ACHILLES

An EPSRC Programme Grant

READING GUIDE 2:

A deeper understanding of deterioration of engineered soils

ADDRESSING INFRASTRUCTURE'S ACHILLES HEEL

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Introduction

The engineering properties (e.g. strength, deformability, permeability) of the soils and compacted fills that form the foundations for our infrastructure are known to change when stresses are applied. These stresses can take the form of increased traffic loading on a road or rail line, or can be produced by the material shrinking and swelling as the material dries out in summer and becomes saturated in winter months. Whilst these drivers of deterioration are known [1,2] the mechanisms through which the deterioration occurs is less well understood. To predict how our infrastructure may deteriorate in the future it is important to understand these processes. One of the aims of the ACHILLES team has been to develop an improved understanding of engineered soil deterioration at the material scale so we can determine the magnitude of changes in soil properties, estimate how long this process will take and identify efficient means of arresting this deterioration.

What is engineered soil deterioration?

ACHILLES defines deterioration as the weather-induced change in the strength, stiffness, structure or hydraulic properties of a clay soil or earthwork (see also *Reading Guide 1*).

Fine grained (clay) soils in cuttings and embankments are susceptible to volume change as their degree of saturation changes. Wetting is driven by rainfall or rising groundwater levels, drying is driven by direct evaporation and vegetation driven transpiration. As the soil goes through cycles of drying and wetting, the size of pores within is changed and cracking can occur [3, 4]. This changes the fabric of the material (as shown in Figure 1), which influences the soil water retention behaviour and the amount of suction that can develop within the soil. The suction within a compacted soil is a measure of the negative pore-water pressure with reference to the pore-air pressure. This suction is generated by surface tension in liquid bridges between soil particles and results in significant apparent cohesion. In other words, higher suction in the soil results in increasing soil strength. If the soil water retention properties of an engineered soil are changed, this can have a significant impact on its engineering performance.

The magnitude of seasonal cycles of porewater pressure is expected to be increased by more extreme and frequent wet and dry events, leading to an accelerated deterioration process.

