Moisture Movement and Mechanisms of Desiccation Crack Development in Engineered Clay Fills

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ABSTRACT: Desiccation cracking is a common phenomenon observed in clay soils subject to drying/wetting cycles. It has implications for clay fill infrastructure (e.g. railway embankments) as cracks can lead to rapid water infiltration, increased pore pressures at depth and hence slope instability. This issue may become more prevalent for UK infrastructure as climate projections predict warmer, drier summers and shorter but more intense rainfall. However, the precise mechanisms controlling crack evolution are not well understood and complex interactions of soil, atmosphere and vegetation must be considered. This study combined field observations with laboratory experiments to address these issues. Field observations of a full-scale embankment tracked the evolution of crack locations and dimensions through the seasons. These were correlated with height, aspect, material density, environmental and soil conditions. Laboratory experiments consisted of cyclic drying/wetting tests within a controlled environmental chamber with crack evolution monitored using digital image analysis. Results showed that material characteristics (plasticity, density, permeability), geometric factors (thickness of the deposit, slope aspect) and environmental factors (humidity, number of drying/wetting cycles) were all influential. The findings suggest implications for the geographic location of infrastructure (related to local materials); construction techniques (historic versus modern) and climatic changes (increased drying/wetting exacerbates crack development).

1 INTRODUCTION

Desiccation cracking is a common phenomenon observed in clay soils that experience volume change when subject to drying/wetting cycles. The phenomenon has potentially severe implications for infrastructure constructed from clay fills (e.g. railway embankments) as cracks can lead to rapid water infiltration and increased pore pressures at a depth that can ultimately destabilise such structures. Hence, the influence of climate on shrinkage and cracking behaviour is key to the sustainable management of geotechnical infrastructure. Jones and Jefferson (2012) reported that, in the preceding 10 years, shrink-swell damage cost the UK economy ~£3 billion; more than for any other geo-hazard. Moreover, in the USA, damage to buildings and infrastructure caused by shrink-swell was estimated to cost of $15 billion annually (Jones and Jefferson 2012).

These issues may become more prevalent for UK infrastructure as climate projections indicate that future weather patterns are likely to exhibit an increased occurrence of warmer summers, causing drying and cracking, and an increase in shorter duration but higher intensity rainfall events, likely to cause increased surface run-off and crack infiltration (Hulme et al. 2002, Jenkins et al. 2010), thus exacerbating the issue of climate-driven destabilisation.

It is known that the availability of water immediately below the drying surface fundamentally governs the moisture exchange mechanism between the soil and atmosphere (Wilson et al. 1997, Tran et al. 2016). As soil dries high pore-water suctions are generated in the very near-surface. As well as generating stresses that cause volume change (shrinkage) and possibly cracking, these heavily influence evaporation via soil surface resistance (Tran et al. (2016)). Where suctions approach the vegetation wilting point (~1500 kPa) this further inhibits the uptake of water by roots, thus limiting the extraction of water by transpiration. Ultimately, these mechanisms reduce the rate of total water loss during drying events and limit the generation of suctions depths that are required to maintain effective stress through wetter periods. As the effective stress reduces, this can then lead to slope instability.

Desiccated conditions also result in very low unsaturated hydraulic conductivity that further limit the migration of water from deeper parts of the soil and reduce the potential for surface infiltration during high-intensity rainfall events. This leads to increased run-off and the possibility of increased infiltration of crack networks, allowing water to reach greater depths and dissipate suctions more rapidly, further increasing the risk of instability.

However, the precise mechanisms and circumstances controlling crack evolution under cyclic drying/wetting conditions are not well understood and the complex interactions of soil, atmosphere and vegetation must be considered.

This study combined a consistent set of field observations and laboratory experiments to develop a better understanding of the factors influencing the development and evolution of fractures in compacted clay fills.

