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Deterioration of Earthworks Due to Changes in Soil Water Retention Behaviour

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Abstract

A study of the long-term deterioration of a clayey fill (glacial till) used in embankment earthworks is described. The deterioration process is induced by cycles of wetting and drying due to weather events. It results in a loss of strength, thus reducing the long-term resilience of earthworks to resist slope failures. Novel equipment for measuring the soil water retention curve (the relationship between water content and suction) is described that can produce continuous curves during multiple cycles of wetting and drying. The study shows that cycles of wetting and drying produce a shift in the soil water retention behaviour of the fill material. After a number of cycles, the suction present in the fill reduces, even at the same value of water content. This can reduce the shear strength to about 50% of the initial, as-compacted strength. As climate change is anticipated to produce greater amplitude of wetting and drying cycles, this deterioration effect could become even more significant in the future.

Keywords: Deterioration, Soil water retention, Climate change, Wetting, Drying

1. Introduction

Stirling et al. (2021) have identified that deterioration processes are occurring over the life of a geotechnical asset (such as an embankment), resulting in a loss of shear strength of the soil material within the earthworks. These are weather-driven processes due to cycles of wetting and drying. It is argued that this is, in part, due to loss of suction caused by changes to the soil fabric.

The results reported here were obtained as part of an investigation of the impacts of climate on long linear assets, such as embankments for transportation infrastructure. The project ACHILLES (Assessment, costing and enhancement of long-life, long linear assets: https://www.achilles-grant.org.uk) has been established as a collaboration between six UK academic partners (Universities of Newcastle, Durham, Loughborough, Southampton, Bath and Leeds), the British Geological Survey and 11 asset owners and industrial partners to investigate the impacts of weather and climate on long linear assets.

The soil used in this study was a glacial till (Durham Lower Boulder Clay) obtained from fill material used in the construction of an experimental embankment (called the BIONICS embankment) constructed at Nafferton Farm in North East England (Hughes et al., 2009). The fill material is a common fill material in North East England and hence representative of earthwork construction in the north of the UK.

To investigate the effects of wetting and drying, novel equipment for measuring the soil water retention curve (the relationship between water content and suction) is described that can produce continuous curves during multiple cycles of wetting and drying. These curves are used to investigate how the soil water retention behaviour changes over these cycles.

The implications for climate change is considered as it is anticipated that there will be greater amplitude of wetting and drying cycles in the future that could impact on the resilience of earthworks.

2. Weather-driven Deterioration Processes

Toll et al. (2017) and Stirling et al. (2021) have reported the progressive loss in mechanical performance of clay fill due to wetting and drying processes. These were observed in a programme of unsaturated triaxial testing carried out at constant water content.

The soil used in this study (Durham Lower Boulder Clay) was prepared by sieving through a 2.8mm sieve to remove the larger particles to reduce the variation in properties (Mendes, 2011). The sieved material comprised

30% sand, 35% silt and 35% clay, i.e., a sandy clay soil. The Liquid Limit was 43.3% and the Plastic Limit was 23.7%, resulting in a Plasticity Index of 19.6. The particle density is 2.66 Mg/m^3.

Specimens were prepared at 22% gravimetric water content (wet of the optimum water content of 15%) and compacted to a dry density of 1.65 Mg/m^3, comparable with the field density achieved in the BIONICS experimental embankment (Hughes et al., 2009). The degree of saturation after compaction at 22% gravimetric water content would be equivalent to 95%. Specimens were then dried to 15%, where the degree of saturation would reduce to 76%.

The dry-wet cycling was performed outside the triaxial cells by air drying and wetting inside a sealed chamber at high relative humidity as described by Mendes & Toll (2016). Samples were then placed inside a double cell triaxial apparatus and subjected to constant water content compression and subsequent shearing, with measurements of suction using high suction tensiometers (Lourenco et al., 2006; Toll et al., 2013). These devices have been used for direct measurement of suction as large as 2000kPa, although the range was limited to 1200kPa for the various tests reported in this paper. Testing was carried out at atmospheric pressure (not using the axis translation technique).

Testing was carried out at different confining pressures (25, 50 and 100 kPa). The data has been plotted to show the decrease in deviatoric stress, q, for each of the three confining stresses in Figure 1. This shows a 60% to 80% shear strength reduction over the first two cycles, however, for cycles 3 to 6 there is little further strength reduction.

