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PREDICTION OF THE SPACING AND PATTERNS OF DRYING CRACKS IN SOILS

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ABSTRACT: *Desiccation cracking of soils is of great importance to geotechnical and geoenvironmental engineering* as *it affects the soil physical integrity. Yet the mechanisms of drying cracking in soils, and the ways to control or avoid it, are still elusive. This paper aims at offering a better understanding of the factors that control the desiccation crack pattern characteristics in soils at the macro-scale. An experimental program is first presented. It consists of the drying of clayey silt slabs, constrained at the bottom and the measuring of the geometrical characteristics of the one- and two-dimensional crack patterns obtained. Then the way desiccation crack spacing and geometry can be predicted is dealt with. It is discussed to which extend the initiation location of successive cracks can be deduced from the form of the stress field. Calculations of the overall energy of the system are further used to derive an estimate of the desiccation crack spacing. An assessment of the obtained desiccation crack spacing value is proposed.*

1 INTRODUCTION

Desiccation cracking affects the bulk properties of soils, especially their strength, compressibility, and permeability. With this respect, the critical parameters are mostly crack connectivity and crack spacing, the latter being focused on here. Desiccation cracking alters the bearing capacity and overall stability of foundations , dams and many earthen structures (Morris et al., 1992), as well as the permeability of clayey soil barriers for waste isolation (Albrecht & Benson, 2001). In soil science, desiccation cracks is of interest as it affects transport of gases, moisture and nutrients to the plant roots (Hillel, 1998).

Evaporation of the wetting liquid (generally water) from the deformable porous medium (here the clayey soil) induces drying shrinkage. Desiccation cracks are likely to occur if the shrinkage is constrained and if tensile stresses are generated in the material, reaching the tensile strength. Desiccation cracks in drying soil generally show a remarkable periodicity, and form geometrical patterns with characteristic crack spacing. It has long been recognized that such spacing depends on both soil material properties and mechanical and drying boundary conditions (Lachenbruch, 1961; Morris et al., 1992; Groisman & Kaplan, 1994; Hong et al., 1997; Bohn et al., 2005; Peron et al., 2008). However, the quantification of crack patterns remains elusive for soils.

This paper aims at offering a better understanding of the factors that control the desiccation crack pattern characteristics in soils at the macro-scale. An experimental program is first briefly presented. It consists of the drying of clayey silt slabs, and the measurement of the geometrical characteristics of the one- and two-dimensional crack patterns obtained. Then the way desiccation crack spacing and geometry can be predicted is discussed. An assessment of the obtained desiccation crack spacing value is proposed.

2 EXPERIMENTAL PROGRAM AND RESULTS

Desiccation of rectangular mud bars has been investigated (length, L, 300 mm, width, l, 50 mm, height, h, 12 mm). The bars made up of initially water saturated remoulded clayey soil, whose shrinkage has been intentionally hampered at the base in the axial direction only. The clay mineral content of the soil is around 25 % (illite, smectite and chlorite); the remaining main minerals are quartz, calcite and feldspar. The evolution of gravimetric water content, w (%) has been monitored by continuous weighing of the samples. A total of 17 bars have been air dried at constant temperature. Replica bars have also been dried in the same conditions, but without any shrinkage constraint at the sample boundaries.

For the hampered tests, after about 17 hours drying time, a regular pattern of 6 cracks (4 bars out of 17), 7 cracks (12/17) or 8 cracks (1/17) has appeared always in the direction parallel to the axial restraint (Figure 1, a and b). All the cracks were rather regularly spaced (Figure 1, a, b and c); considering the average value of seven cracks, the mean crack spacing at the moment when cracking ended was 4.1 cm. The distribution of crack spacing (for the bars exhibiting seven cracks) is shown in Figure 1. Before parallel cracks appearing, slight detachment of the specimen from the base has occurred at the two bottom corners. The entire formation of the observed final crack pattern lasted a non-negligible amount of time, about 1.5 hours to 2 hours (spanning an overall moisture decrease of about $\Delta w = 2$ % in absolute value).

