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Precise observation of soil surface curling

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ABSTRACT

The process of drying in soil is often associated with complex deformations. Due to the complexity of both the soil structure and the coupled hydro mechanical processes occurring during drying, different forms and shapes can be created during drying. Soil curling is recognized as one of the typical phenomena taking place during shrinkage, when the surface layer is curled up or down by different mechanisms triggered during drying. A precise non-contact electro-optical technique based on a 2D laser profile scanner with motion controller to systematically track the evolution of the exposed surface of a natural soil during controlled drying conditions was used in this research. Different stages of curling were identified at different elapsed times. These stages are discussed in detail. To gain a better understanding of the different curling stages and their associated mechanisms, a set of drying experiments were performed on artificially prepared mixtures of kaolin and silica sand. Particularly, two basic mechanisms were studied: differential drying and differential shrinkage effects. A simple conceptual model is also proposed and discussed to help in the interpretation of the test results involving the curling.

1. Introduction

The desiccation process in soils generally leads to shrinkage with a major rearrangement of the soil particles and significant changes in the stress state. The shrinkage deformations can be divided into two main groups: i) intra-deformations, those located within the particle arrangement (visible under the microscope); and ii) global deformations, observed visually volumetric changes of a given sample or specimen (i.e. shrinkage, cracking or curling). The first group includes the deformations associated with grain redistribution (i.e. Kirkpatrick and Rennie, 1973) and/or aggregate formation (Jim, 1990; Tang et al., 2011). Both kinds of deformations (i.e. global and intra) are intimately related, because most of the global deformations during drying depend on intra-deformations. At that level the whole process initiates, driven by the changes in the capillary pressures (p_c); defined as the excess of the air pressure (p_a) over the (negative) pore liquid pressure (p_l). It is well known that the increase of capillary pressure (or matric suction 's', i.e. $s = p_c = p_a - p_l$) leads to the strengthening of the soil mass (i.e. Fredlund et al., 1978; Ho and Fredlund, 1982; Nearing and West, 1988; Nearing et al., 1988).

The changes in the soil state during drying described above may cause the soil to curve. This phenomenon, called soil curling, can take place in two different ways: i) with edges curling upwards also known as concave-up and ii) edges curling downwards known as convex-up. Curling is a natural soil deformation which occurs during the desiccation process. Soil curling can develop in different environments, such as mud (Allen, 1986), remoulded samples (Nahlawi and Kodikara, 2002, 2006) and compacted construction material (Berney et al., 2008). Curling in soils is generally closely associated with desiccation cracking. Amongst other effects, it has been observed that curling enhances the formation/enlargement of the sub-horizontal cracks in the soil mass (Berney et al., 2008).

Curling has been a topic of a long research tradition in soil physics with the emphasis on physical modelling (Dow, 1964; Kindle, 1917; Kindle and Cole, 1938) and numerical simulations (Allen, 1986; Kodikara et al., 1999). Past research clearly highlight three main factors controlling the curling in soils:

a) Material properties (e.g. soil grain size distribution, mineralogy and soil microstructure);
b) hydraulic boundary conditions (e.g. moisture gradient, differential drying); and
c) other coupled processes involving chemical interactions.

The following phenomena are the dominant ones when looking at the effect of material properties on curling (i.e. factor a) above): differential contraction due to non-homogeneous distribution of soil particles,

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re-distribution of grain particles, and particle aggregation during drying (e.g. Allen, 1986; Kindle, 1917, 1926; Kodikara et al., 2004; Nahlawi and Kodikara, 2002; Valentin and Bresson, 1992). As for factor b), previous studies have been mainly focused on the effect of differential drying conditions; moisture gradients; access of relative humidity to sub-horizontal cracks; and evaporation/infiltration boundary conditions (e.g. Berney et al., 2008; Bradley, 1933; Longwell, 1928; Minter, 1970; Style et al., 2010; Ward, 1923). Other processes that affect the curling (i.e. factor c) are as follows: gradients of salt concentration; solvent evaporation during drying, presence of salt crystals; and changes in matric and osmotic suction and their spatial distribution (e.g. Bradley, 1933; Dow, 1964; Kindle, 1926; Minter, 1970).

The differential drying and differential contraction due to particle distribution are among those mechanisms most researched in the past (Allen, 1986; Bradley, 1933; Kindle, 1917, 1923; Kindle and Cole, 1938). In addition to the aforementioned curling mechanisms, some other factors were recognized to be associated with the curling, for example, the elevation of deposits, clay presence and its type, underlying layer and salt content (e.g. Bradley, 1933; Dow, 1964; Kindle, 1926; Minter, 1970; Ward, 1923). Kindle (1917) appears to be one of the first scientists publishing about soil curling. His drying-pan experiments revealed that the clay content can influence the direction of polygon curling. He was the first to observe that high salinity mud polygons curl downward and those formed in the fresh water curl upwards. A similar observation was later performed by Plummer and Gostin (1981). Some exceptions are known, for example: Minter (1970) reported concave downward polygons forming in the sediments left after flooding on the elevated river embankments. This was due to the contraction at the bottom of the layer, in which drainage was greater than evaporation causing differential drying. Ward (1923) highlighted that the difference in the surface underlying mud flats can also have some influence on the direction of curling. According to Bradley (1933) and Valentin and Bresson (1992), the soil layer will curl towards the finest grained material and the rate of curling will depend on the grain size distribution. Allen (1986) proposed a model to calculate the curvature of curled polygons which was validated against field and laboratory observations.

