Desiccation Cracking Behavior of Soils

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ABSTRACT

The formation of desiccation cracks on soil surface is a common natural phenomenon as it is subjected to drought climate. The presence of cracks can significantly affect the hydro-mechanical behaviour of soil, and results in various geotechnical problems. With increasing frequency of severe drought climate, better understanding of soil desiccation cracking behavior is becoming an increasingly significant issue. In this investigation, laboratorial desiccation tests were performed on soils by simulating long term drought climate. A camera was mounted above the specimen to monitor the initiation and propagation behaviour of desiccation cracks. Image processing technique was employed to quantify and characterize the obtained crack patterns. It is observed that the desiccation cracking generally takes place in three stages: main-cracks firstly start on soil surface and form main-clods; subsequently, main-clods are split into several sub-clods by sub-cracks; after the size of all clods is stable, cracking terminates and the final crack pattern is formed. It is shown that the image processing technique is efficient to accurately determine the geometrical parameters of crack patterns during drying, including crack width, length, clods area, etc. The introduced density function is effective in describing the distribution characteristics of the geometrical parameters of crack patterns.

Keywords: Desiccation cracking; fine content; influencing factor; crack pattern quantification; Image processing technique

1 INTRODUCTION

It is a natural phenomenon that desiccation cracks develop in clayey soils as they exposed to drying. These cracks create zones of weakness in a soil mass causing reduction in the overall strength and increase in compressibility. Stability of buildings and structures that constructed on clayey soils would be affected by mechanical changes caused by cracking. Moreover, the presence 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, because the size (width, length and depth) and tortuosity of cracks determine the rate and velocity at which water are transported in the soil profile. The claysoil-based structures such as waste containment facilities can be compromised by the formation of desiccation cracks. The diffusion of pollutant along the cracks may speed up and at a much greater rate than the surrounding matrix.

As indicated by IPCC, the changing climate is accompanied by more intense and longer droughts and an increase in frequency of extreme temperatures. Major geotechnical infrastructures and natural geostructures are exposed to the atmosphere and are strongly affected by climatic loading. For example in UK, about one in five buildings are at risk from damage caused by drought because they are built on clays, whose engineering properties are very sensitive to climate change. The Association of British Insurers (ABI) predicts that by 2050 the annual average cost of building damage claims could increase from £300 million to £600 million, with an extreme or ‘event’ drought year costing £1,200 million. A comprehensive understanding of the soil responding especially the cracking behavior to drought climate is therefore vital to adaption and mitigation of the consequences.

In the past decades, soil desiccation cracking behavior has attracted much attention from researchers and a number of works have been done to examine the involved mechanisms (Abu-Heijleh and Znidarcic 1995; Morris et al. 1992; Tang et al. 2008, 2010, 2011a). Corte and Higashi (1960) pointed out that desiccation cracks would occur if the soil shrinkage was constrained or the induced surface tensile stress exceeds the bonding strength of grains. 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. Yesiller et al. (2000) conducted tests to investigate desiccation cracking of compacted liner soils subjected to wetting and drying cycles. However, as soil is a highly complex material, its desiccation cracking behavior is governed by a large number of factors (e.g. mineral composition, clay content, relative humidity, layer thickness and size, boundary conditions, etc.) (Albrecht and Benson 2001; Nahlawi and Kodikara 2006; Rodríguez et al. 2007; Tang et al. 2011b, 2011c, 2012). To date, the essential mechanism of desiccation cracking is still not well understood.

In this paper, for better understanding the initiation and propagation behavior of desiccation cracks, continuous drying tests were performed on three different clayey soils by simulating extreme drought climate. A camera was employed to record the dynamic cracking process of soil surface patterns at different intervals during drying. Image processing technique was applied to quantitatively characterize the crack pattern. The geometric parameters of the crack patterns, such as number of intersections and crack segments, average crack length, width and clod area, surface crack ratio and the related distribution characteristics, were determined.

2 MATERIALS AND METHOD

2.1 Materials

Three different clayey soils (Soil 1, 2 and 3) were collected in Nanjing, China. The soils were air-dried, crushed and sieved at 2 mm. Table 1 lists the physical and mechanical properties of the three soils used.

| Soil properties | Soil 1 | Soil 1 | Soil 1 |
|-----------------|--------|--------|--------|
| Specific gravity | 2.73   | 2.70   | 2.62   |
| Consistency limit | 36.7% | 34.5% | 52.6% |
| Liquid limit | 18.9% | 22.7% | 32.9% |
| Plastic limit | 17.6 | 11.8 | 19.7 |
| USCS Classification | CL | CL | CL |

2.2 Sample preparation

Initially saturated slurry specimens were prepared by mixing soil powder with distilled water at a water content of about 90%. The obtained slurry was carefully mixed by hand, and then a desired slurry quantity was poured into three rectangle glass containers with a size of 20×20 cm. Each specimen corresponds to a different soil type (soil 1 (S1), soil 2 (S2), soil 3 (S3)). Additionally, in this test, to better observe the dynamic cracking process of soil surface, one specimen (S4) was prepared using saturated slurry soil 3. To remove entrapped air bubbles in soil slurry, these boxes were placed on a vibration device for 5 minutes. Finally, the slurries were covered for at least 24 h. The final settled slurry thickness was about 5 mm.