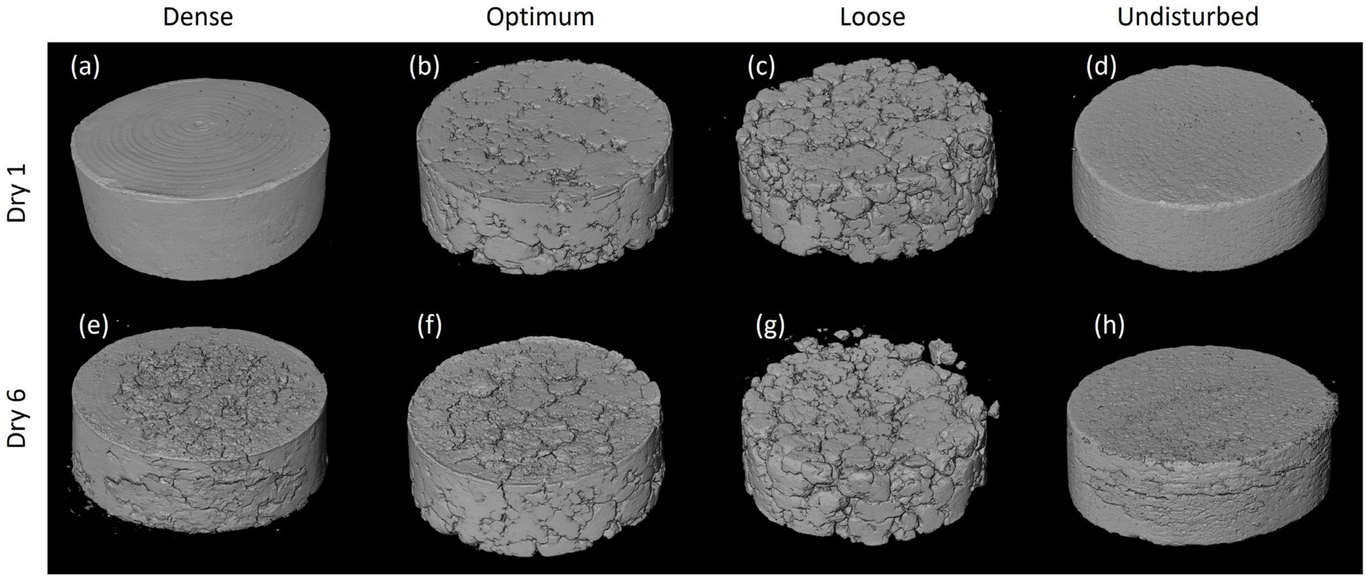

Figure 1: Evidence of engineering soil deterioration observed from images generated by X-ray Computer Tomography. These samples have been subjected to 6 wetting and drying cycles. The top row shows the initial state, the bottom row the state after the 6th cycle. Samples were prepared to be initially in a dense state, compacted at optimum moisture content, in a loose state and in an 'undisturbed' state (taken from in situ samples).

Our main outcomes

ACHILLES has improved the measurement of deterioration

Determining changes that cycles of drying and wetting within soil requires measurement of Soil-Water Retention Curves (SWRC), which relates suction (attractive forces between particles) to water content. The change in this property over time results in changes in the mechanical behaviour of the soil in its unsaturated state that can be interpreted as the deterioration of soil [1].

Also, shrinkage curves, that relate void ratio to suction or water content, reveal some important information regarding deterioration, such as the accumulation of deformations observed in high plasticity clays [5,6,7].

The ACHILLES team developed improvements have been made in laboratory equipment to allow for accurate and easier quantification of the SWRCs. These include development of SWRC measurement rigs [9], the improvement of the measurement range of tensiometers which measure suctions within soils [10, 11], and wetting/drying systems to simulate precipitation and evaporation in the field [6].

A loss of suction is a good indicator of a deteriorating soil

ACHILLES research has shown that cycles of wetting and drying result in a progressively lower suctions generated within soils at the same water content, evidenced by the movement of Soil Water Retention Curves (SWRC) [1,5,7,8]. Measurement of soil shrink-swell curves (SSSC) also reveals accumulation of deformations (fatigue) which influences the SWRCs. Consequently, the soil will progressively present lower shear strength and stiffness over time as suction keeps decreasing with increasing number of cycles [5,7].

The SWRCs quantified on London clay revealed that the compaction conditions and the amplitude of wetting and drying cycles play a role in the types and magnitude of changes of the SWRCs [5,7].

When the soil dries beyond a threshold (around its shrinkage limit) accumulation of deformations are observed. Nonetheless, independently of the range of the cycle, the soil tends to progressively lose the ability to hold suction with cycling [5].

The initial conditions of a soil have a significant effect on the rate of soil deterioration

Tests performed on London clay compacted at varying water content and density show that dense soil tends to progressively swell while loose soil tends to accumulate shrinkage behaviour with increasing number of cycles until an equilibrium state is reached [7]. This accumulation of deformations influences the SWRC of active clays because SWRC is dependent on the volume change.

The evolution of suction loss in soils can be used to forecast deterioration

The SWRC evolution can be predicted using different methods that require different inputs and calibration data [7]. These methods consider the changes in volume resultant from drying-wetting cycles for a better representation of the behaviour of active clays (see Figure 2).

Climate change is expected to enhance the rate of deterioration in high plasticity soils

The magnitude of the seasonal cycles of pore-water pressure is expected to be increased by more extreme and frequent wet and dry events, leading to an accelerated deterioration process. This behaviour can be captured numerically using a kinematic hardening constitutive model, developed by ACHILLES, that incorporates bounding surface plasticity which allows the retaining of some information of recent stress and suction history and the prediction of stiffness degradation, and the hysteretic response during mechanical cyclic loading [12].

