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One-dimensional cracking model in clayey soils

Modélisation unidimensionnel de la fissuration des sols argileux

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ABSTRACT: It is difficult to formulate a general model to capture cracking initiation and evolution, because there are multiple factors that influence these processes. In order to simplify the evaluation and get more insight on the phenomenon, a series of shrinkage tests were performed inducing one-dimensional primary cracking on remolded clay from Bogotá. The results allowed the proposal of a conceptual model that, based on mould shape factor, initial moisture content and evaporation rate, may predict time for crack initiation and identify the location and direction of primary and secondary cracks. Results indicate that boundary conditions play a significant role in cracking evolution, due to the restrictions imposed to the free shrinkage and to the homogeneous evaporation rate. The moulds used for soil desiccation, allowed the induction of predefined cracks when their shape factor values were greater than 1.5. In these cases the model is simple and may be considered as a model of cracking with one degree of freedom. When moulds have a shape factor between 1 and 1.5, the degrees of freedom increase dramatically leading to much more complex crack patterns.

RÉSUMÉ : La fissuration des sols est un phénomène complexe contrôlé par de multiples facteurs qui rendent difficile la formulation d'un modèle qui permette de capturer l'initiation et l'évolution des fissures. Afin de simplifier l'évaluation des facteurs et d'améliorer la compréhension du phénomène, une série d'essais de retrait, induisant une fissuration primaire, ont été effectuées sur de l'argile remoulé de Bogotá. Les résultats ont permis de proposer un modèle simple qui, en fonction du coefficient de forme du moule, la teneur en eau initiale et le taux d'évaporation, peut prédire le moment d'initiation des fissures et identifier l'emplacement et l'orientation des fissures primaires et secondaires. Les résultats indiquent que les restrictions portant sur le libre retrait du sol et l'homogénéité de la vitesse d'évaporation jouent un rôle important dans l'évolution des fissures. Les moules qui ont permis l'induction de fissures prédéfinies étaient caractérisés par un facteur de forme supérieur à 1.5. Dans ces cas-là, le modèle est simple et peut être considéré comme un modèle de fissuration avec un degré de liberté. Lorsque les moules ont un facteur de forme compris entre 1 et 1.5, le degré de liberté s'accroit considérablement, conduisant à des schémas de fissuration beaucoup plus complexes.

KEYWORDS: Cracking, unsaturated soil, shrinkage test, Bogotá clay.

1 INTRODUCTION

Cracking has an important impact on soil behaviour because it affects aspects such as drainage, compressibility and strength. Desiccation processes, conditions of crack initiation, crack evolution and cracking patterns have been studied on different soils under distinct boundary conditions (Marinho, 1994, Miller et al. 1988, Lloret et al. 1998, Kodikara et al. 2000, Yessiller et al. 2000, Vogel et al. 2005, Ávila et al. 2005, Lakshmikantha 2009, Peron et al. 2009, Tang et al. 2010, Lakshmikantha et al. 2012). When drying test on soils are conducted in square or circular moulds, the cracking patterns are in general complex and very difficult to predict. Nevertheless, when the shape of the moulds force a predominantly one-dimensional contraction, cracks tend to appear in a systematic pattern and it is possible to make predictions about the place and direction of the primary, secondary and in some cases, tertiary cracks. One-dimensional conditions lead to a very favourable situation to get some insight in the apparently erratic evolution of the cracking patterns.

This article shows the experimental results obtained in desiccation tests performed on clay samples from Bogotá city where cracking sequences were observed. From these results a simple one-dimensional cracking conceptual model is proposed based on contraction restrictions and soil tensile strength.

This work is a part of a comprehensive research program to study the problems of soil shrinkage and cracking that affect Bogotá city.

2 CRACKING SEQUENCE DURING DESSICATION TESTS ON BOGOTÁ CLAY

Geological and geotechnical characteristics of the subsoil of Bogotá and the effects of surface deformation and cracks on the infrastructures have been discussed by some authors (Lobo-Guerrero et al. 1992, Ingeominas 1996, Ingeominas and Los Andes University 1997, Ávila 1998, Ávila 2003, Ávila et al. 2005). The test described in this paper have been done on samples of Bogotá clay taken between 2 and 4 m depth (w_L = 62-65%, PI = 30-35% and Activity = 0.52-0.57). These samples are representative of the layers subjected to desiccation and cracking in many sectors of the urban area.

Although different type of desiccation tests were conducted for the comprehensive evaluation of shrinkage and cracking of this clay, the discussion presented in this paper is basically focused on the cracking sequence observed in the experiments made in the double T shaped moulds shown in Figure 1. These moulds impose restriction to shrinkage and induce systematic cracking patterns. Those patterns are particularly interesting for the analysis of the process of formation and propagation of initial cracks and the subsequent process of cracking.