2 METHODOLOGY

2.1 *Field Study*

The field investigation consisted of regular walkover surveys carried out on a full-scale, instrumented embankment test site (BIONICS, Newcastle University - Hughes et al. (2009) - Figures 1 & 2). The embankment, which is constructed of Durham Boulder Clay runs roughly East-West and is constructed in panels with different levels of compaction; *well-compacted*, representative of modern construction practice, and *poorly-compacted*, representative of aging UK infrastructure of ‘end-tipped’ construction.

Figure 1. BIONICS Full-scale embankment test site, Newcastle University.

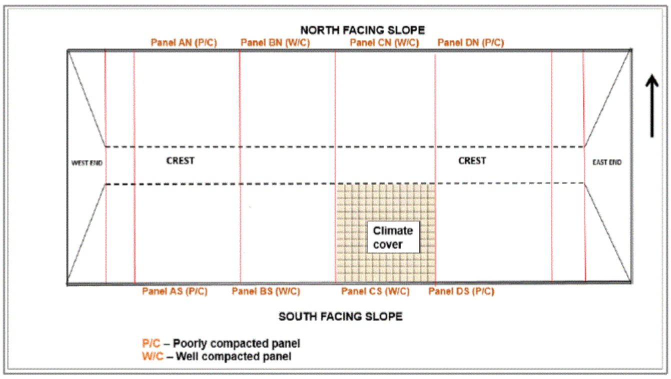


Figure 2. BIONICS Full-scale embankment test site, construction schematic.

Measurement capabilities in and around the embankment include inclinometers, piezometers, tensiometers, theta probes and weather stations. More detail of the construction and instrumentation can be found in the sister paper to this one (Stirling et al. 2018) and in Eminue (2018).

The surveys extended over a period of more than a year during which the evolution of crack morphology was tracked over the course of the changing seasons through measurements of locations and dimensions. These measurements were then correlated with their locations on the embankment with regards to height, aspect to the prevailing weather and material density, as well as to extensive records of environmental and soil conditions available via the wide range of instrumentation at the site.

2.2 *Laboratory Study*

The laboratory study consisted of a set of tests in which soil materials representative of common embankment fills and construction methods in the UK were subjected to cycles of drying and wetting.

The tests were conducted within a bespoke, controlled environmental chamber (Figure 3). The set up comprised of a soil box measuring 310mm deep, 380mm wide and 330mm long and a climate system with which the humidity (typically set to 30%) and the volume of air flow over the samples could be controlled. The mass of the sample was continuously logged for estimation of moisture loss and desiccation profiles. The soils were compacted in layers using different amounts of effort to achieve the desired densities and total thicknesses (between 180mm and 230mm). The moisture content profile through the depth of the samples was monitored and logged using an array of TDR probes mounted at various positions from the outside of the sample box. A transparent window in the top cover of the chamber allowed time-lapse photographs of the samples to be taken automatically throughout the drying and wetting cycles using a digital SLR camera. The time evolution of cracks was then assessed using digital image analysis to calculate the Crack Intensity Factor (CIF), which is defined as the ratio of the total surface crack area to the total surface area of the soil (Miller et al. 1998).

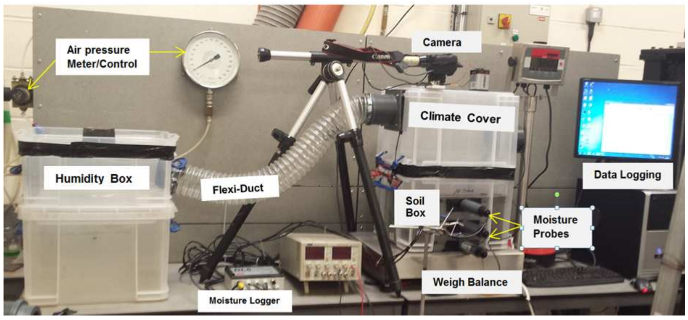


Figure 3. Bespoke, controlled environmental chamber and laboratory test set up.

In total 9 tests were carried out. In each test, the soil sample was prepared at plastic limit before compacting in the soil box by tamping blows using a laboratory rammer. Variation of parameters showed that material characteristics (plasticity, density, and permeability), geometric factors (thickness of the deposit, slope aspect) and environmental factors (humidity, number of drying/wetting cycles) were all influential. More details of the test set up, soil parameters and results can be found in Eminue (2018).

