles would concentrate at much more locations (usually at weak zones) by comparing with the first drying cycle, and the heterogeneous stress distribution corresponding to heterogeneous soil texture may significantly influence the desiccation behaviour and result in irregular and coarse crack networks as shown in Fig. 7(b) and (c). Omidi et al. (1996) reported the cracking was still in progress at the end of the second wetting–drying cycle, and found that effects of wetting–drying cycles on desiccation cracking behaviour depend on soil compositions. However, Al Wahab and El-Kedrah (1995) reported the results of tests conducted on compacted clay. They observed that the amount of cracking did not change significantly after three wetting–drying cycles. Therefore, it can be inferred that the effect of wetting–drying cycles on soil desiccation cracking behaviour is not infinite and related to soil properties and initial state. For further understanding on this issue, microstructural investigations should be carried out by using mercury intrusion pore size distribution measurements and scanning electron microscope (SEM). These will be the subject of a subsequent study.

### 5.4. Effect of soil types on the crack pattern

Several crack quantitative parameters of soils 1–3 were obtained at the same experimental conditions. The number of intersections and crack segments in soil 3 are higher than that in soils 1 and 2 (Table 6). It indicates that the surface of soil 3 is more cracked or fragmented. The average crack length in soil 2 is the longest among the three soils, while, comparing with soils 1 and 3, its average crack width is much smaller. It is easy to predict that crack segments in soil 2 are threadlike, and crack segments in soil 3 are podgy. Table 6 also shows that the average aggregate area in soil 3 is smaller than that in soils 1 and 2. In general, the more the number of crack segments or intersections in crack pattern, the smaller the aggregate size. It is observed that CIF in soil 3 is clearly higher than that in soils 1 and 2.

The related PDFs of $f(l), f(w)$ and $f(a)$ of the three soils are presented in Fig. 8. It can be seen from Fig. 8(a) that the MPV of crack lengths for soil 2 is higher than that of soils 1 and 3. Especially for soil 3, more than 70% of the crack lengths range in 30–90 pixels. The EV of crack widths for soil 2 is smaller than that of soils 1 and 3 (Fig. 8(b)). The width of cracks in soil 2 mainly distributes in a narrow range of 3 to 7 pixels, about 60% of the crack widths being around 5 pixels. In Fig. 8(c), it can be observed that the distribution ranges of aggregate areas of soil 1 and 2 are much wider than that of soil 3. Most of the aggregate areas of soil 3 distribute in the range of 2500–7500 pixels. It indicates that the aggregates show somewhat uniform size for soil 3 after drying. In addition, the MPV of aggregate areas for soil 2 is little larger than that of soils 1 and 3. By summarizing the changes of crack parameters with the investigated factors, it has been found that the changes of MPVs of crack length, width and aggregate area are generally consistent with the change of average values of these three parameters.

By referring to the physical properties of the three soils in Table 1, it can be concluded that the average crack width and CIF are related to the fines content (% silt + % clay) or $I_p$. The higher fines content and $I_p$ of soils, the higher CIF and average width of cracks are obtained. It is generally recognized that the CIF can reflect the shrinkage properties of soil. It is obvious that the material with lower fines content shrinks less, such as the lower CIF of crack pattern of soil 2. In the fines–rich material, the volume shrinks at a higher rate and high CIF is obtained in soil 3 (the fines content is 98%). In some cases, the clay content of soil is recognized as the most important factor that affects the shrinkage properties and cracking behavior. However, in this investigation, it is observed that CIF in soil 1 is higher than the CIF in soil 2, although the clay content in soil 1 is lower than that in soil 2.