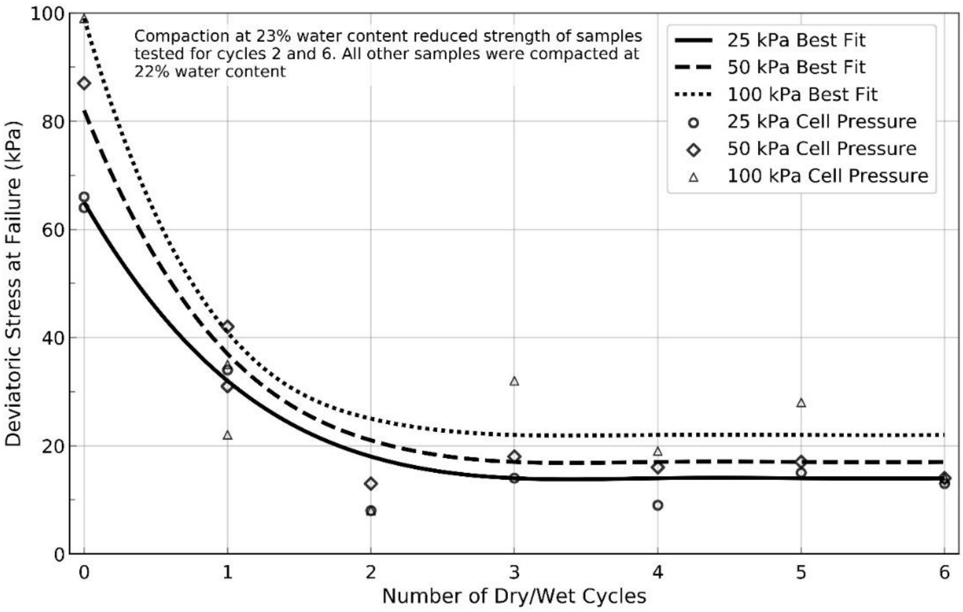

Figure 1: The loss in strength observed after cycles of drying and wetting (Stirling et al. 2021).

While the loss in strength might be restricted to the first two cycles in these tests where cycling is continued between fixed water contents of 22% and 15%, it will be argued later that if the cycles of drying and wetting are extended to greater amplitude, then further losses in strength can be expected.

2.1 Soil Water Retention

To understand the changes in shear strength brought about by drying and wetting, we need to relate these observations to changes in suction that occur during cycles of drying and wetting. We will do this by studying soil water retention curves. A typical soil water retention curve (in terms of volumetric water content) is shown in Figure 1. This relationship has also been called the Soil Water Characteristic Curve (SWCC). However, since the relationship is highly dependent on other factors, such as void ratio, it cannot be properly referred to as a "characteristic" and hence the term Soil Water Retention Curve (SWRC) is preferred. The SWRC can be defined in terms of gravimetric water content (the conventional measurement in geotechnical engineering), volumetric water content or degree of saturation.

The SWRC is hysteretic in nature, with different paths observed for drying and wetting. The primary drying curve defines a drying curve starting from a saturated state. The primary wetting curve is that followed when wetting from a fully dry state. Specimens that start from different water contents (other than the saturated or dry states) will follow a scanning curve (drying or wetting), within the envelope defined by the two primary curves.