3 RESULTS AND DISCUSSION

The results are presented and discussed in two general themes; climatic control and hydrological response in the materials as well as the cracking characteristics of these conditions

3.1 *Climate condition and hydrology response*

The hydrological analysis showed that soil moisture fluctuates in the near surface of the embankment (Figure 4).

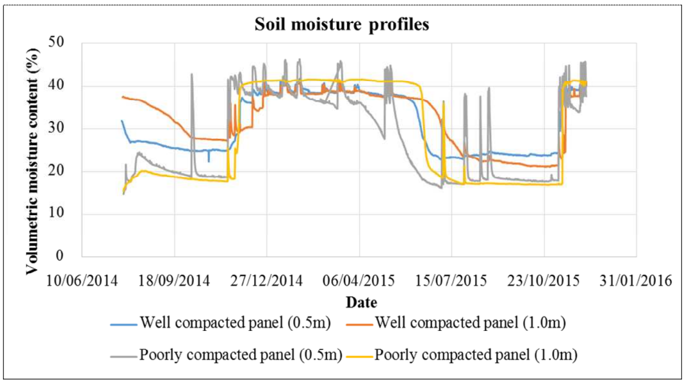


Figure 4. Changes in soil moisture at 0.5m and 1.0m depth at mid-height on the embankment in the engineered panels AS (poorly compacted) and BS (well compacted) of the south slope – See Figure 2

The fluctuation was greatest in the poorly-compacted panels where moisture could move easily through the loose soil structure (i.e. the permeability of the poorly compacted panel was far greater than that of the well-compacted panels - Hughes et al. (2009)). Moisture loss was also more prominent in the south-facing slope (Figure 5). This was due to greater insolation compounded by the prevalent south-westerly wind direction in the locality leading to a higher evapotranspiration recorded in this part of the slope.

The changes in soil hydrology were accompanied by corresponding changes in the soil water potential (or suction), the two soil parameters being interrelated through the effect of capillarity in unsaturated soil. Characteristically, periods of high soil moisture corresponded with high pore water pressure (or low suction) and vice versa, and this correlated with rainfall and sunshine events respectively, indicating a direct response of the soil to prevailing weather conditions (Figure 6).

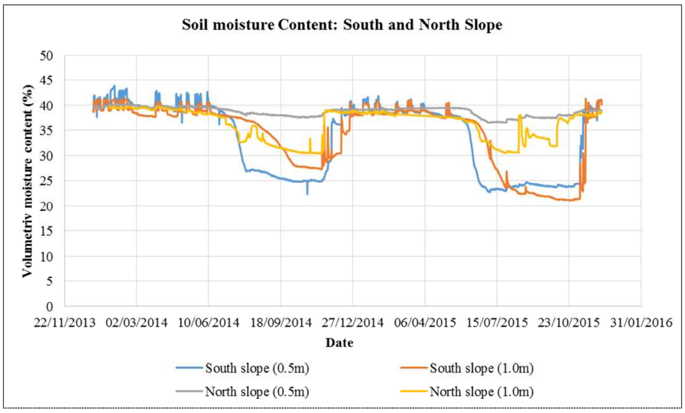
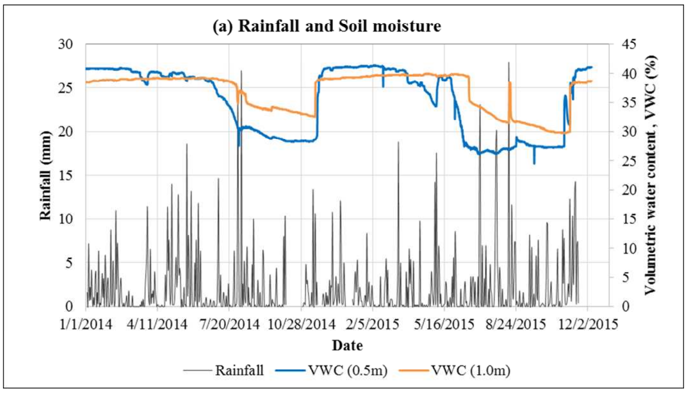


