Formation and repeatability of crack network in soil

Formation et répétabilité de réseau de fente dans le sol

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ABSTRACT
The formation process and repeatability of desiccation cracks in soils was studied through field surveys. The changes of crack porosity and aperture with drying time and water content were studied. Results show that the process of crack formation can be divided into three distinct stages: initial stage, primary stage, and steady state stage. In the initial stage few cracks appeared with gradually decreasing water content. After a few cracks appeared in the soil, the soil water would evaporate from the crack walls horizontally in addition to the water loss from the ground surface in the vertical direction. Formation of the crack network in this stage took place rather rapidly within one or two days and this was the primary stage. In the steady sate stage, both the crack porosity and crack aperture increased very slowly and tended to reach a steady state. The pattern and locations of the cracks during several wetting-drying cycles were found to be repeatable. Relatively large cracks might still be open at near saturation for a fresh soil experiencing the first few drying-wetting cycles because shrinkage during the first few drying cycles could cause irreversible fabric changes. Small cracks may disappear due to swelling of soil aggregates. However the cracks remained to be potential discontinuities when the crack aperture is not large enough to allow mitigation of soil particles in the cracks so that healing of cracks cannot take place.

RÉSUMÉ
Un essai sur le terrain a été effectué pour étudier le processus de formation et la répétabilité des fissures de dessication dans les sols. Les changements de la porosité et de l'ouverture de fente avec le temps de séchage et la teneur en eau ont été étudiés. Les résultats montrent que le processus de la formation de fente peut être divisé en trois étapes distinctes: étape initiale, étape primaire, et étape équilibrée. A l'étape initiale peu de fissures sont apparues avec la teneur en eau graduellement décroissante. La formation du réseau de fente à l'étape primaire a eu lieu plutôt rapidement dans les un ou deux jours. Dans l'étape équilibrée, la porosité de fente et l'ouverture de fente ont augmenté très lentement et ont tendu à atteindre un équilibré. Les types et les endroits des fissures pendant plusieurs cycles de mouillage-séchage se sont avérés qu'on peut répéter. Les fissures relativement grandes pourraient encore être ouvertes près du point de saturation pour un sol frais éprouvant les cycles premiers de séchage-mouillage. Les petites fissures peuvent disparaître en raison du gonflement des agrégats de sol. Cependant les fissures sont restées pour être des discontinuités potentielles quand l'ouverture de fente n'est pas assez grande.

1 INTRODUCTION

Formation of cracks in soils can be due to different causes including desiccation and shrinkage, temperature changes, uneven settlement, lateral movements, construction process, and synaeresis etc. Fine-grained soils are often affected by desiccation cracks. The formation and extent of desiccation cracks are dependent on the type and amount of mineral particles, water content, mechanical properties of soils, confining pressure, temperature, and cycles of drying and wetting (Morris et al. 1992; Mitchell & Soga 2005). Many laboratory tests have been conducted to study the effects of direction of drying, sample size, and sample thickness on the crack formation and morphology (e.g., Shorlin et al. 2000). Particularly, Mizuguchi et al. (2005) studied the process of formation of columnar structures and the directional crack propagation phenomena observed in the drying process of a 5 mm thick starch-water mixture.

Small-size laboratory tests may not represent well field conditions where the soil often contains coarse particles and has strong interactions with the atmosphere. Field tests conducted on in-situ soils under atmosphere conditions would be more realistic for engineering applications. Dasog et al. (1988), Konrad & Ayad (1997) and Moe et al. (2003) observed crack geometric characteristics in soils. The study on the formation process and repeatability of cracks under natural atmosphere conditions is of practical significance and needs further study.

Whether cracks are repeatable or not during a cyclic drying-wetting process has drawn much attention (Yesiller et al. 2000; Rayhani et al. 2007). Yesiller et al. (2000) found that subsequent wetting cycles provided some healing to the cracks that developed in the first wetting-drying cycle. Rayhani et al. (2007) found that the hydraulic conductivity of saturated samples after cracking was still at least one order of magnitude larger than that of the corresponding intact samples, which indicated that the cracks did not close completely upon wetting. If the cracks do not close under saturated conditions the safety of a cracked soil slope can decrease significantly (Li 2009).