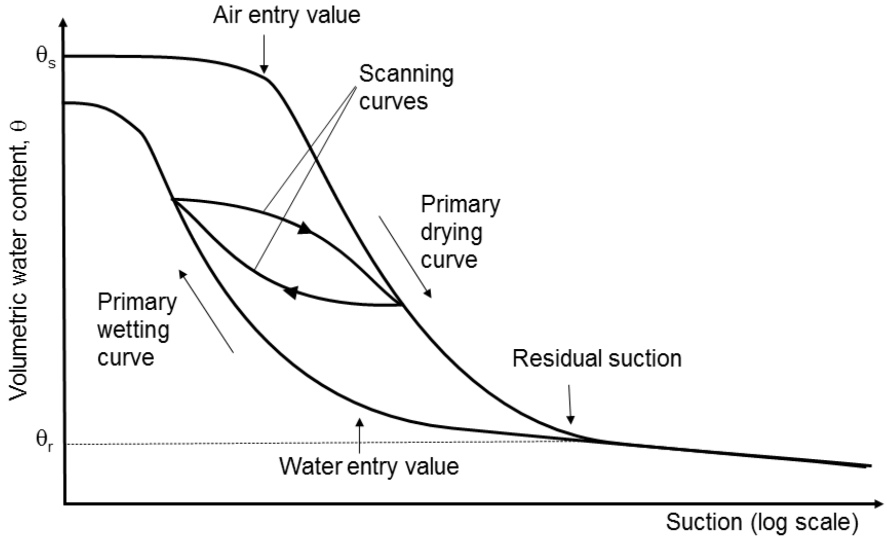

Figure 2: Typical Soil Water Retention Curve (after Toll, 2012).

2.2 Durham University Soil Water Retention Apparatus

The Durham University Soil Water Retention Apparatus has been developed to allow continuous measurements of water content, suction and volume change (Toll et al., 2015; Liu et al., 2020). The apparatus has been further modified by using a light-weight aluminium frame (replacing the PVC prototype) and a support plate to hold the sample (shown in Figure 3). Changes in water content are measured as changes in mass, as the frame is placed on an electronic balance to provide continuous readings of mass. This apparatus is the first piece of equipment to provide natural drying (as opposed to axis-translation), unconstrained shrinkage or swelling with continuous measurements of volume, suction and water content in a way that could readily be used in engineering practice.

A key development was the ability to measure volume change continuously, to support the other measurements of suction and water content. Fredlund (2015) advocated the measurement of volume (in this case, the shrinkage curve for the first drying) on a separate specimen to provide the essential information on volume change to allow calculation of degree of saturation or volumetric water content. However, it is clearly preferable to measure the volume change on the same specimen for which suction and mass changes are being observed. Toll et al. (2015) noted that volume change measurements are essential, as different volumetric paths are followed in different tests for determining water retention curves (e.g. pressure plate and tensiometer techniques). Therefore, water retention curves should never be measured without the accompanying volumetric response.

For volume change measurements, four displacement transducers were attached to the four outside beams of the frame to measure radial displacement of the specimen and two more displacement transducers were fitted through the upper beam to measure axial displacement (change in height) as shown in Figure 3(a). Volume change of the specimen could then be calculated from the radial and axial deformations.

A high suction tensiometer (Lourenco et al., 2006; Toll et al., 2013) was used to measure suction (Figure 3(c)). The tensiometer was fitted through a hole in the support plate (the white spot in Figure 3(a)), with a tight-fitting rubber O-ring to secure it in place. All transducers were connected to a real-time data acquisition system (Toll, 1999). The experimental apparatus was placed in a laboratory in which the temperature was controlled between 22.3^{o} and 23.3^{o} C and the recorded relative humidity fluctuated from 46.5% to 51.1% during the tests.

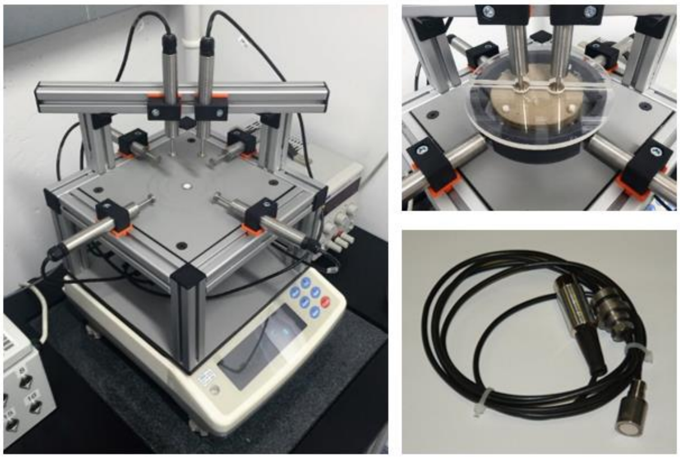

Figure 3: Durham University Soil Water Retention Apparatus (a) view of the frame positioned on an electronic balance (b) view of specimen on the frame (with cowl for controlling rate of drying of specimen) (c) high suction tensiometer.