Reconstituted clay samples were prepared at different initial water content and they were left to dry to an open atmosphere to observe the characteristics of the cracking process evolution.

Figure 2 shows three stages of the desiccation process that were observed on three different tests (labeled 1 to 3 in Figure 2) conducted at the same time and under equal atmospheric conditions. First sequence corresponds to a picture taken 4 hours after the initiation of the desiccation process for which moisture contents of the samples ranged between 40% and

41.2% (stage 1). In all cases cracks initiate at the vertices located in the change of geometry of the moulds.

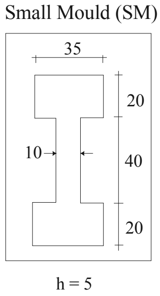

Figure 1. Small moulds (SM) used in the desiccation tests.(from Ávila, 2004). Dimensions are in mm.

The second sequence represents an intermediate stage and the picture was taken 4h:35min after the beginning of the test. Moisture content ranged between 36% and 37.2%. It is clear the complete formation of primary cracks and in all cases their location and form are similar. The volumetric soil contraction can be observed as a separation of the sample from the walls of the moulds.

The third sequence represents the final stage and the picture was taken after 22 h of the test initiation. The primary cracks were completely open and a secondary crack, located near the central part of the sample appears in all samples oriented in parallel direction with respect to the primary cracks. It is remarkable the great similarity observed in the three tests. Note that cracking test repeatability is not frequent due to the multiple variables involved, as previously mentioned.

Similar results were obtained in other tests sequences with different initial water content, as observed in Figure 3. In these tests also tertiary cracks appear in the extremes of all the moulds directed perpendicular to the primary cracks and located in the middle of the extreme areas of the moulds.

During the desiccation process, moisture content of the samples were controlled by weighting them carefully at different times. The relation between initial water content of the samples and water content at initial cracking is presented in Figure 4. It is clear that, the higher the initial moisture content the higher the moisture content at cracking. The relation between both variables implies a greater potential volume change for initially wetter samples due to moisture reduction during desiccation.

3 SIMPLE ONE-DIMENSIONAL CONCEPTUAL MODEL TO EXPLAIN SYSTEMATIC CRACKING

When a soil sample is subjected to a homogeneous drying process, volumetric contraction tends to occur. In free shrinkage conditions, with not friction restrictions in the base or laterally, the sample cracks are not expected because no tensile forces act on it. This condition is sketched in Figure 5 and represents the common case of shrinkage limit tests in which a lubricant is used to reduce friction between the sample and the mould. However, if the sample composition or if the drying conditions are not totally homogeneous the sample may crack due to tensile forces generated inside it.

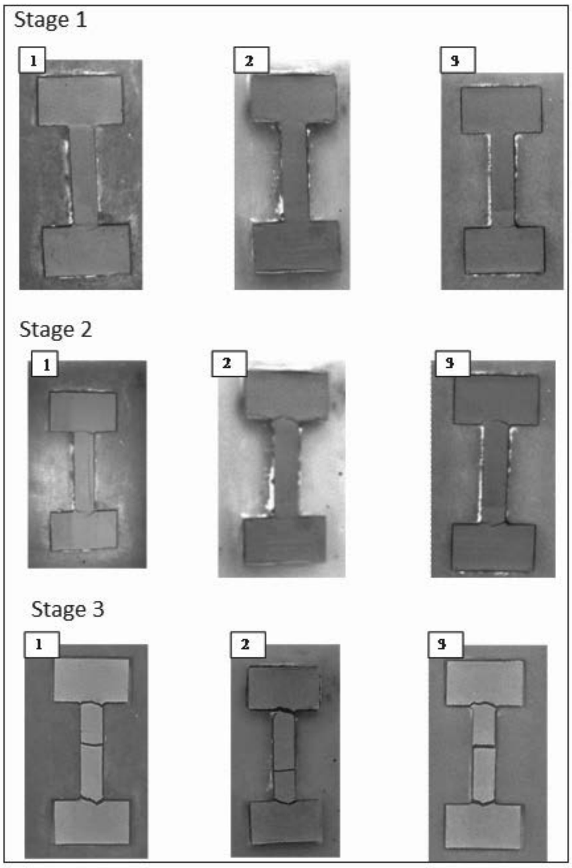

Figure 2. Sequence of cracking of three samples in SM moulds. Primary and secondary cracks are generated in a systematic and homogeneous way in each case.