The main objectives of this research are to study the processes of formation of cracks in soil grounds through field surveys and to investigate the conditions under which repeatable cracks develop during multiple drying-wetting cycles.

2 FIELD EXPERIMENTAL STUDY

A field study was conducted at the Huangshan slope, which is beside Nanxu Avenue in Zhenjiang, Jiangsu province, China. The test plot was excavated and backfilled in 2002. In 2003, a landslide occurred in the area after a heavy rainstorm. The dry unit weight of the backfilling soil is 16.7 kN/m^3. The liquid limit, plastic limit, and shrinkage limit are 40.4%, 15.6%, and 13%, respectively. The expansive index, defined as 1000 times the difference between the final and initial heights of a specimen divided by the initial height (ASTM 2003), is 56 according to which the backfilling soil is classified as a silty clay with a medium expansivity. An expansive soil exhibits significant swelling and shrinking upon wetting and drying. Consequently, densely populated cracks may develop at shallow depths. A digital imaging method was used to measure the cracks in the surface soils which were fully exposed to rainfall and evaporation.

3 PROCESS OF CRACK NETWORK FORMATION

The field observation period spanned 11 days, which was after a rainfall of 28.9 mm. A series of digital photographs were

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taken on the test ground periodically during the drying process. Fig. 1 shows the digital photographs for the backfilling soil ground. The process of crack formation revealed in the digital photos can be characterized by three distinct stages: initial stage, primary stage, and steady state stage.

Initial Stage

When there were no cracks in the soil initially, the soil water evaporated primarily one-dimensionally in the vertical direction from the soil matrix and the evaporation rate was slow (as shown in Fig. 2(a)). The crack development with the slowly decreasing water content was also slow. This stage of slow crack development was the initial stage. In this stage, only few cracks appeared randomly with their locations governed by the heterogeneity of the properties of the soils in the grounds. Fig. 1 shows that cracks developed slowly in the first three days. Only a few cracks appeared on the backfill ground (Fig. 1(a)) and these cracks grew very slowly as shown in Fig. 1(b). The cracks are almost isolated and cannot form an effective flow pathway for water flow in the horizontal direction in the initial stage.

Primary Stage

After a few cracks appeared in the soil, the soil water would evaporate from the crack walls horizontally in addition to the water loss from the ground surface in the vertical direction (as shown in Fig. 2(b)). Because the evaporation rate in two dimensions was much larger than that in one dimension, the desiccation process would accelerate and the crack development entered the primary stage. In the primary stage, cracks developed abruptly as water content continued to decrease. In the primary stage, both the number of cracks and the crack aperture increased quickly. Cracks shown in Fig. 1(c) are much denser and wider than those in Fig. 1(b), which indicates that cracks developed abruptly during this period. The cracks in this stage formed a polygonal network due to the influence from both the stress field and the moisture field in the soil. Because the evaporation from the crack walls was more rapidly than from the bulk soil, the water content gradient was large at the ends and turning points of the existing cracks. As a result, the tensile stresses at the ends and turning points would increase and the branches of cracks were most likely to appear at these points. Small cracks also developed from the middle of the existing cracks, which were approximately perpendicular to the parent cracks. The new cracks connected to the existing cracks and formed a polygonal network. The crack network formed in the primary stage provides preferential flow pathways for water flow. The saturated hydraulic conductivity of the crack network will increase rapidly because of the formation of crack network and the increase in crack aperture.

Steady State Stage

When the water content of the soil was very low, a balance between the water content of the soil and the humidity of atmosphere was obtained (as shown in Fig. 2(c)). The evaporation rate became very slow and the cracks also developed very slowly or were at a steady state. This is the steady state stage. The cracks were connected and formed a crack network with a polygonal pattern. In this stage, the number of cracks was almost constant and the increase in the crack aperture was also small. Figs. 1(e) and 1(f) are almost identical to Fig. 1(d), which indicates a steady state in the crack development.