2.3 Test method

After the specimens were prepared, they were moved to an oven to dry under a controlled constant temperature of 40°C. A digital camera was installed above the specimen S4 to record the surface desiccation cracking process at varying time intervals. The specimen S4 was weighted to an accuracy of 0.01 g to record the water loss during drying, as the setup shown Fig. 1. The obtained crack patterns of the specimens (S1, S2, S3) at the end of drying were quantified by image processing technique. In order to eliminate the boundary effect, only the center part (18×18 cm) of the specimen was selected for image processing.

![Fig. 1 Schematic drawing of set-up used in the desiccation test.](image)

2.4 Image processing

The procedure of digital image processing is shown in Fig. 2. Firstly, the colored photograph of the crack pattern was changed to a grey level image; secondly, the grey level image was segmented into cracks and aggregates through binarization operation, which results in a binary black and white image (Fig. 2(a)). Thirdly, because of the impurities in the soil surface, there are some small black spots in the white area representing the soil block after the binarization operation. Thus, the function of noise elimination is designed to eliminate the “noise” on the crack pattern (Fig. 2(b)). Fourthly, in order to determine the crack intersection and length, schematized structure of crack pattern was created by skeletonizing operation (Fig. 2(c)).
(c)). The middle line of crack segment was extracted as the skeleton of crack network. Finally, the morphology parameters of crack segment, intersections, and so on were determined. Details of the image processing were introduced by Tang et al. (2008).

![Crack image processing](image)

Fig. 2 Crack image processing procedures.

In order to quantitatively characterize the crack patterns, the following parameters are defined and determined: (1) Number of intersections $N_n$ and crack segments $N_{seg}$. It can be seen from Fig. 2 that the structure of crack network can be described as a sequence of crack segments which intersect other segments, and these segments define the outline of the crack pattern. In general, $N_n$ and $N_{seg}$ 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 noted that the crack length is determined by calculating the distance between two adjacent intersections after the image is skeletonized, as it is shown in Fig. 2 (c). The crack width is determined by calculating the shortest distance from a stochastic point on one boundary to the opposite boundary of crack segment. In this investigation, a total of 15000 stochastic points are selected from each crack pattern; (3) Average area of clods $S_{av}$. The clod is defined as the independent closed area which is split by cracks, namely the closed white area on Figs. 2 (d); (4) The surface crack ratio $R_{sc}$, which is the ratio of the crack area to the total surface area of soil specimen. The $R_{sc}$ is an indicator of the extent of surficial cracking; (5) Density function of crack length $f(l)$, crack width $f(w)$ and clod area $f(s)$. The density function is a very useful statistical approach to describe the distribution characterizations of related geometrical parameters of crack network. The definition and physical significance of the density function was introduced by Tang et al. (2008). Set the density function 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 $l$ and $l+\Delta l$, $f(l)dl$ gives the fraction of the crack length ranges between $l$ and $l+dl$. Assuming that the crack length $l$ ranges from $a$ to $b$, the follow equation is established:

$$\int_a^b f(l)dl = \int_0^n \frac{dn}{n} = \frac{1}{n} \int_0^n dn = 1$$

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.

3 RESULTS AND DISCUSSION

3.1 Crack propagation process

Fig. 3 shows the crack patterns of S4 at different time intervals. It is found that desiccation cracking generally takes 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 (Figs. 3 (a) ~ (c)). Here these single cracks are called main-cracks on crack pattern, it is always formed in the early drying period. 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° (Figs. 3 (c) and (d)). The clods split by these main-cracks are called main-clods in this stage of crack pattern formation.

2. When after the main-clods formation, if the main-clods size is big enough, branch cracks begin to form 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 (Figs. 3 (d) ~ (g)). During this process, the big main-clods are split to small sub-clods. In some cases, the sub-clods may be split again if the size is still bigger than their stable size.

3. Although the drying is not complete, no new cracks are formed after all clods sizes are stable (Figs. 3 (h)). The existing cracks just become wider until the drying process comes to the end. From Fig. 3 (h) to the final crack pattern Fig. 3 (i), it is observed that no news crack initiates and crack network reaches stabilization. Fig. 3 (h) and (i) also shows that the main-cracks are usually wider than sub-cracks. Blocks and cracks form the final cracking network after all three stages are completed.
Fig. 3 Evolution of desiccation crack propagation during drying. (a) After drying for 1201 min, (b) after drying for 1420 min, (c) after drying for 1509 min, (d) after drying for 1628 min, (e) after drying for 1872 min, (f) after drying for 2041 min, (g) after drying for 2125 min, (h) after drying for 2653 min, (i) after drying for 4413 min.

