E-UNSAT 2008, First European conference on unsaturated soil, Durham, United Kingdom. Study of desiccation crack evolution using image analysis

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ABSTRACT: Desiccation cracking can be heavily detrimental on the performance of clay soils in various engineering applications. Typical engineering applications include compacted clay barriers in waste containment, dam cores, canal liners and road pavements. The evolution of desiccation cracks has not been clearly understood and explained. A series of laboratory tests were conducted using Merri-Creek clay. The evolution of cracks was captured by automated digital photography. It was revealed that under the conditions tested, the cracks occurred sequentially subdividing the overall surface area into cells. The relationship between desiccation rate, average cell area, thickness of the specimen and crack initiation are examined and discussed.

# 1 INTRODUCTION

Clay soils undergo shrinkage cracking during desiccation. Cracks can be a major unwanted feature in a number of geoengineering applications as well as in some other disciplines. For instance, in geoengineering shrinkage cracking is significant in earth embankments, slopes, foundations and roads. In agricultural engineering, cracks can stimulate the water and solute flow through soil in irrigated land. Clay liners are commonly used for lining and covering waste landfills in geo-environmental engineering. Shrinkage cracks can highly compromise the primary function of these clay liners by promoting water and leachate migration. A substantial amount of research work has been conducted in materials engineering on this issue to study the glazing and thermal fracturing in ceramics (e.g. Chiu & Cima, 1993) and printing, painting & washing (e.g. Deegan et al., 1997).

Despite the significance of cracking on these applications, the essential understanding about the soil shrinkage crack evolution and propagation is still far from satisfactory. A majority of previous research has been qualitative and behavioural (Corte & Higashi, 1960; Muller, 1998; Kodikara et al., 2000). Many researchers have worked on the final state of the cracking process (Morris et al, 1991; Konrad & Ayad, 1997; Kodikara et al., 2000). Nahlawi and Kodikara (2006) presented results of cracking tests, where they measured the on-set of first crack, cracking water content and subsequent crack evolution. A similar study was undertaken by Lakshmikantha et al (2006). In contrast, using the time-lapse video

technology, we were able to capture the complete process of shrinkage cracking in laboratory test specimens. Results are presented in image format as well as in video clips. These videos will be uploaded to a web link in near future.

## 2 LABORATORY CRACKING TESTS

Merri-Creek clay was used in the experiments. Merri-creek clay is found in Northeastern Melbourne. This very heavy and sticky grey to black clay soil has been used by other researchers (e.g., Chan et al., 2007) and its basic properties includes: LL=74%, PL=33%, PI=41%, Linear shrinkage = 13%.

The Merri-Creek clay used for the tests was processed for commercial use and contained a considerable amount of tiny plant roots. This clay is commonly used for construction of cricket pitches in Melbourne, including the Melbourne Cricket Ground.

# 2.1 Merri-Creek clay

A series of tests were conducted with Merri-Creek clay. The unprocessed clay samples were lightly crushed using a rubber hammer and sieved through a 1.45mm sieve. The plant roots were removed as mush as possible for the soil samples. The initial moisture content of soil was determined using the oven dry method.

The material that passed through 1.45mm sieve was mixed with water to its liquid limit (74%), and stirred well until it attained a visibly homogeneous state. The prepared clay mixture was placed in a plastic tray, which was then placed into two polythene bags and was sealed for moisture leakage. The tray was kept in a cool, damp place for 48 to 72 hours allowing the clay paste to gain adequate moisture homogenization.

Circular glass containers of 140mm diameter were used to make the specimens. An air vibrator was used while preparing the specimen in order to remove entrapped air. Then the glass container was placed on an electronic balance which was connected to a computer. This system automatically measured and stored the weight of the specimen at every 30 minutes.

Specimens were dried using flood lamps each of 500 Watts. Four lamps were placed above, surrounding the specimen at a distance of 50 cm. A digital camera, which was operated by a computer, was positioned directly above the specimen. The camera was programmed to take photos at every 30 second interval and the data were automatically saved in the computer. The tests were conducted at varying lamp distances (35, 50 & 75 cm) as well as with varying specimen thicknesses (5, 10 & 20 mm).

Although the tests were not performed in a temperature or humidity controlled environment, both surrounding temperature and relative humidity were reasonably constant at  $50^{0}$ C and 20% respectively owing to the constant heat emitted by lamps.

## 3 RESULTS

It is interesting to observe that all specimens produced predominantly sequential, orthogonal crack patterns (Figs 1&2), leading to subdivision of the crack area into smaller cells.