4 CHANGE OF CRACK APERTURE AND POROSITY IN THE PROCESS OF CRACK FORMATION

In this section the stages of crack formation are investigated quantitatively based on changes in crack porosity and crack aperture. The average crack aperture is calculated by averaging the aperture values of all the cracks in the observed area. The crack porosity refers to the total area of cracks divided by the area of the soil ground surveyed. The saturated hydraulic conductivity of the cracked soil could increase with the increase in crack aperture and crack porosity (Li 2009).

Fig. 3(a) shows the changes of crack porosity and crack aperture with the drying time. Fig. 3(a) shows clearly the three stages of crack development with drying time. In the first three days of drying, the crack porosity and aperture increase slowly. This is the initial stage. Then from the third day to the fifth day the crack porosity increases rapidly to 84% of the steady crack porosity, and the crack aperture increases to 98% of the steady crack aperture. The primary stage of crack formation can be identified by the much higher rates of increase in crack porosity and crack aperture. After the fifth day of drying, the changes in crack porosity and crack aperture are rather limited, which means the cracks have nearly reached the steady state. The crack porosities at the steady state are 3.1% and the crack aperture at the steady state are 0.43 mm. The three stages of crack

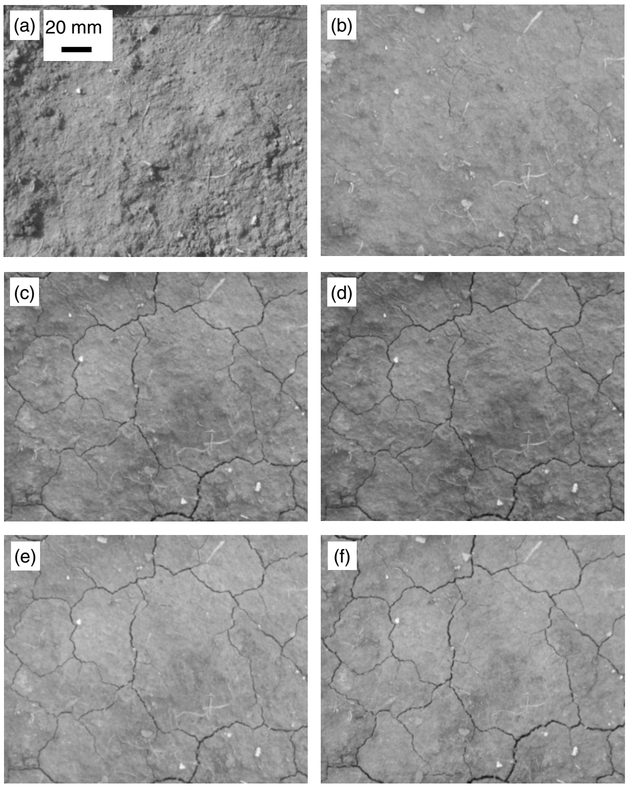

Fig. 1. Crack formation process on the backfilling soil ground during a drying process: (a) One day after rain. (b) Three days after rain. Cracks developed very slowly during the first three days. This was in the initial stage of crack development. (c) Five days after rain. Cracks developed abruptly from the third to the 5th day. This was in the primary stage of crack development. (d) - (f) Six, eight, and 11 days after rain, respectively. The cracks developed slowly and approached the steady state of crack development.

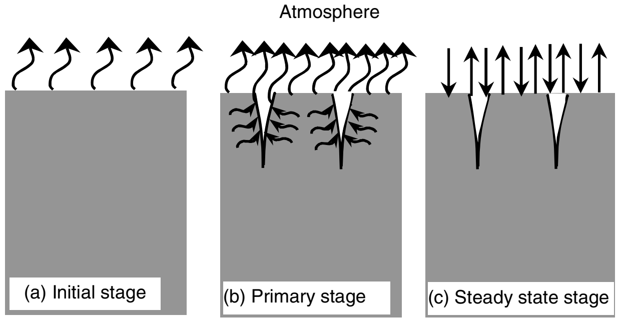

Fig. 2. Three stages of crack development.