Most commonly the successive cracks would cut the bar in two pieces (first crack) and the formed pieces again in two pieces (successive cracks). However, occasionally, a number of cracks would appear simultaneously (either initial cracks, or subsequent cracks between two adjacent pre-existing cracks). The bars with no boundary constraints did not crack.

In addition to the 1D-constraint tests considered so far, six desiccation tests were performed, for which a bottom substrate was devised with 2D constraints. Square slabs (300 x 300mm) with two different heights (3 slabs of 4mm high and 3 slabs of 12mm high) were tested.

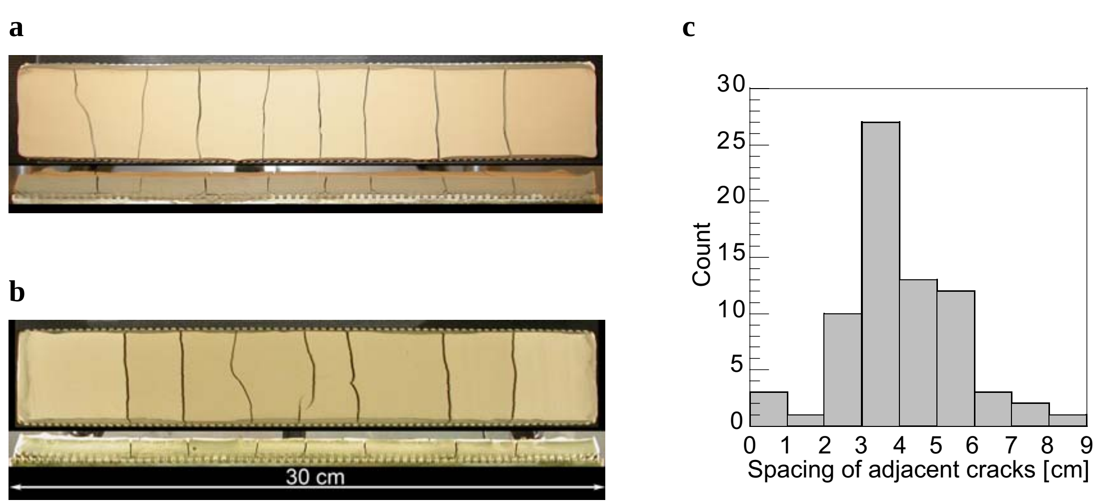

Fig. 1. Experimental desiccation crack patterns. **a**, final crack pattern with height fractures, top view (upper picture) and side view (lower picture). **b**, final crack pattern with seven fractures, top view (upper picture) and side view (lower picture). **c**, repartition of crack spacing values for the bars with seven cracks

All tested samples cracked, leading to formation of a bi-dimensional net of cracks (see Figure 2). Marked differences were observed between samples that were 4 mm high and samples that were 12 mm high. The former ones experienced a large number (from 160 to 352) of relatively thin cracks; the latter ones experienced a small number of relatively wide cracks (from 16 to 31 depending on the tests). Corte and Higashi (1960) observed the same trend when drying similar square shaped slabs. It appears that the 2D constraint tends to originate two limiting kinds of crack patterns: 90° intersecting and 120° intersecting cracks.

In the following, two different approaches are presented, in order to explain some of the characteristics of the crack patterns previously shown.

3 MODELING OF THE CRACK PATTERN FORMATION

3.1 Local Approach

As a first approach, one can consider that the location of crack initiation arises from the form of the stress field. The stress state then meets the material strength criterion, which includes the tensile strength component at some points, due to a particular body shape or boundary conditions.

So as to further quantify such a process, the stress field arising from the desiccation has been modelled via finite elements. Advantage has been taken of the analogy between the equation describing moisture transport and the elastic response to changes in water content, on the one hand, and the thermo-elasticity of the heat diffusing elastic medium, on the other hand. With such a formulation, drying induced stresses arising from both mechanical boundary conditions and water content heterogeneities are computed (Hu et al., 2006; Peron et al., 2007).