These features are essential to capture the effects of continuous soil-atmosphere interaction, and the recurring hydraulic cyclic behaviour caused by more severe atmospheric changes due to climate change. The increase in magnitude of water content change during the different cycles is expected to cause a higher deterioration of shear strength. These shrink/swell cycles can give rise to cumulative, irreversible deformation of the soil mass, and it is important to take this into account in long-term geotechnical assessments of slopes and other structures. For plastic soils, there is an additional risk that this cyclic deformation might lead to deterioration due to softening, and ultimately to failure, as the soil progressively loses its strength over time [13].

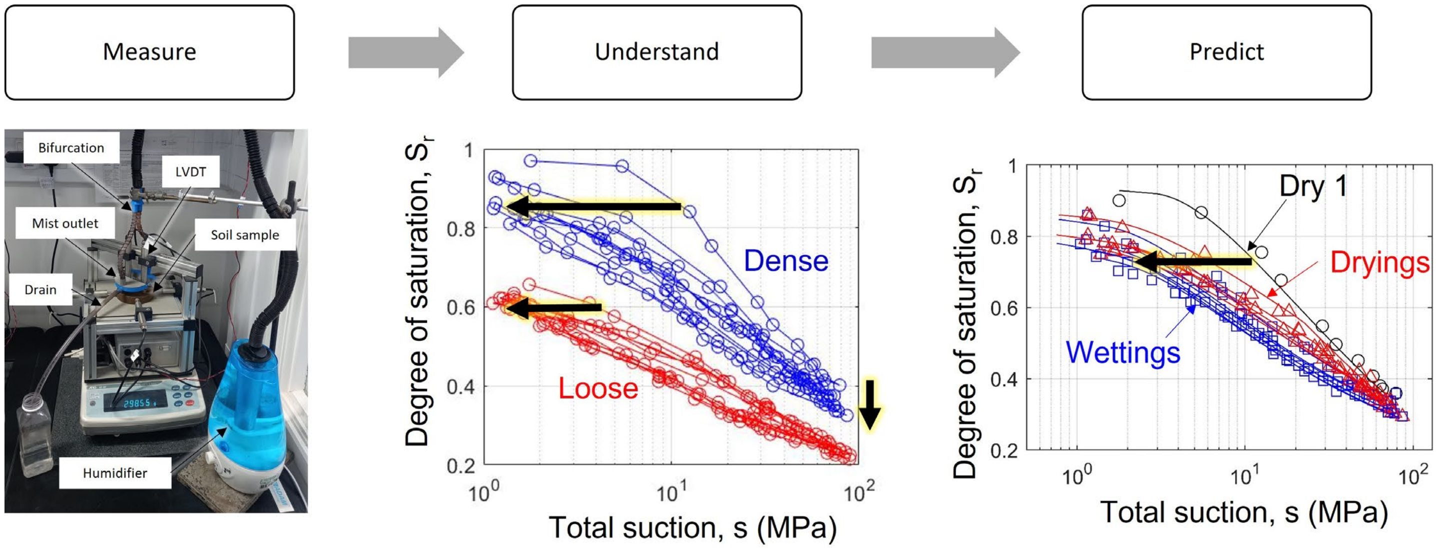

Figure 2: Improvements in the experimental set-up allows the acquisition of higher quality experimental data [6]. The experimental measurements support the understanding of the deterioration mechanisms, as it was observed how soil density plays a role in the loss of suction with increasing number of moisture cycles. These observations are then used in the development of predicting models.