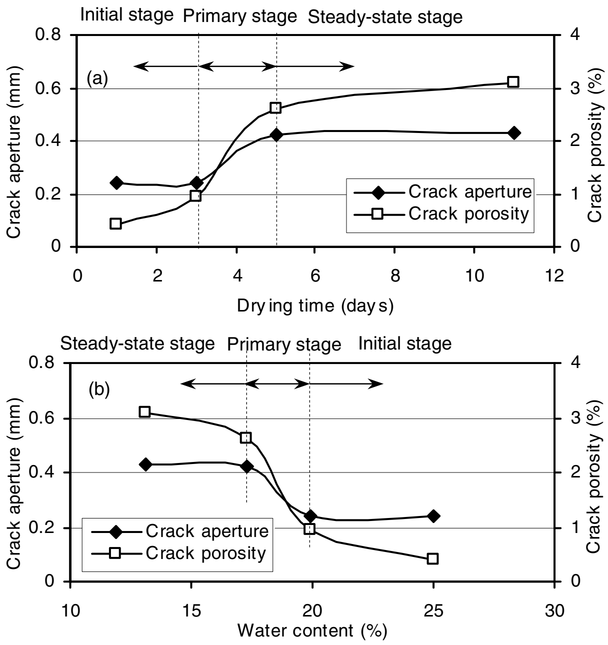

Fig. 3. Changes of crack aperture and crack porosity with: (a) drying time; (b) water content.

formation quantified by the crack aperture and porosity are consistent with those observed from the photographs in Fig. 1.

The water contents of the cracked soil during the drying process were also measured. The development of cracks with water content shows the same three stages more clearly. Fig. 3(b) shows the changes of crack porosity and crack aperture with water content. In the initial stage, the water content decreases from 30% to 19.9%. The significant decrease in water content only leads to a small increase in crack aperture and porosity. In the primary stage, the water content decreases from 19.9% to 17.3%. Both the crack porosity and crack aperture increase significantly with the small portion of water loss. The water content is 13% in the steady state stage. Fig. 3(b) shows that the crack porosity and aperture increase much faster in the primary stage than in the initial stage and the steady state stage. Take the crack porosity as an example; the slope of the curve in the primary stage is 12 times of that in the initial stage and 14 times of that in the steady state stage, as shown in Fig. 3(b).

5 REPEATABILITY OF CRACK NETWORKS

The repeatability of cracks was investigated on the backfilling soil ground. Fig. 4 shows the cracks at the end of four wetting-drying cycles. The cracks are repeatable on the pictures. The mechanisms of crack repeatability can be studied from a perspective of soil behavior. The soil pore structure can be classified as intraelemental pores, intraassemblage pores, interassemblage pores, and transassemblage pores (Collins & McGown 1974). Generally, the adsorbed water in the intraelemental pores is in the form of diffuse double layer and hard to remove from the soils. Therefore, the intraelemental pores play little role in soil cracking during wetting and drying. The swelling /shrinkage of soils occurs predominantly due to a change of free water from the intraassemblage pores, interassemblage pores, and transassemblage pores, e.g., cracks (Mitchell & Soga 2005).