Figure 5. Changes in soil moisture with aspect (at 0.5m and 1.0m depth at mid-height on the embankment in the engineered panels BN and BS (both well compacted) – See Figure 2)



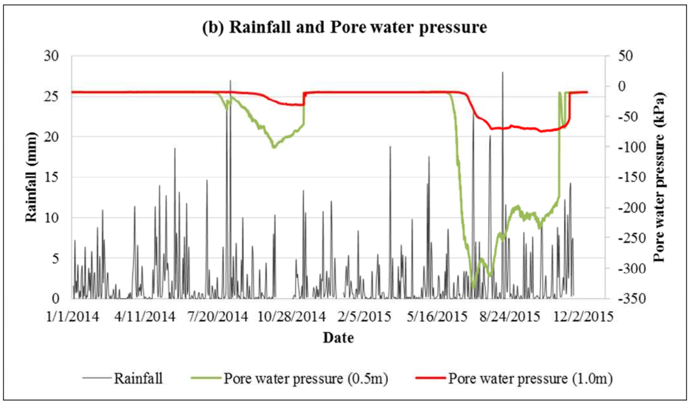


Figure 6. Correlation between rainfall and (a) soil water content (b) pore water pressure, at mid-height on the embankment in the engineered panel BS (well compacted) of the south slope – See Figure 2

3.2 *Cracking behaviour of clay embankment*

The embankment also displayed different cracking behaviour connected to the impact of wet and dry conditions, location/geometry and engineered condition. Figure 7 shows the most prominent cracking occurred in the poorly compacted panel of the south slope (Panel AS) (i.e. most exposed to wind and sun).

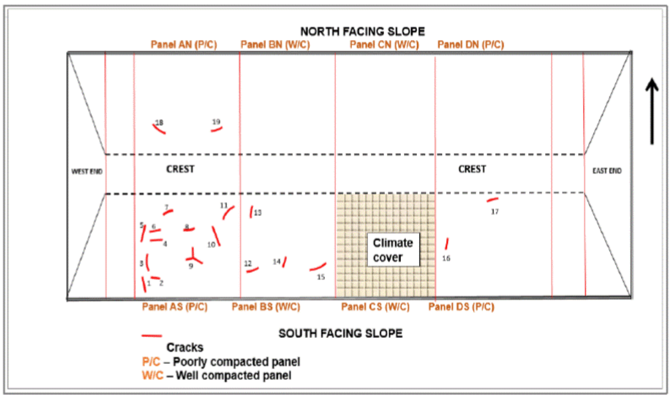


Figure 7. Crack distribution on the BIONICS embankment

Crack opening occurred in late spring as rainfall significantly reduced leading to decreasing soil moisture towards the onset of the dry months. During this period, suctions in the near soil surface increased and reached a maximum in the summer period, both in 2014 and 2015 respectively (Figure 6b). The crack geometry properties correspondingly reached their maxima during the summer period (Eminue 2018).

Furthermore, image analysis of the time-lapse photography obtained from the soil cracking experiments carried out in the laboratory confirmed consistently decreasing cracking intensity factor as the soil density increases (Figure 8). This is possibly because of the potential increase in mechanical strength as the compaction of the soil structure increases. Under the effect of hydrologic stress generated by restrained shrinkage in the soil during drying, the low-density soil would experience more cracking than the high-density soil.