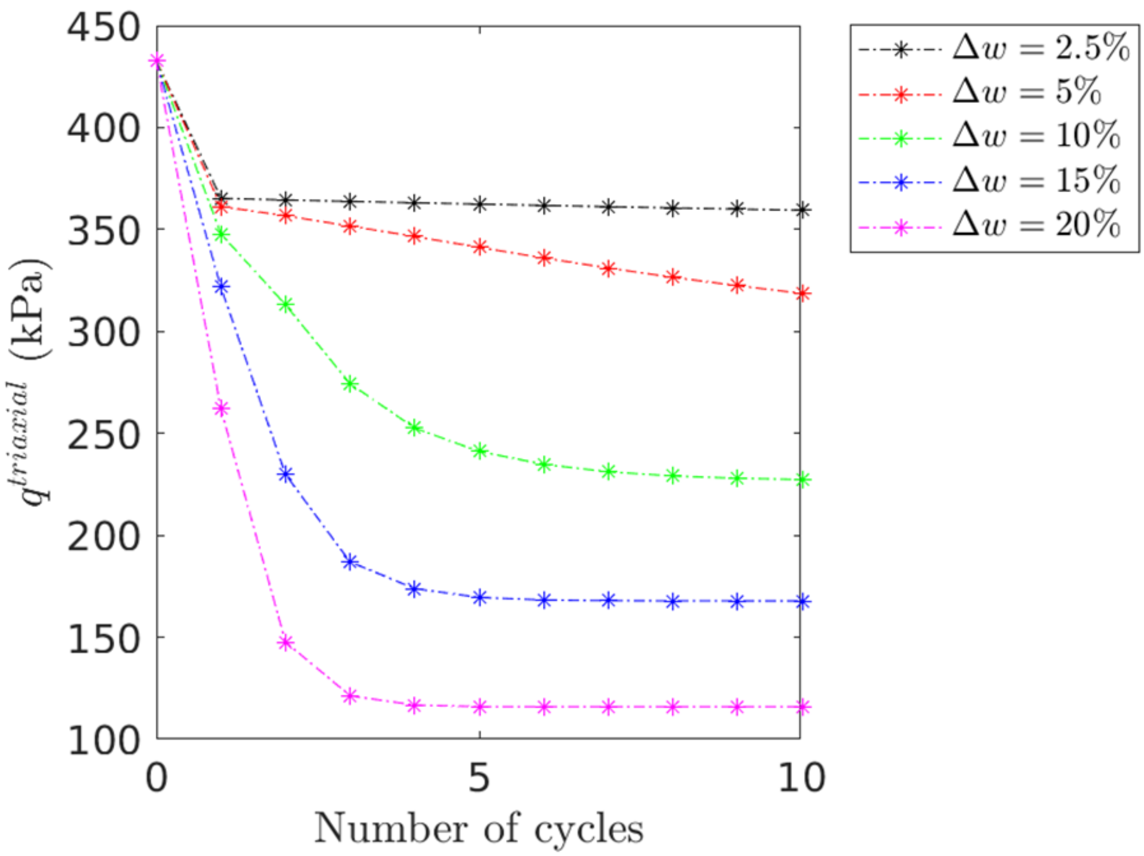

Figure 3: The progression of shear strength deterioration with increased number of cycles, and with increased magnitude of change in water content.

Further reading

Please also refer the other ACHILLES reading guides where you can find out more about what we have achieved. *Reading Guide 1* explains the context of the ACHILLES Programme Grant. *Reading Guide 3* extends our understanding of deterioration to the long linear geotechnical asset scale. *Reading Guide 4* outlines the ways in which we can assess the condition of our long linear geotechnical assets. *Reading Guide 5* provides an overview of the design tools that ACHILLES has developed. *Reading Guide 6* explains how ACHILLES sees data analytics playing a role in addressing deterioration of long-linear geotechnical assets. *Reading Guide 7* discusses the complexities of the business case of timely intervention and mitigation.

Advanced experimental testing on unsaturated soil subjected to drying-wetting cycles.

Shrink/swell cycles can give rise to cumulative, irreversible deformation of the soil mass, and it is important to take this into account in long-term geotechnical assessments of slopes and other structures.

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The ACHILLES Reading Guide Series

1. The ACHILLES concept
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4. Asset condition assessment
5. Design considerations for clay earthworks
6. The role of data analytics in decision-making
7. Intervention strategies and business case

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