Fig. 5 shows a schematic soil water characteristic curve (SWCC) over several drying-wetting cycles. The saturated water content at full saturation (i.e., at extremely low suctions) represents the soil porosity. The water content decreases slowly with increasing suction during the drying process and increases with

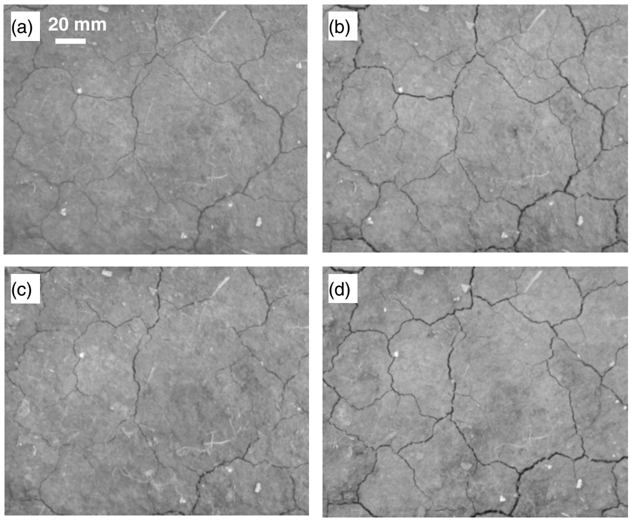

Fig. 4. Photos of cracked soil at the same plot on a natural soil ground at the end of four different drying cycles: (a) Four days after a rain of 12.7 mm precipitation; (b) Ten days after a rain of 3.1 mm precipitation; (c) Four days after a rain of 14.7 mm precipitation; (d) Ten days after a rain of 28.9 mm precipitation.

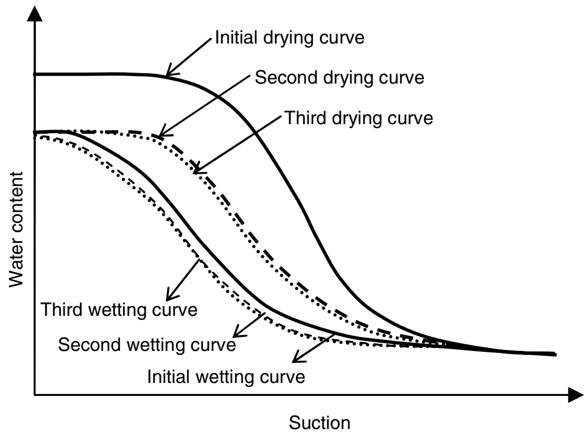

Fig. 5. Schematic soil water characteristic curves during several drying wetting cycles.

decreasing suction during the wetting process. However, the porosity after the first drying-wetting cycle is smaller than its original value (e.g., Ng & Pang 2000 for a silty clay). The decrease in porosity is due to two main reasons: the irreversible volume change during the drying-wetting cycles and the trapped air in the soil pores. Shrinkage-induced volume change is equal to the sum of the volume change of the soil matrix and the volume of the cracks occurring in the desiccation process. As shrinkage of clay during the first few drying cycles can cause irreversible fabric changes (Yong & Warkentin 1975), the cracks may still be present in the subsequent drying-wetting cycles. Fig. 6 shows clearly this phenomenon on a fresh soil ground. Fig. 6(a) shows the cracked soil after ten days of drying. The water content of the cracked soil was 8.9%. An interconnected polygonal crack structure formed. After a rain of 28.9 mm, the same plot of cracked soil is shown in Fig. 6(b). The water content of the cracked soil increased to 19.7%. Almost all the large cracks are still present after the wetting of the fresh soil because shrinkage caused a large decrease in crack porosity and irreversible changes in the soil matrix fabric.

The porosity decreases with the number of drying-wetting cycles, but at a reduced rate. After many drying-wetting cycles the porosity will reach a steady value. At this state, some cracks may heal if they are filled by fine particles migrating through the cracks. Fig. 1 shows a silty clay ground that has experienced several drying-wetting cycles. Although small cracks disappear at low suctions (Fig. 1(a)) due to swelling of the active soil aggregates, the cracks are repeatable when suctions become high. This means that the cracks are not filled with fine particles.