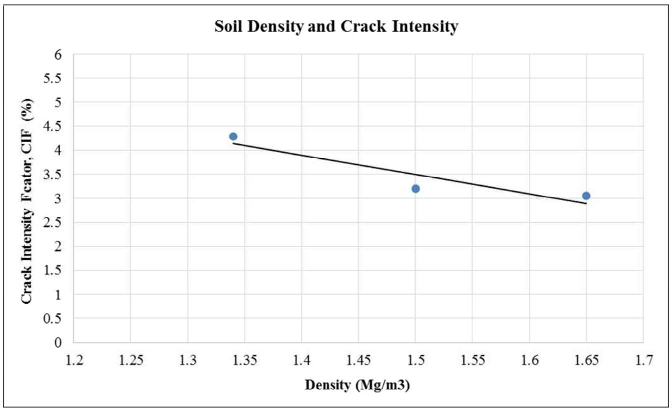


Figure 8. Changes in cracking intensity with soil density (NB – plot shows mean values of two repeats at high and low density where the individual results were so close together that they cannot be separated on the graph, indicating very strong repeatability)

In considering density in relation to construction practice the laboratory study also considered the effect of soil layer thickness as may be varied as part of the compaction process. This showed that a thick soil layer allows more significant moisture gradients to develop and more shrinkage to occur than in a thin soil of the same density. Hence, crack width and depth were also greater in the thicker layer. Furthermore, when the soil was compacted in 1-lift the crack intensity was found to be greater (CIF = 0.86%) than for soil compacted in 2-lifts (CIF = 0.77%). This is attributed to the difference in their density and hence their relative strength. Where the volume of soil remained constant, the applied mechanical energy per unit area would have been less effectively distributed in the thicker, single lift resulting in a lower density (1.63Mg/m^3) compared to that compacted in two lifts (1.65Mg/m^3). Even this relatively small difference in density appears to be significant and this may be particularly important in the construction of some geotechnical structures such as waste covers and nuclear liners which involve thin compacted clay layers.

3.3 *Soil plasticity and cracking*

Important in the engineering behaviour of clay soils is the plasticity index. Plasticity is a soil property controlled by the amount and type of clay minerals within the material and relates strongly to the shrink-swell behaviour of the soil in response to changes in moisture content.

When plastic soils lose moisture, they experience volumetric shrinkage, as the particles are drawn together in the emptied voids by capillarity forces. The extent of shrinkage will depend on their moisture retention potential, a property that generally increases as the plasticity increases. Very high plasticity soils have potential to retain large volumes of water due to their high specific surface for adsorption and hence also exhibit relatively large shrinkages upon dehydration. Under such extreme volumetric changes, greater tensile stresses are likely to be generated within the soil matrix leading to increased cracking.

Three soils with different plasticities and representative of embankment construction materials from different locations within the UK were tested for their cracking characteristics. The soils were intermediate plasticity Durham clay (PI = 20.1), high plasticity Gault clay (PI = 39) and a very high (VH) plasticity clay representative of extreme values documented for London clay (PI = 52). Synthesis of the results indicates that the crack intensity factor increases exponentially as the plasticity increases (Figure 9). A general increase in cracking with increasing plasticity was also reported by Morris et al. (1992) and Dyer et al. (2007).

Under the same environmental conditions, the crack intensity in the very high plasticity clay soil was nearly 4 times higher than the intermediate plasticity clay soil. Therefore, embankments constructed with very high plastic soils, as are typical in the south eastern parts of the UK, are likely to experience significantly more cracking under the same environmental conditions, than those constructed of intermediate plasticity boulder clays typical of the northern parts of the UK.