2.3 Test procedure

The soil was prepared at around 20% water content, comparable to that of soil compacted in the experimental embankment in the field (Hughes et al, 2009). The wetted soil was sealed in plastic bags for more than seven days to equalise. The soil was compacted by drop-hammer compaction to form a sample of 200mm height and 100mm diameter. This sample was subsequently sliced into 5 sub-samples of 40mm high and 100mm diameter. Before testing, these sub-samples were trimmed to specimens with 20mm thickness and 75mm diameter.

During drying paths, the specimen was dried to the atmosphere allowing evaporation from top and side surfaces. A water content change from about 20% to 15% was obtained in about 12 hours. The specimens could not be dried to a lower water content as that would induce cavitation of the tensiometers, so a drying path was ended when the suction increased close to the limit of the tensiometers (~1500 kPa).

Wetting paths were accomplished by gently injecting a calculated mass of distilled water using a syringe on to the specimen surface. The water was applied in the evening and the specimen was then covered with a wetted sponge and plastic membrane and left overnight, so the specimen was evenly moisturised and drying out was limited. Repeated drying and wetting cycles were carried out as described above. After completion of the test, the specimens were oven-dried, which allowed calculation of their water content.

2.4 Test results

Liu et al. (2020) reported on a series of drying and wetting tests but the focus of the work was on volume change. Two of the tests where the soil was subjected to drying and wetting are presented here in terms of the SWRC using a conventional log-scale for suction. They are labelled Test 5 and Test 6 for consistency with Liu et al. (2020) (Tests 1-4 only involved a single phase of drying and are not discussed here). Continuous measurements were only made during the drying phases of the dry-wet tests, so results are only presented for the drying paths of the tests.

Test 5 (Figure 4) shows a specimen starting from a water content of 19.2%. The first drying phase follows a scanning curve that approaches the primary drying curve as suction increases. The specimen was then wetted back to the starting water content and then subjected to drying again. It can be seen that the second drying curve is shifted to the left (lower suction) compared to the first drying curve. The data for the third drying cycle was lost due to a datalogger malfunction, so the next curve is that for the 4th drying phase. It can be seen that the shift to the left continues, although with less significant movement, and this is also seen for drying phases 5 and 6.

Test 6 (Figure 5) shows a specimen starting from a water content of 20.2%. Four cycles of drying are shown (part of the data for the drying phase 2 were lost through a datalogger malfunction). It can be seen that the shift to the left (lower suction) with each cycle is seen as for Test 5. In the final drying phase 4, drying is continued to a lower water content (15%) and the scanning curve approaches the primary drying curve.

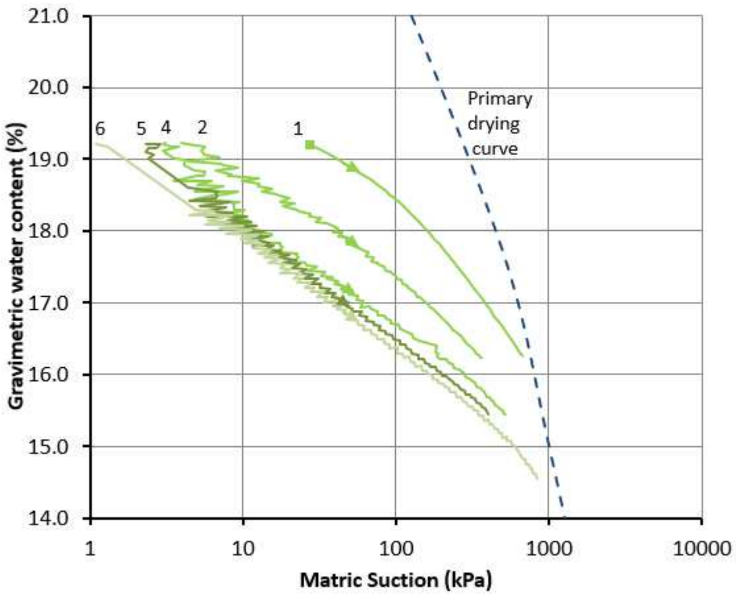

Figure 4: Drying-Wetting test showing drying paths (Test 5).