### Table 5

<table>
<thead>
<tr>
<th>No. Wet–dry cycles</th>
<th>Number of intersections ($I_p$)</th>
<th>SD of $I_p$</th>
<th>Number of crack segments ($S_a$)</th>
<th>SD of $S_a$</th>
<th>Average length of cracks ($l_w$)</th>
<th>SD of $l_w$</th>
<th>Average width of cracks ($w_a$)</th>
<th>SD of $w_a$</th>
<th>Average area of aggregates ($a_{av}$)</th>
<th>SD of $a_{av}$</th>
<th>CIF</th>
<th>SD of CIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 First</td>
<td>90</td>
<td>11.58</td>
<td>152</td>
<td>15.51</td>
<td>91.53</td>
<td>1.20</td>
<td>8.70</td>
<td>0.47</td>
<td>14920</td>
<td>528.77</td>
<td>11.92</td>
<td>0.18</td>
</tr>
<tr>
<td>6 Second</td>
<td>120</td>
<td>10.28</td>
<td>209</td>
<td>84.51</td>
<td>1.86</td>
<td>6.41</td>
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<td>13050</td>
<td>244.80</td>
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<td>0.17</td>
<td></td>
</tr>
<tr>
<td>6 Third</td>
<td>145</td>
<td>3.74</td>
<td>259</td>
<td>3.87</td>
<td>73.60</td>
<td>1.56</td>
<td>5.09</td>
<td>0.17</td>
<td>12787</td>
<td>187.48</td>
<td>9.55</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Fig. 6. Probability density functions of crack parameters in the multiple wet–dry cycles test. (a) Probability density function of crack length \( f(l) \), (b) probability density function of crack width \( f(w) \), and (c) probability density function of aggregate area \( f(a) \).
This result may be attributed to the differences in mineral compositions of soils 1 and 2.

5.5. Visual observations

Visual observations of cracking in the soils indicated that cracking took place in three stages.

(1) Cracking starts at some independent random positions in the soil, and single cracks propagate while growing randomly at their tips (Fig. 9(a) and (b)). Here these single cracks are called main-cracks on crack pattern. When some main-cracks come close to an existing crack, they are attracted towards it, and terminate once they meet it, typically at an angle of about 90° (Fig. 9(b) and (c)). The aggregates split by these main-cracks are called main-aggregates in this stage of crack pattern formation.

(2) When, after main-aggregates formation, if the main-aggregates size is big enough, branch cracks begin at random positions on existing main-cracks. These branch cracks are called sub-cracks, whose initial growth directions are perpendicular to the existing main-cracks, and terminate when they rejoin another existing main-crack perpendicularly (Fig. 9(c), (d) and (e)). During this process, the big main-aggregates are split to small sub-aggregates. In some cases, the sub-aggregate may be split again if the size is still bigger than their critical crackable size.

(3) Although the desiccation is not complete, no new cracks are formed after all aggregates sizes are smaller than critical crackable size. The existing surface cracks just become wider until the desiccation comes to the end. From Fig. 9(e) to the final crack pattern Fig. 9(f), it is observed that nothing was altered except the crack width after desiccation for approximately 300 min. Fig. 9(f) also shows that the main-cracks are usually wider than sub-cracks.

During wetting process, the changes of crack pattern with time are shown in Fig. 10. Once the water was put into the glass plate, immediate collapse of the aggregates was observed and the cracks were filled. At the same time, many air bubbles came out from the aggregates. Maybe it was because the pore air was excluded by water entering. After 1 min of wetting, it can be seen from Fig. 10(b) that most of the original cracks were disappeared while a lot of new mini cracks were formed in the aggregates. This may be due to the swelling of soil particles and the excluding of entrapped air at the beginning of wetting. After 2 min later (Fig. 10(c)), no air bubbles came out again. With the elapse of time, the original cracks were almost fulfilled and the mini new cracks also disappeared completely (Fig. 10(d)). But the sample surface is not as smooth as that formed after sedimentation from initial slurry state, and it seems that there are some suspended clay particles in the low-lying tanks of surface.

6. Conclusions

Four influencing factors (temperature, thickness of soil layer, times of wetting and drying cycle and soil types) of cracking behavior of clayey soils were investigated. The geometrical structure of crack patterns obtained during different desiccation conditions were quantified with six parameters and three probability density functions (PDF): the number of intersections \( l_i \), the number of crack segments \( S_n \), average crack length \( l_{av} \), width \( w_{av} \) and aggregate area \( a_{av} \), CIF, and PDF of crack length \( f(l) \), width \( f(w) \) and aggregate area \( f(a) \), respectively. The following conclusions were derived:

1. The geometrical structure of crack pattern is strongly influenced by temperature, thickness of soil layer and times of wetting and drying.