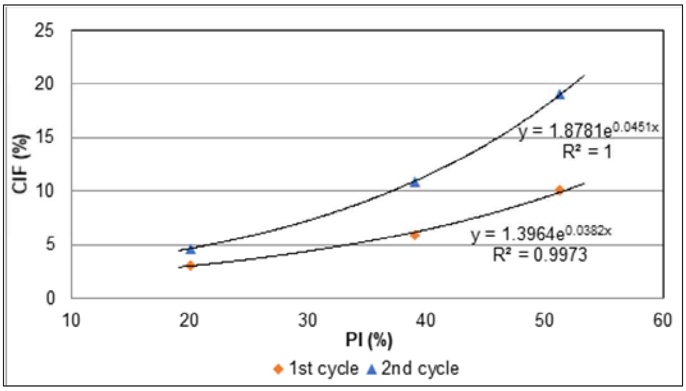


Figure 9: Changes in cracking intensity with soil plasticity

3.4 *Effect of wetting and drying cycles*

To characterise the effects of the cyclic wetting and drying experienced by infrastructure slopes during seasonal climatic variations all of the laboratories test samples were exposed to at least two cycles of drying and rewetting. In the tests involving different soil densities, thicknesses and plasticity, the cracking intensity was found to be higher in the second cycle (Figure 7). Wetting generally reduces the soil strength as interparticle bonds are broken under increased pore water pressure. This combined with the previous crack history renders the soil more susceptible to mechanical failure. However, it was also found that this increase in cracking under cyclic drying and wetting does not continue indefinitely as testing up to 6 cycles showed that the crack intensity tended to level towards a constant value after the third cycle (Figure 10).

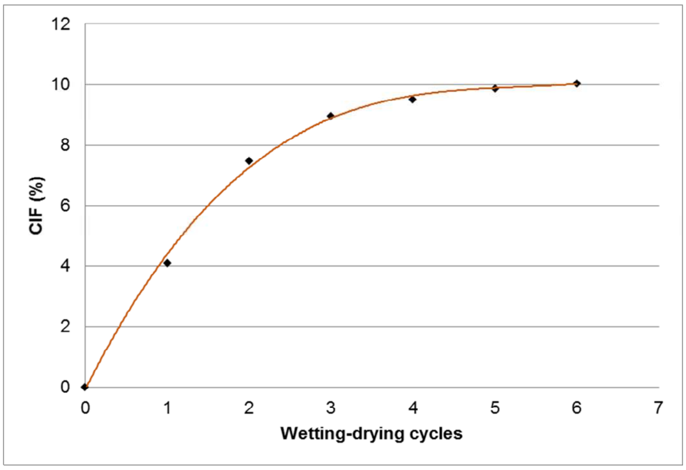


Figure 10. Cracking development with multiple cycles of drying and wetting

The trend suggests a possible stability in the structural dynamics of the soil. This has also been reported by Kodikara et al. (1999) and Tang et al. (2011). As wetting continues in the partially saturated soil, the wet soil loses its strength initially and at the same time, gradual structural changes take place through aggregate coalescence without a complete disintegration often associated with flooded surfaces. Essentially, the clay soil under unsaturated conditions results in enhanced aggregate cohesion by capillary forces. In this analysis, it is considered that the coalescence gradually rebuilds stronger interparticle bonds in successive drying until the effect of wetting collapse is no more visible. As shown in the cyclic CIF, cracking significantly reduces after the 3rd drying cycle. Since the soil mass remained constant, the change can be considered to arise from a structural rearrangement.

4 CONCLUSIONS

The study indicates that desiccation cracking in engineered soil is affected by both environmental and material factors. The cracking response mainly relates to the rate of moisture loss in the different test conditions representing a typical embankment. These include geometry (aspects, soil layer thickness), soil property (plasticity, density, permeability) and environment (humidity, number of drying/wetting cycles). The study specifically reveals that:

1. Desiccation cracking is increased subject to increased drying factors such as on an embankment face exposed to the wind and sun
2. A low humidity climate characterised by warm, dry conditions favours desiccation and the conditions for cracking as compared to a wet climate, which rather causes cracks to close by soil swelling
3. Desiccation cracking intensifies in thicker compaction layers
4. Poorly compacted soils, implying low density and high permeability show increased cracking because of low mechanical strength and a significant volume change in the loose soil structure.
5. The intensity of cracking increases as soil plasticity increases. This is associated with greater shrinkage possible when high plasticity soil loses its large volume of retained moisture
6. Cracking is exacerbated by cyclic wetting and drying. However, this may become insignificant in later cycles as soils tend to attain internal stability against deformation after a threshold of wetting and drying

The above findings ultimately suggest that crack development in an engineered slope has implications for (1) construction techniques, particularly the old embankments constructed to lower densities and in thicker layers, (2) climatic changes as drying/wetting cycles exacerbate crack development, and may lead to more rapid infiltration and (3) geographical locations of infrastructure related to locally sourced fills and their material properties as characterised by plasticity.

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