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Research paper

Modelling the deterioration of the near surface caused by drying induced cracking

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ABSTRACT

Assets such as roads, railways, pipelines and flood embankments are inherently vulnerable to the action of weather and in the long term, climatic change. Their exposure makes them highly susceptible to deterioration during the course of their design life and beyond. The drivers of deterioration are believed to be human (e.g. traffic, maintenance) and environmental (e.g. weather, pollution, burrowing) but the actual deterioration *processes* are not well understood. Among the weather-driven processes, it is believed that desiccation of the near-surface and the development of cracking can significantly influence the mechanical, hydrological and thermal behaviour of geotechnical structures primarily by impacting the transmission of water between the atmosphere and soil. Enhanced infiltration during rainfall events can potentially lead to rapidly elevated pore water pressures and reduced shear strength and is widely cited as the strength reduction mechanism behind the wide spread failure of infrastructure slopes. This paper describes the development of a pseudo-discrete continuum Finite Difference model and its application to investigate the influence of soil properties (including elastic modulus, hydraulic conductivity and soil-water retention) on the desiccation process and eventual crack initiation and propagation behaviour. The generation of a desiccated crust typified by highly negative pore pressures and increasingly disintegrated texture is demonstrated. The influence of projected higher drying rates and seasonal drying-wetting cycles (that could result from climate change) on crack pattern development is investigated to gain an understanding of progressive deterioration. This points towards the potential for increased future deterioration rates of geotechnical infrastructure.

1. Introduction

Geotechnical assets are fundamental to the delivery of critical services, such as roads, railways, pipelines and flood protection structures and are characterised by a number of common features. These include a relatively long physical length and design life (with many assets actually being maintained as serviceable for long periods in excess of their design life). This spatial and temporal 'length' means that these assets are also characterised by their exposure to the action of weather, including a range of extreme events, and climatic change, which causes the asset to 'deteriorate'. These assets are all constructed either with or within engineered or natural soil, making them susceptible to weather driven changes in water content which accelerates and/or causes further 'deterioration'. Furthermore, the soil component of the asset is materially highly heterogeneous, meaning that its current state (relative to the required design performance) is unknown, as is its rate of deterioration. This means that our most critical infrastructure is in an unknown state of repair, and there is currently little understanding of the rate of deterioration of these assets and how this may be affected by extreme weather events or climate change. There is an urgent need to better understand weather-related deterioration processes, the materials most susceptible to these processes and how these might alter in a changing climate.

One such deterioration process is desiccation cracking, a widely observed phenomenon brought about by changes in volume due to drying. The majority of published studies are concerned with investigating small-scale cracking behaviour under controlled laboratory conditions and, in recent years, the development of sophisticated numerical tools to characterise this behaviour e.g. Konrad and Ayad, 1997; Yesiller et al., 2000; Albrecht and Benson, 2001; Kodikara et al., 2004; Nahlawi, 2004; Nahlawi and Kodikara, 2006; Rodriguez et al., 2007; Tang et al., 2008; Peron et al., 2009; Tang et al., 2010; Sánchez et al., 2014. Studies into cracking commonly necessitate the simulation of water removal which is primarily the result of seasonal drying due to evaporation. Additionally are the effects of vegetation and the infiltration potential of the soil surface; therefore, cracking related

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deterioration is largely governed by climate. The implications of climate on shrink-swelling behaviour are central to the sustainable management of our geotechnical infrastructure. It was reported by Jones and Jefferson (2012) that damage due to shrink-swell cost the UK economy £3 billion in the preceding 10 years, surpassing that of any other geo-hazard. Furthermore, an annual cost of $15 billion due to shrink-swell damage to buildings and infrastructure is estimated in the US (Jones and Jefferson, 2012). Projected climate change for the UK indicates an increased occurrence of warmer summers causing drying and a greater number of short duration and high 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 deterioration.

The availability of water immediately below the drying surface is recognised to fundamentally govern the moisture exchange mechanism between the soil and atmosphere (Wilson et al., 1997; Tran et al., 2016). The high pore-water suctions generated in the very shallow zone as soil dries strongly influence the actual evaporation via soil surface resistance (Tran et al., 2016). Furthermore, suctions > 1500 kPa (known as the 'vegetation wilting point') inhibit the uptake of water by roots, thus restricting the extraction of water by transpiration. A reduced rate of total water loss during drying events limits the generation of suction at depth that is required to maintain effective stress through wetter periods (leading, for example to slope instability). Very low unsaturated hydraulic conductivity resulting from desiccation limits the migration of water from beneath and also reduces the infiltration potential during rainfall events. This leads to increased run-off which has the potential to contribute to by-pass flow via crack networks, allowing water to dissipate suctions more rapidly, thus enhancing the risk of instability.