3.2 Crack patterns of three soils

Fig. 4 show the final crack patterns of S1, 2 and 3. It can be seen that, for different soils, the overall morphology of the crack patterns show some differences. In S1, there are several big clods which are not split into smaller ones. In S2, the crack segments are much more slender than that in S1 and 3. For S3, the crack width is obviously greater than that in S1 and 2. Moreover, the crack patterns show relative uniform clod areas.

![Fig. 4 The obtained final crack patterns of S1, S2 and S3.](image)

3.3 Quantitative analysis of crack patterns

Several crack parameters were determined by image processing technique, as described above. The results of quantitatively analyzing the final crack patterns of S1, 2 and 3 are shown in Table 2. The number of intersections and crack segments in S3 are higher than those in S1 and 2. It indicates that the surface of S3 is more cracked or fragmented. The average crack length in S2 is the longest among the three soils, while, comparing with S1 and 3, its average crack width is much smaller. In S3, the average crack length is the lowest while the average crack width is the highest among the three soils. It is easy to imagine that crack segments in S2 are threadlike, and crack segments in S3 are podgy. It is consistent with the observations shown in Fig. 4. Table 2 shows the average clod area in S3 is smaller than that in S1 and 2. In general, the more the number of crack segments or intersections in crack pattern, the smaller the clod size. In Table 2, it is observed that the $R_{cl}$ in soil 3 is much higher than that in S1 and 2. The $R_{cl}$ in S3 is 24.24 %, indicating that 24.24 % of the surface area is covered with cracks. The $R_{cl}$ is 13.65 and 9.34 % for S1 and 2, respectively.

| Soil type | $R_{cl}$/% | $N_o$ | $N_{av}$ | $L_{av}$/pixels | $W_{av}$/pixels | $S_{av}$/pixels |
|-----------|------------|-------|----------|----------------|----------------|----------------|
| S1        | 13.7       | 92    | 148      | 93.4           | 10.2           | 14538          |
| S2        | 9.3        | 122   | 212      | 80.0           | 5.6            | 11843          |
| S3        | 24.2       | 258   | 384      | 63.1           | 11.4           | 6001           |

Due to the significant un-uniform distribution of crack length, width and clod, the average values shown in Table 2 cannot properly reflect the distribution characteristics. The related density functions of $f(l)$, $f(w)$ and $f(s)$ were therefor employed and are presented in Fig. 5. It can be seen that the MPV of crack lengths for S2 is higher than that of S1 and 3 (Fig. 5(a)). Especially for S3, more than 70 % of the crack lengths ranges in 30 ~ 90 pixels. The MPV of crack widths for S2 is smaller than that of S1 and 3 (Fig. 5(b)). The width of cracks in S2 mainly distributes in a narrow range of 3 to 7 pixels, about 60 % of the crack widths being around 5 pixels. In Fig. 5(c), the distribution ranges of clod areas of S1 and 2 are much wider than that of S3. Most of the clod areas of S3 distribute in the range of 2500 ~ 7500 pixels. It indicates that the clods show somewhat uniform size for S3 after drying. This is consistent with the observations in Fig. 4. In addition, the MPV of clod areas for S2 is little larger than that of S1 and 3. By summarizing, the changes of MPVs of crack length, width and clod area in Fig. 5 are generally consistent with the change of average values shown in Table 2.
4 CONCLUSIONS

Laboratorial tests were conducted on three clayey soils to investigate the desiccation cracking behavior by simulating drought climate. Image processing technique was employed to quantify the obtained crack patterns. The following conclusions can be drawn:

(1) Desiccation cracking generally takes place in three stages: main-cracks firstly start on soil surface and form main-clods; subsequently, main-clods are split to several sub-clods by sub-cracks; after all clods size is stable, cracking terminates and the final crack pattern is formed.

(2) Image processing technical presents high efficiency and reliability on quantifying soil desiccation crack pattern. The proposed crack quantification parameters, including number of intersections and crack segments, average crack length, width and clod area, surface crack ratio, are helpful to properly describe the geometric and morphological characteristics of crack pattern. Moreover, the introduced density function provides a more reasonable approach to present the distribution behavior of some specific crack parameters.

(3) For a general crack pattern, the number of intersections, number of clod and surface crack ratio can be recommended as the three basic parameters for the quantification. The results of statistical analysis indicate that the values of crack length, width and clod area are average strongly related to their distribution ranges as well as the most probable values determined by the probability density functions.

(4) Different soils usually show different desiccation cracking behavior. It is found that the crack pattern of soil is significantly conditioned by fines content and plasticity, which are good indicators of soil cracking extent. Generally, soil contains higher fines content or has higher plasticity may initiate more cracks and present higher surface crack ratio as subjected to drought.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (Grant No. 41572246, 41772280), National Science Foundation of Jiangsu Province (BK20171228, BK20170394), National Natural Science Foundation of China for Excellent Young Scholars (Grant No. 41322019), Key Project of National Natural Science Foundation of China (Grant No. 41230636), and the Fundamental Research Funds for the Central Universities.

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