Strains are viewed as a combination of a drying shrinkage induced (volumetric) part ε_h proportional to water content change Δw, and a mechanical part generated to satisfy strain compatibility (which induces stresses). In what follows we limit our considerations to the linear, coupled theories. Note that this is a single-phase approach. No pore water pressure and/or effective stress effects are addressed. The elastic formulation that is used here produces a valid stress field (Peron et al., 2008), but one has to be aware that most of the deformations produced during the first drying of a soil mass are irreversible (Peron et al., 2007).

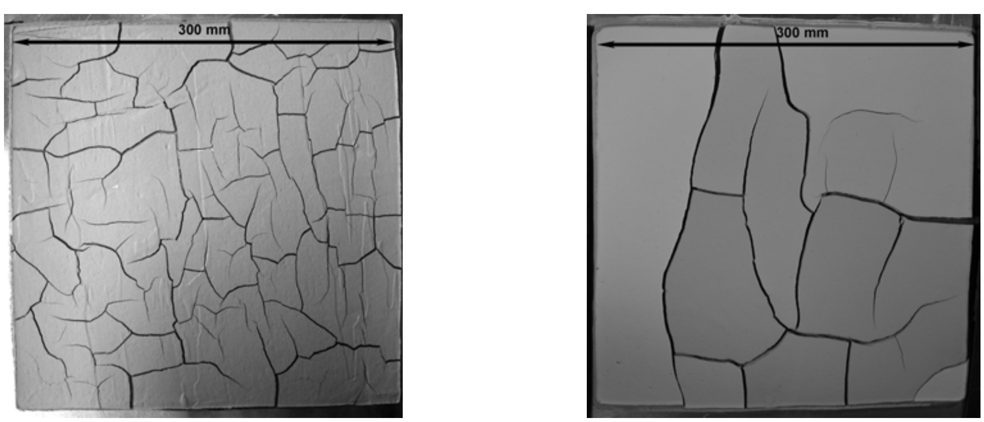

Figure 2- 2D desiccation tests, final stage of cracking (left, samples 4 mm in height, right, samples 12 mm in height)

A 2D model of the bar used in desiccation tests has been examined. The bar (under plain strain hypothesis) has been subjected to a condition of zero displacement at the bottom. Drying boundary conditions has consisted in imposing decreasing water content values on the surfaces of the top and side extremities of the bar, with a constant rate of 1.2% per hour (as recorded during the experiments). The simulation has been performed with the finite element code GefDyn (Aubry et al., 1995). The extensive results can be found in Hu et al. (2006), Peron et al. (2009); only the main results are summarized here, regarding crack initiation location.

Results (Figure 3) show that maximum tensile stress (in absolute value) in horizontal direction is reached along the central vertical section, indicating the first vertical crack would initiate at this location. In Figure 3a the lines stand for the orientation and the intensity of the principal stresses, the length of the line is proportional to the principal stress absolute value. In the conditions of the simulation, fracture mechanics theory shows that such a crack is unstable (Irwin, 1958; Bai et al., 2000), and should fully propagate through the specimen thickness. The cracking process could be resumed in the new sample pieces resulting from the first vertical cracking, leading to the formation of regular crack spacing. The slight detachment experimentally observed near the bottom extremity is explained by a shear effect. It induces large but concentrated tensile stresses, generating conditions for early crack formation. The complex stress field in this zone certainly prevents from larger crack extension.

3.2 Fracture Mechanics Approach

The simulations reveal that minor stress is rather uniformly distributed in the central region of the bar (Figure 3b). Eventually, if the specimen is sufficiently large, the tensile stress field is likely to be quasi-constant at least along surfaces parallel to the external drying surface. Therefore, when tensile strength is reached, the regular crack spacing cannot be deduced from a deterministic stress field. In the scheme presented above, all the cracks should form simultaneously at any location of the bar.