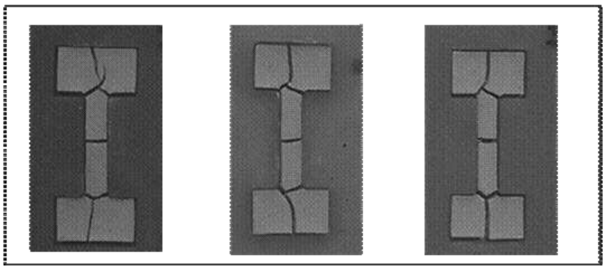

Figure 3. Homogeneous pattern cracking observed at the final stage of three tests similar to those of Fig. 2 but starting from higher water content.

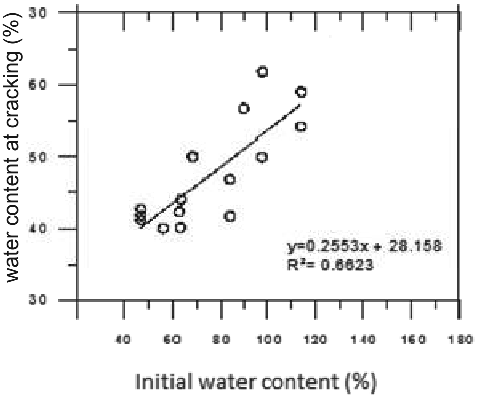

Figure 4. Relation between initial water content and water content at cracking for SM samples.

Cylindrical shape is convenient to ensure uniform drying and homogeneous contractions, however if the base of the mould is not smooth and friction between the mould and the sample develops during desiccation, nonhomogeneous tensile forces are generated producing complex drying patterns.

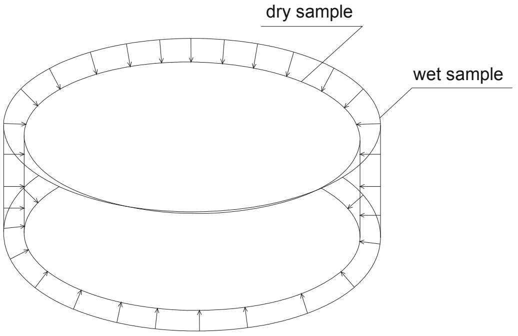

Figure 5. Sketch of a uniform and free contraction of a homogeneous sample subjected to drying. Under these conditions, cracks are not expected.

Stress changes are generated as a result of the forces induced when the soil tends to shrink but the boundary conditions restrict the free shrinkage. Figure 6 represents a simple picture of the forces that may progress in the different sectors of the sample during the desiccation process. Abu-Hejleh and Znidarcic (1995) and Konrad and Ayad (1997) proposed similar patterns for desiccation cracks formation in clayed soils subjected to one-dimensional consolidation and contraction caused by suction increments. In the central sector (sector 2) action forces tend to occur due to the contraction of the sample and these forces are counterbalanced by the reaction forces generated in the extremes of the sample (sectors 1 and 3) where the reaction walls play an important role in avoiding the contraction of the soil. Primary cracks tend to initiate precisely in the vertices of these reaction walls (points a, f, g or l, in Figure 6) because it is where an important stress concentration occurs. Primary cracks progress in a direction perpendicular to the main action forces, as sketched in Figure 7.

Once the primary cracks have been completely developed, shrinkage continues and new stress conditions appear in the different sectors of the sample. In sector 2 (Fig. 6) action forces are directed to the center of the sample trying to produce contraction or length reductions whereas reaction forces are generated by the friction between the soil and the base of the mould avoiding the sample contraction. As a combination of the action and reaction forces, non-uniform tensile stresses are mobilized along the sample. As it is illustrated in Figure 8 primary cracks appear at the points where mobilized tensile stress equals the tensile strength of the soil (points b and d). In the points a and e the mobilized tensile stress are low because restrictions to contraction are not so strong. On point c some restrictions to shrinkage are produced by the base and sides of the mould and a tensile stress is mobilized but of lower value than stress on points b and d. For that reason sample does not crack at this point.

As soon as primary cracks are completely developed, the sample stress distribution changes drastically and a sketch of the possible distribution is depicted in the lower part of Figure 8. This stress distribution may explain the occurrence of secondary cracks in the middle of the sample (point c) generated by the restriction to shrinkage produced mainly by the base of the mould. In this point mobilized tensile stress equals tensile strength of the sample.