<table>
<thead>
<tr>
<th>No.</th>
<th>Soil type</th>
<th>Number of intersections (( l_i ))</th>
<th>SD of ( l_i )</th>
<th>Number of crack segments (( S_n ))</th>
<th>SD of ( S_n )</th>
<th>Average length of cracks (( l_{av} ))</th>
<th>SD of ( l_{av} )</th>
<th>Average width of cracks (( w_{av} ))</th>
<th>SD of ( w_{av} )</th>
<th>Average area of aggregates (( a_{av} ))</th>
<th>SD of ( a_{av} )</th>
<th>CIF (%)</th>
<th>SD of CIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Soil 1</td>
<td>92</td>
<td>2.16</td>
<td>148</td>
<td>4.12</td>
<td>94.44</td>
<td>3.14</td>
<td>10.17</td>
<td>0.07</td>
<td>14538</td>
<td>400.96</td>
<td>13.70</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>Soil 2</td>
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<td>10.32</td>
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<td>76.40</td>
<td>3.39</td>
<td>5.59</td>
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</tr>
<tr>
<td>8</td>
<td>Soil 3</td>
<td>258</td>
<td>3.74</td>
<td>384</td>
<td>5.80</td>
<td>63.10</td>
<td>3.58</td>
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<td>6001</td>
<td>180.07</td>
<td>24.24</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Fig. 7. The typical surface shrinkage crack pattern of soil after different times of wetting and drying cycle. (a) After the first wetting and drying cycle, (b) after the second wetting and drying cycle, and (c) after the third wetting and drying cycle.

Table 6. Average values of crack network parameters and the corresponding standard deviation (SD) for soil 1–3.
Fig. 8. Probability density functions of crack parameters of soils 1–3. (a) Probability density function of crack length $f(l)$, (b) probability density function of crack width $f(w)$, and (c) probability density function of aggregate area $f(a)$. 
cycle. On account of the effect of temperature on soil properties and structures, the cracking behavior and mechanisms are also influenced by temperature. There is a tendency for crack length, width, aggregate area and their increase with an increase in temperature. The increase of thickness of soil layer may result in the changes of stress state during desiccation and affects the transfer of water and thermal energy distribution. With an increase in soil layer thickness, the average crack length, width, aggregate area and CIF are enhanced, as well as the main distribution ranges of these parameters. When the soil is subjected to multiple wetting and drying cycles, the soil surface becomes more cracked, cracks become more irregular and coarse, and short and narrow crack segments increase significantly, while the CIF decreases with an increase in wet-dry cycles.

2. For different soils, the extent of cracking is correlated directly to the fines content and \( I_p \). The greatest CIF and crack width are observed in the soils with the greatest amount of fines content and highest \( I_p \). The clay content of soils is an important influencing factor of shrinkage properties and cracking behavior.

3. The shapes of crack notes are generally “+” and “T”. No matter what the desiccation conditions, the ratio of \( S_{\text{crack}}/l_{\text{crack}} \) value mainly falls between 1.5 and 2 for these studied soils.

4. In common, the average crack length and width vary with the average aggregate area of crack pattern of a soil. The bigger the aggregates, the longer and wider the cracks. With varying the investigated factors, the increase or decrease in MPVs of crack length, width and aggregate area are generally consistent with the change of their average values.

5. It is observed that cracking takes place in three stages. Main-cracks firstly start on soil surface and to form main-aggregates. Subsequently, main-aggregates are split to several sub-aggregates by sub-cracks. After all aggregates size is stable, cracking terminates and the final crack pattern is formed.

In general, morphological measurements or geometrical characterization of desiccation crack patterns in clayey soils appear to give relations between quantitative parameters of crack and soil properties or mechanical behavior. However, natural soils are highly complex, being conditioned by a large number of variables, which often affects the cracking behavior. Further, more work should be conducted in order to provide more precise information for these relations that are indispensable to some models about soil desiccation cracking behavior.

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Fig. 10. Change of crack pattern during wetting process. (a) Original crack pattern, (b) 1 min later after adding water, (c) 2 min later after adding water, and (d) 120 min later after adding water.