Considering a material with homogeneously distributed flaws, a lower bound for the crack spacing should then stem from the available energy to form cracks. Once the tensile strength is reached, energy conservation requires that the elastic strain energy released due to crack formation to be fully converted into the surface energy of the cracks (Bazant & Cedolin, 1991; Thouless et al., 1992; Hong et al., 1997).

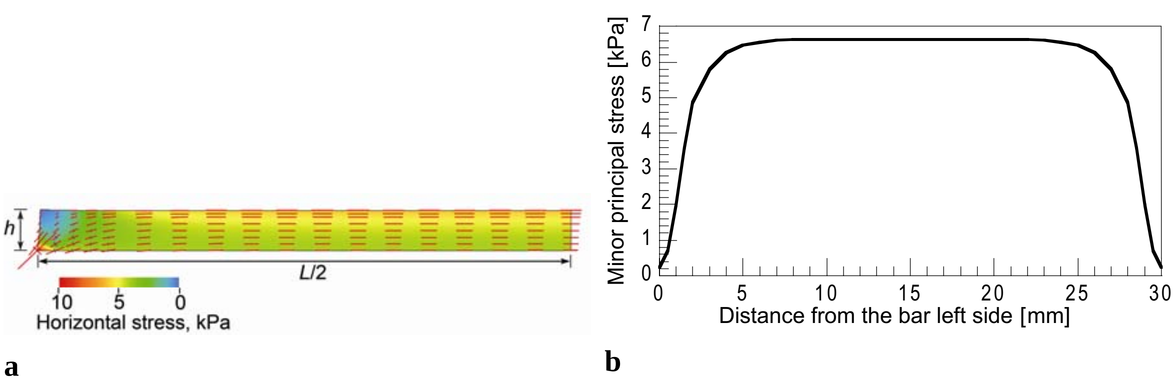

Fig. 3. Plane strain simulation of constrained desiccation tests (tensile stresses are positive). **a**, minor principal stress and horizontal stress fields (half bar), onset of cracking (colour scale: red lines are for tensile stresses, blue lines for compressive stresses). **b**, minor principal stress profile along the bar top surface (same simulation as **a**).

Using this concept, we derive hereafter an expression for crack spacing for the soil sample with a length L, width l and height h. The energy W_s required to form a system of N_C fully-penetrating cracks is given by:

$$W_s = N_C hlG_c \tag{1}$$

where G_c is the critical strain energy release rate. In the desiccation tests discussed here, it is reasonable to do the simplifying assumption that shrinkage is totally prevented in the axial direction, and totally free in the other directions, over the whole bar of clayey soil. Furthermore, it is considered that all the elastic strain energy U is released during the process of cracking. Therefore:

$$U = \frac{ELhl\left(\varepsilon_x^{m,e}\right)^2}{2} \tag{2}$$

where E is Young's modulus and $\varepsilon_x^{m,e}$ is the elastic part of the mechanical strain in the axial direction just before cracking. Setting W_s and U, equal yields the number of cracks:

$$N_C = \left(\frac{E}{G_c}\right)\frac{L\left(\varepsilon_x^{m,e}\right)^2}{2} \tag{3}$$

Crack spacing N_c is directly deduced from Eq. (3). This calculation conforms to the intuitive expectation that states that the more drying soil volume there is, the more cracks are likely to formed. Comparable calculations (in the case a moisture gradient forming from the drying surface) can be found in Bazant & Cedolin (1991) and in a more sophisticated way in Hong et al. (1997), without the simplifying assumptions of fully penetrating cracks and total strain energy release. In Bazant & Cedolin (1991), partial strain energy release is introduced via an empirical coefficient scaling the value of energy U.