For clay cracking as evident from Figures 1 & 2 the number of cracked cells and the average cell area are found to be dependent on the specimen thickness and the lamp distance (or the desiccation rate). As the thickness of the specimen increases, number of cracked cells decreases, in turn increasing the average cell area. Similarly, an increased desiccation rate (or decreased lamp distance) will result in an increase of number of cracked cells and a decrease in the average cell area. Some statistical features of cracked specimens are given in Table 1. An exceptional situation can be seen at 35cm lamp distance. where for 5mm thick specimen, the average cell area is larger than that for the 10 mm thickness. The desiccation rates for each test condition were computed on the basis of the automatic weight measurements during drying.



Figure 1 Crack patterns for 5, 10 & 20 mm thick specimens (a, b & c respectively) at 50cm lamp distance



Figure 2 Crack pattern for 35, 50 & 75 cm lamp distances (a, b & c respectively) for 20mm thick specimen

Table 1: Statistical features of clay specimens

| Lamp     | Thickness of | Desiccation rate     | Average         |
|----------|--------------|----------------------|-----------------|
| Distance | the specimen |                      | cell area       |
| cm       | mm           | g/hr.cm <sup>2</sup> | mm <sup>2</sup> |
| 35       | 5            | 0.1939               | 224             |
|          | 10           | 0.0884               | 217             |
|          | 20           | 0.0574               | 296             |
| 50       | 5            | 0.1196               | 113             |
|          | 10           | 0.0420               | 326             |
|          | 20           | 0.0252               | 481             |
| 75       | 5            | 0.0677               | 134             |
|          | 10           | 0.0298               | 294             |
|          | 20           | 0.0220               | 362             |

### 4 DISCUSSION

#### 4.1 Desiccation rate

The average cell area of the final crack pattern was dependent on the desiccation rate and the thickness of the specimen. It can be seen from Table 1, that the desiccation rate increases when the lamp distance decreases or the clay thickness decreases. In general, the higher the desiccation rate is, the lower is the average cell area. At higher desiccation rate, more cracks are needed to release the rapid increase of stress in the specimen, subsequently reducing the crack spacing and the size of the cells. With a low desiccation rate, the specimen has enough time to release the stress increment with a few slowly opening cracks.

#### 4.2 Specimen thickness

The decrease of the average cell area with reducing specimen thickness has been presented by several previous researchers (Nahlawi & Kodikara, 2006; Lakshmikantha, et al. 2006). The exceptional behaviour (noted in the previous section) of 5mm thick specimen at 35cm lamp distance is being further investigated using thinner specimens. Kodikara et al (2007) theorized that the spacing between cracks decreases when the specimen thickness decreases up to a certain critical thickness, below which the spacing between cracks becomes larger, increasing the area of the cells. It may be possible that this behaviour is relevant for interpreting the current experimental results, or it may be one-off result dependent on the specific conditions of testing.

#### 4.3 Crack evolution





Figure 3a-f Evolution and propagation of shrinkage cracks in 5mm thick clay specimen at 75cm lamp distance

Generally, the evolution and propagation of shrinkage cracks cannot be categorized as pure orthogonal or pure non-orthogonal patterns. The final state of the crack pattern is generally a mixture of orthogonal, non-orthogonal, simultaneous and sequential cracks (Kodikara et al., 2000). However, crack patterns in all the clay specimens contained almost all orthogonal, sequential cracks where subdivision was the dominant feature in propagation.

Figure 3 highlights some of the main features of cracking process. Onset of cracking is dependent on tensile stress distribution was well as the flaw distribution within the material. As theorized by Kodikara and Choi (2006), the maximum stress is likely to occur at the middle of a layer or cracked cell, if cracks have already formed, otherwise predominantly uniform stress conditions might prevail, as applicable to initial cracking. However, the exact location of crack formation will depend on the existence of a flaw that can be propagated with the prevailing stress level at that location. Therefore, the initial cracking is generally associated with edge cracking, where the material can be weakly attached to the container. However, it is possible for several cracks to initiate simultaneously because the stress conditions are relatively uniform at the beginning. Thereafter, cracks can occur somewhere in the vicinity of the centre of a layer or cracked cell, although theoretically, the tensile stress development would likely to be maximum at the centre. Numbers 1, 2, & 3 in Figure 3(a) refers to the onset of first three cracks respectively. Once a crack is open, it tends to spread in both directions until it intersects another crack or the boundary. It is hardly seen two cracks meet at an angle of  $120^{\circ}$  to form one crack, or an existing crack bifurcate to form a  $120^{\circ}$  nucleation. This can be identified by following the crack no. 1, 2, 3, 4 & 5 in Figure 3 (a) to (f).