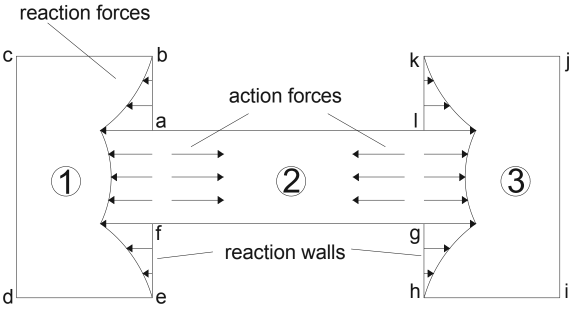

Figure 6. Conceptual representation of the forces that may be developed for producing primary cracking in the sample.

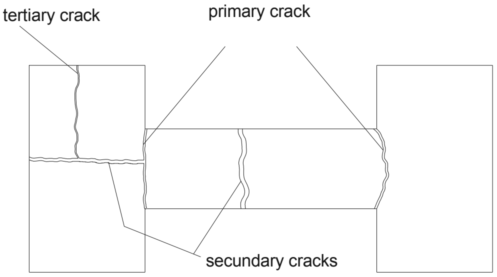

Figure 7. Position and orientation of primary, secondary and tertiary cracks in the drying test.

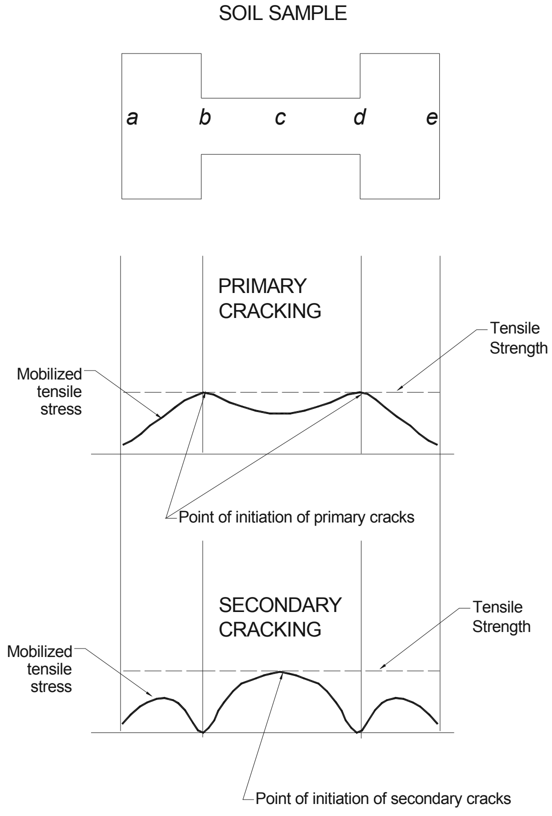

Figure 8. Conceptual stress distribution in the sample for producing primary and secondary cracking.

The tertiary cracks shown in Figure 3 could be generated in a similar way than the secondary crack. For that reason the cracks develop in the middle of the area subjected to tensile stresses. But as previously mentioned, these tertiary cracks are only formed when initial water content of the samples is high, because under these conditions the soil continued to shrink after secondary crack. However the base of the mould constrains that shrinkage producing the new level of cracking.

The model illustrated in Figure 8 is limited to one dimensional shrinkage, this condition is imposed by the shape of the mould where soil desiccation occurs. The shape may be considered by the shape factor (SF) that relates the major to the minor dimensions. For a square or a circle, SF is equals to 1 but for a rectangle SF is greater than 1. Shape Factors greater than about 1.5 tend to impose conditions of one-dimensional shrinkage and cracks appear in a more or less systematic way. For FS lower than 1.5 more than one degree of freedom are present in the shrinkage and cracking sequence, consequently the orientation of those cracks are much more complex to predict (Ávila, 2004).

4 CONCLUSIONS

The prediction of the initiation points and orientation of cracks produced by a desiccation process is in general very complex because many degrees of freedom are present and tensile stresses are mobilized in multiple directions. However under one-dimensional shrinkage that may be imposed to a soil, systematic cracking patterns tend to occur and they may be predicted. The experimental program on small samples prepared under similar conditions and subjected to a common drying atmosphere, showed the repeatability of cracking patterns for primary, secondary and in some cases tertiary cracks.

For laboratory desiccation experiments systematic cracking are commonly observed for moulds that have shape factor (relation length to width) equal or greater than 1.5, for lower values of shape factor the cracking is more complex and difficult to predict.

A simple conceptual model is here proposed to explain why the cracks appear in specific locations and following a particular sequence under the described conditions. This is important for the better understanding of the cracking phenomena in clayey soils, and particularly for the development and validation of numerical analysis of the hydro-mechanical problem of cracking applied to more complex scenarios.

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