To estimate the value of N_c for the Bioley silt constrained desiccation tests, the value G_c = 0.35 N/m is chosen (taken from Ayad et al., 1997, for marine sensitive clay). Strain ε_x^h is determined from the water retention curve (obtained upon drying and wetting paths, Peron et al. 2007, Peron 2008). If one assumes that during the loss of water content ranging from the liquid limit to cracking, the value of suction increases from 5 kPa to 100 kPa, then the elastic part of shrinkage deformation (the free shrinkage strain) is 0.12%. With the above assumptions, a number of cracks of N_c = 19 is obtained. This result is dependent on the choice of the energy release rate G_c, which is not known for the present soil. For instance, Avila et al. (2002) report values of G_c varying from 3.8 to 6.5 N/m for lacustrine clay; the obtained crack number is then much smaller (with G_c = 6.5 N/m, N_c = 1). Incidentally, the estimated values (N_c ranging from 1 to 19) are not inconsistent with the observed crack spacing obtained in the constrained desiccation tests (N_c is about 7, Figure 1). If the desiccation process continues beyond the first cracks, higher order cracks can form in the cells of soil volume isolated by previous cracks, following the same rules as stated above. Note this method could be extended to the bi-dimensional case (Figure 2) to calculate the number (or characteristic size) of cells of soil volume between cracks.

One can finally note that in the above analysis, the decomposition of total strain into a mechanical strain and a free shrinkage strain has been implicitly used; the mechanical behaviour is controlled by the total stress.

However, in the case of the 2D test series (Figure 2), the proposed relation fails to explain the experimental evidence showing that crack spacing tends to increase with slab height. Considering a system of parallel cracks, Bazant and Cedolin (1991) propose a bifurcation analysis that could help understanding the latter behaviour (the same interpretation was provided by Irwin (1958), also by Lachenbruch (1961), heuristically). Bazant and Cedolin (1991) consider the case of a semi-infinite material volume subjected to drying from the surface. A dry zone thus propagates from this surface towards the interior of the volume. A fracture mechanics analysis leads to the conclusion that, while the first cracks are advancing from the surface, their effective spacing increases (discretely) as some of them stop and only proceed and eventually become critical. Therefore, if a semi-infinite slab is considered, the thicker the slab, the more cracks are bound to vanish and the larger the final crack spacing. This analysis holds only if a moisture gradient is developing in the material. This would also mean that in the 2D tests, non-homogeneous drying (from the surface) plays an important role in the crack pattern formation.

4 DISCUSSION ON CRACK SPACING VALUE

The above approach (Section 3.2) provides a theoretical frame to the formation of a crack pattern throughout a homogeneous stress field at a given level of drying. To address further drying, the global approach can be reformulated, or alternatively, the local approach (Section 3.1) can be invoked. In the following, the way in which final crack spacing (at drying completion) is controlled is discussed.

The local approach is now applied again. The stress is likely to be the highest along the centre section of the bar (although the minor stress is almost constant in a large central part of the bar), so the first crack should split the bar in two equal pieces. As a first interpretation, successive cracks, as they appear at lower and lower total water content values, are the result of the constrained shrinkage in the newly formed bar segments. It is noted that the entire process of formation of the observed crack system lasted about 1.5 hours to 2 hours, but a number of cracks appeared simultaneously. This process is not endless. At a certain time, the experimental results show that further cracking ceases, whereas the soil keeps on drying (water loss is not completed). As an explanation, one can assume that the stress field between two adjacent cracks does not comply anymore with crack formation conditions (in terms of tensile strength, or in terms of stress intensity factor). In this case, the geometry of the drying body (for instance the spacing to thickness ratio, Bai et al., 2000), or the mechanical boundary conditions (Groisman & Kaplan, 1994) including interface delamination, can be invoked more specifically as factors controlling the final crack spacing the drying soil body.

5 CONCLUSIONS

It is likely that the experimentally seen crack patterns may be interpreted adopting a combination of the two approaches discussed in this paper, since cracks tended to appear either successively (at clearly decreasing overall water content) or simultaneously. Actually, the local approach for desiccation cracking should be invoked only when intact cells of material with a reduced, well-defined size are individualized. The interpretations and modelling proposed here provides an explanation to general observations about crack spacing in clayey soils.

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