Crack no. 7 & 8 in Figures 3 (c) & (d) are examples for subdivision. Instead of subdivision, only rarely cracks appear to bifurcate to form new cracks. In Figure 3, crack no. 9 appears to bifurcate into two cracks. Certain few cracks that appear to start from one point simultaneously and propagate in three directions making approximately 120<sup>0</sup> angles among them. Crack no. 6 in Figures 3 (b) to (f) is an example for such a formation. However, closer examination of these crack formations reveals that these can very well be explained by the presence of certain flow orientations and the influence of stress relief caused by other already formed cracks. In this regard, the crack formation observed in these tests can be considered to form generally orthogonal patterns. This is very common when cracks propagate in subdivision, as a requirement of the prevailing stress regimes influenced by formed cracks. An example is shown in Figures 3 (b) to (f) by crack no.10.

#### 4.4 Crack initiation

The distribution of cumulative crack length over the drying period illustrates a similar behaviour for

specimens with same thickness at different lamp distances.



Figure 4 Variation of percentage crack length with average water content of a 5 mm thick layer – the legend shows the lamp distance.

Figure 4 shows the increase in crack length as a percentage of the final crack length for 5mm thick specimens as the drying progressed. All the specimens were prepared at their liquid limit (74%). The specimen under highest desiccation rate (lamp distance=35cm) starts cracking first as expected. These results show that the average cracking water content (as determined from overall weight measurements) is also higher when the first crack occurred. However, the actual cracking water content may be different and was not measured in these tests. Once the cracks are initiated, they grow rapidly to the final state where the crack length becomes stabilized. When desiccation rate is low, cracks open up reasonably late, but continue to grow until the soil is almost fully dried.



Figure 5 Number of cracks initiated during the first few hours of the drying of 5mm thick specimen at 75cm lamp distance

Using the photos taken at various time intervals, the frequency of crack initiation was analyzed within each hour. A typical distribution is shown in Figure 5. Almost all the cracks have opened up within the initial stage of drying. This distribution shows the likely distribution of flaws that were propagated at various moisture contents. In other words, it represents the flaw distribution with associated fracture stress given by the corresponding moisture content. This analysis can be extended further to develop detailed flaw distributions as well as flaw orientations that are required for numerical modeling of crack evolution.

### 4.5 Strain analysis

Particle Image Velocimetry (PIV) is becoming a powerful too in studying failure mechanisms and material failure parameters in geomechanics (White et al., 2003, Thusynathan, et al. 2007). This paper presents some preliminary results of application of this technique to study the desiccation crack evolution.



Figure 6 displacement vectors of a cracked specimen generated using PIV analysis

Figure 6 shows the displacement vectors of a cracked specimen of Merri-Creek clay that was analyzed using PIV technique. We used the PIV image software developed at the University of Cambridge, UK (White, 2002, Take, 2003). It is clear that despite large deformations cracked cells have experienced, it is possible to track their strains and displacements provided that additional texture is provided to the cracking surface. In this instance, fine white sand was randomly distributed on the clay surface at the beginning to provide sufficient textural properties for image tracking by the software.



Figure 7 Cracks analyzed with PIV technique

PIV can produce plots of strain contours which distinguish the strain localization prior to the crack

initiation. For example, the analysis was focused on the initiation of a selected single crack in the specimen shown in Figure 7. Plots generated from a preliminary analysis are shown in figure 8a-c. Initially, soil was undergoing almost uniform strain over the entire region as shown in Figure 8a. Strain localization close to the top right and left corners of the region before the crack initiation can be seen in Figure 8b. The color code on the right of the each figure refers to the value of strain in pixels as the images were not calibrated. In Figure 8c, the crack has already opened increasing the maximum strain from 1.8 to 18.



Figure 8 a-c Plots of strain build-up around the crack opening

#### 5 CONCLUSION

This paper presents the results of laboratory cracking tests undertaken on a reactive clay. The evolution of crack patterns was studied using image analysis, and time-lapse videographs were produced giving a complete picture of crack evolution. Tensile stress distribution within the material and the flaw distribution govern the crack evolution. The spacing between cracks or the average cell area decreased the increasing of either the desiccation rate and (or) the specimen thickness. In line with previous observations on desiccation cracking, clay specimens cracked mainly orthogonally by sequential subdivision after the crack initiation, which was associated with some simultaneous cracking, influenced by flaw and tensile stress distributions.

Preliminary analyses were undertaken using Particle Image Velocimetry (PIV) technique in order to capture the development of strain prior to crack initiation. This technique will further be used in future experiments for further studies.

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