The study presented herein makes several significant scientific advances over previous work in this field. The numerical model developed is capable of capturing the influence of soil properties (mechanical and hydrological) on the weather-driven deterioration process of cracking and further development of crack patterns with drying-wetting cycles. Furthermore, the material properties used in the simulation have been determined from both laboratory and field testing of the same soil and provide a comprehensive suite of soil-specific parameters. Additionally, field testing was used to determine the in-situ density and permeability parameters used in the study to enhance the relevance of the work to field conditions. The model developed has then been employed to investigate the cracking behaviour that results from drying in soils of differing material stiffness, permeability and soil-water retention properties as well as the effect of tensile strength reduction (i.e. the resistance of soil to cracking) due to seasonal drying-wetting cycles. The significance of this work is that the susceptibility of engineering soils to cracking related deterioration may be better understood in the context of current and future climatic conditions. This understanding can then be used to determine the implications of both extreme and repeated seasonal drying on the deterioration of geotechnical infrastructure. This has the potential to be used to quantify the increase in investment required to maintain the long-term performance of assets.

2. Material

Lower Durham Boulder Clay was simulated in this work and was used in the construction of the BIONICS full-scale trial embankment near Newcastle-upon-Tyne UK as described in Hughes et al. (2009) and Glendinning et al. (2014). The use of this material enabled both laboratory derived soil parameters and as-placed parameters to be included. The following composition was established by XRD analysis: quartz 63.5%, feldspar 7%, phyllosilicates/clay minerals including undifferentiated mica species 18.2%, kaolinite 7.1% and chlorite/smectite 0.7%. A range of Geotechnical classification tests have also been performed, the results of which are presented in Table 1.

Table 1
Material classification.

Property		Value
Liquid limit[a], L_l (%)		45
Plastic limit[a], P_l (%)		24
Plastic index[a] (%)		21
Optimum moisture content[b] (%)		15
Maximum dry density[b] (Mg/m^3)		1.82
Particle density[a] (Mg/m^3)		2.64
In situ dry density at < 1 m depth (Mg/m^3)		1.65
PSD[a]	Coefficient of uniformity, Cu	9.6
	Coefficient of curvature, Cz	1.2

[a] BS 1377-2 (British Standard Institute, 1990a) particle density determined using the Gas Jar method.
[b] BS 1377-4 (British Standard Institute, 1990b) 2.5 kg (light) compaction method.

3. Numerical model

A finite difference model was developed to capture the drying processes and eventual crack initiation and propagation using the ITASCA code, FLAC 2D v.4.00. FLAC was selected as it allows the user to access an in-built programming language FISH (Flac-ISH language), which enables complex geometry creation and variable dependent property functions to be automated. The model geometry (Fig. 1) represents the central cross-section through an indicative laboratory experiment consisting of a compacted soil mass within a steel, semi-circular mould (Fig. 2).

Bench top experiments were conducted in order to better constrain the model boundary conditions and for the purposes of numerical-physical model comparison. The steel moulds were approximately 10 times larger than moulds used for linear shrinkage testing according to BS 1377-2 (British Standard Institute, 1990a) while retaining the same length-width ratio.

A total of 5 experiments were conducted using material hand sieved to < 20 mm in order to remove coarse gravel and any substantial organic matter i.e. large roots. This was then air dried on a bench top before being wetted up to an initial water content of between 20 and 25% and allowed to equilibrate for a period of 48 h. The soil was then compacted in three layers using a 2.5 kg hammer to achieve a consistent dry density. This was based upon core cut samples of the in situ embankment fill which were found to have an average dry density of 1.65 Mg/m3, wet of optimum (15% optimum moisture content) at a depth < 1 m from the surface. Drying experiments subject to constant environmental conditions were run for a duration of 144 h (6 days). During this time, the specimen was systematically weighed at 0.5 h intervals for the first 5 h followed by daily intervals for the remaining time in order to ascertain the rate of water loss through drying for the given clay mass, density and drying configuration.

The upper mesh represents the remoulded clay component and comprises four-node quadrilateral elements, each equivalent to 3 mm^2. The soil-steel interface at the base of the experiment was simulated by incorporating a fully fixed region and horizontal interface elements that form a continuous plane subject to shear behaviour. Potential for crack generation was simulated by vertically orientated interfaces that allow the mesh to divide according to normal effective stress (e.g. Amarasiri et al., 2011; Sánchez et al., 2014). This facility is commonly used by numerical simulation packages to simulate jointing, faulting, bedding or any discontinuous feature of a material, typically in a rock mass (e.g. Helm et al., 2013). The general concept used to define the plane between two mesh regions is depicted in Fig. 3.

Grid-points positioned on both sides of the interface are recorded and checked for contact with their opposing neighbour. If for example, point N is found to lie on the segment between points M and P, then the vector normal to the interface is calculated. In addition to this, the length, L, is defined as half the distance to the nearest grid-point to the left (regardless of whether this grid-point is on the opposite or same