Whether or not cracks can be filled with fine particles can be examined by a comparison of the soil particle size and the crack aperture. Fig. 7 shows the particle size distribution and the crack aperture distribution at different times for the ground in Fig. 1. The particle size distributes in a wide range of 0.0001 - 50 mm. The soil grain diameter below which 85% of the soil will pass (i.e., d_{85}) is 1.2 mm. The crack aperture size distributes in a predominant range of 0.1 – 1 mm. The average apertures of the cracked soil in Figs. 1(a), (b), (c), and (f) are 0.24 mm, 0.24 mm, 0.42 mm, and 0.43 mm, respectively. The 15%-percentile values of crack aperture (i.e., D_{15}) are 0.15 mm, 0.13 mm, 0.25 mm and 0.26 mm, respectively at the four different moments. Terzaghi & Peck (1948) suggested that soil particles can mitigate in pores if D_{15} is larger than four times d_{85}. This criterion cannot be satisfied for the cracked soil concerned here, which means the soil particles from the soil matrix cannot migrate through the cracks. Therefore, the bonds on the crack walls are weaker than those inside the aggregations. The previous cracked zones between different aggregations will be the weaker places and the most likely cracking areas. This means the cracks can be largely repeatable during cyclic drying and wetting.

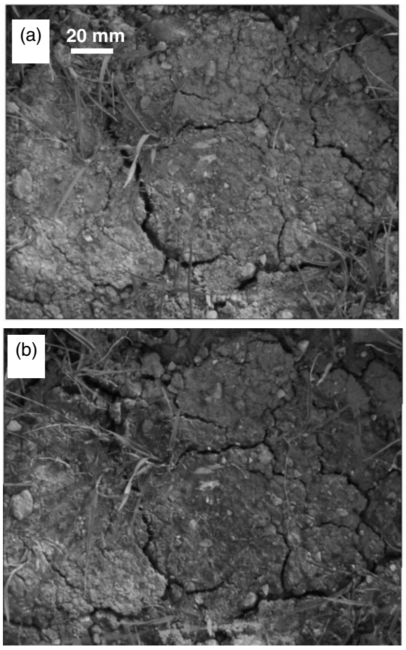

Fig. 6. Snapshots of a cracked soil with two different water contents: (a) Water content is 19.7%; (b) Water content is 8.9%.

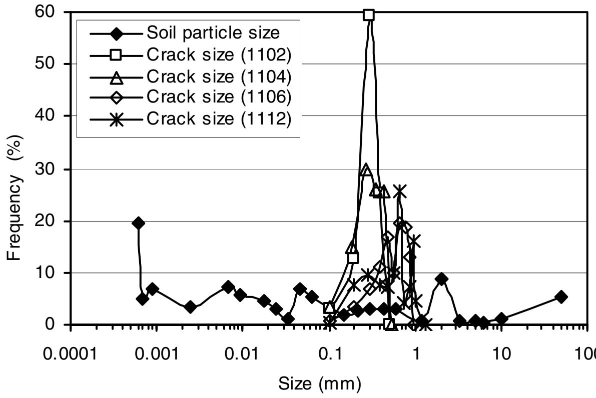

Fig. 7. Frequency of soil particle and crack sizes at different moments.

6 CONCLUSIONS

A field study was conducted to investigate the formation process and repeatability of desiccation cracks. The crack porosity and crack aperture were measured for each crack network during desiccation. The relationships between these crack geometric parameters and the water content/drying time were presented. The conditions for the development of repeatable cracks are also explored. This study leads to the following conclusions:

1) Desiccation cracks generally develop in three stages: the initial stage, the primary stage, and the steady state stage. The rate of increase in crack porosity and crack aperture in the primary stage are much larger than those in the initial stage and the steady state stage.
2) The cracks may still be open near saturation in a fresh soil ground experiencing the first few drying-wetting cycles because the shrinkage of clay during the first few drying cycles can cause irreversible soil fabric changes.
3) The cracks may close due to swelling of soil aggregates. However the cracks remain to be potential discontinuities when the crack aperture is not large enough to allow mitigation of soil particles in the cracks so that healing cannot take place.

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