Curling in soils is strictly associated with water evaporation and generally occurs at the edge of drying polygons formed by the desiccation cracks. Laboratory desiccation experiments looking at soil curling under non-constrained conditions are usually carried out using a slurry paste placed either in circular or rectangular plates (e.g. Kindle, 1923; Kodikara et al., 2004; Nahlawi and Kodikara, 2002). Peron et al. (2009) studied the curling in the laboratory under constrained conditions. In that research, a metallic base with 2 mm spaced parallel grooves across its length was used. Rectangular sample of Bioley silt prepared at around 1.5 the limit liquid (i.e. 1.5 × LL) were used in this study. Although Peron et al. (2009) do not report curling, it is evident that even the shrinkage was restricted in the longitudinal direction, some moderate concave up took place in the uniformly structured soil bar. This curling was moderate compared with the one observed on the Werribee clay (i.e. 1 × LL) and reported by Nahlawi and Kodikara (2002). The presence of smectite minerals in the last one may explain this difference in soil curling.

Curling in soils has been studied using traditional measuring methods (e.g. callipers) and the interest has been mainly focused on the description of the direction of curling (Allen, 1986; Bradley, 1933; Kodikara et al., 2004; Minter, 1970; Ward, 1923). A problem associated with the study of curling in soils is that measurements have to be performed in an extended area; so conventional point-wise measuring-devices are not convenient because a set of synchronized devices will be required. Moreover, the measuring device should not be in contact with the desiccating soil. This is recommended to prevent any perturbation in the stress field that may spuriously affect the phenomenon of curling.

Previous researches have been mainly focused on field and laboratory observations of mud polygons and the slurry paste rectangular samples. However, no attempt has been made to measure the rate of a curvature during drying. Moreover, the spatial nature of curling and the soft nature of the soil at high water contents make it almost impossible to measure the soil curvature using conventional (contact) tools (such as linear vertical displacement transducer (LVDT), calliper or similar devices). In this context, recent measuring techniques based on the processing of digital images appear very convenient for this kind of studies. Digital image analyses are widely used in a number of soil science-related investigations. For example, they are used to study the volume change in soils (e.g. Alshibli and Al-Hamdan, 2001; Alshibli and Sture, 2000; Gachet et al., 2006; Macari et al., 1997; Ören et al., 2006; Puppala et al., 2004), the displacement field in soil samples (e.g. Guler et al., 1999; Messerklinger and Springman, 2007; Obidat and Attom, 1998; Romero et al., 1997), and the morphology of desiccation cracks (e.g. Lakshmikantha et al., 2009, 2012; Li and Zhang, 2010; Velde, 2001). However, a shortcoming of this technique is that a limited number of parameters can be gathered using one camera only. This limitation is dictated because digital images flatten the object to a 2-dimensional set of pixels; which make the third (vertical) dimension not visible. This problem can be overcome by taking pictures at two different angles with two digital cameras (e.g. Kikkawa et al., 2006; Kitzhofer et al., 2010), but this technique is not very common because it makes the measurements much more complicated.

Linear displacement laser sensors (i.e. 1D laser) have been recently used with success in soil-related research (e.g. Hong et al., 2006; Romero et al., 1997). Various 3D laser scanners have also been used in the agricultural science to measure the soil surface roughness (Aguilar et al., 2009; Bertuzzi et al., 1990; Huang and Bradford, 1990, 1992; Römkens et al., 1986) and to study erosion under different rainfalls (Römkens et al., 2001; Wells et al., 2003). However, they have not been used yet to study features of drying soil behaviour, as for example curling.

Some recently developed non-contact technology brings up new possibilities on how to overcome the problem of tracking spatially distributed deformation such as the evolution of curling. In the present work, a high precision profile laser is proposed as a new tool to study the formation of curling. Two main experimental campaigns were carried out to study the process of curling and to understand the mechanisms controlling it. Two different kinds of samples were studied: a natural soil and reconstituted mixtures of kaolin and silica sand. The soil and kaolin/silica mixtures studied in this research and other experimental aspects related to the drying tests are presented in detail. Background information associated with the problem of curling in soils is also introduced. In this paper, the main focus is on the phenomenon of curling, with particular emphases on a better understanding of the different stages of curling.

2. Material and methods

The soil curling phenomenon is governed by physical and mechanical processes which are usually not easy to capture in the natural environment. The proposed laser setup, provides very precise non-contact measurement of the distance between the group of the points organized as a linear beam generated by the laser and the surface. It gives very accurate and real time profile which is obtained at the current position of the laser above the scanned object. A number of parallel 2D profiles and further data processing allow the construction (with high resolution) of a 3D image of the scanned surface. The results gathered with the laser device can be used to explore different features associated with the behaviour of drying soils. The two different samples studied in this work are briefly described below.

2.1. Samples description

Two different materials were investigated in this work: natural soil samples and reconstituted mixtures made up of kaolin and sand. The