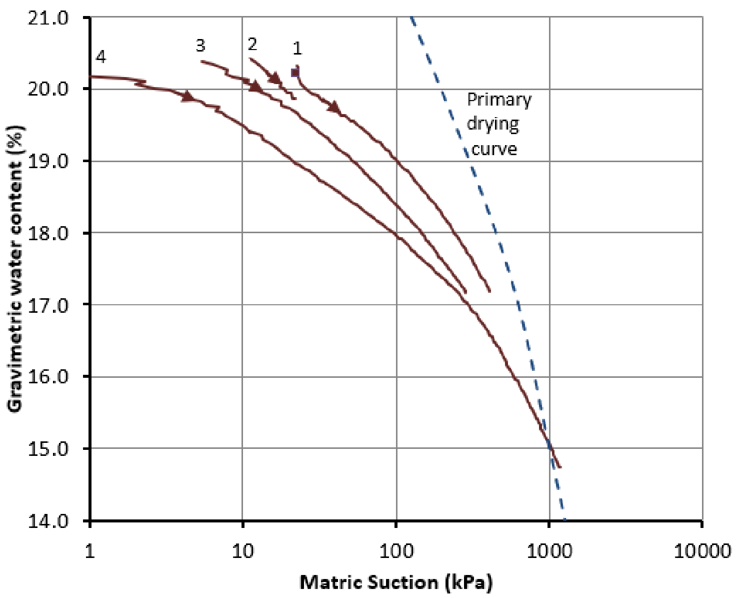

Figure 5: Drying-Wetting test showing drying paths (Test 6).

The results show that with each cycle of wetting and drying, the drying path of the water retention curve becomes shifted to lower suction. The shift is most noticeable in the first three to four cycles but continues to a lesser extent even up to cycle 6.

Therefore, at the same water content, each time the soil is subjected to a wetting and drying event, the suction is reducing. This loss of suction can explain the loss of strength observed in Figure 1, as the presence of suction (negative pore-water pressure) will cause an increase in strength. As the suction reduces, the shear strength will also reduce. It is this mechanism that can explain the deterioration in mechanical performance.

It is observed that the shift in suction becomes less pronounced as the number of cycles proceeds and this is consistent with the greatest loss in strength during the first 3 cycles observed in Figure 1. It might be assumed that this deterioration mechanism would only affect the soil during the first 2-3 cycles. However, these observations are based on cycling over a fixed range of water contents.

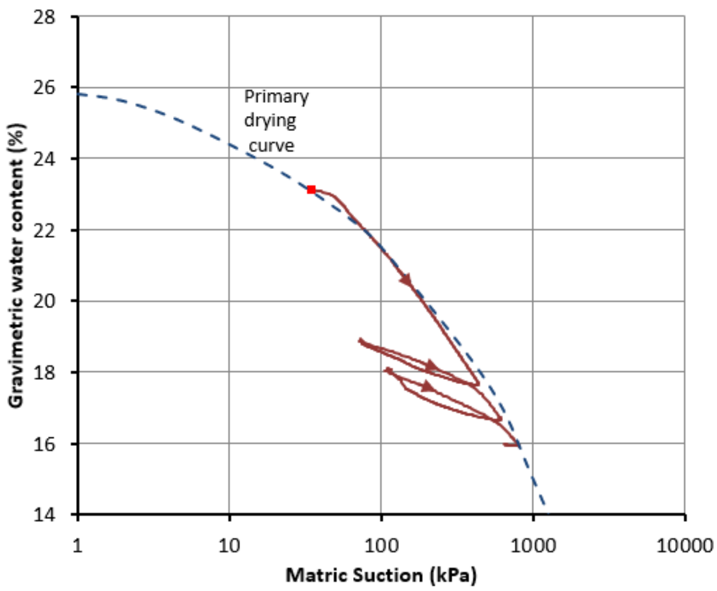

Figure 6: Drying-Wetting test with cycles progressing to lower water content.

In contrast, Figure 6 shows a test where, after the first drying-wetting cycle, the second cycle is continued to dry to a lower water content. The scanning loops of wetting and drying are shifted downwards. The effect of this is for the second scanning loop to exist at lower suctions (if compared at the same water content). Therefore, a more extreme drying event, that goes beyond the water content where cycling was settling into a stable pattern, would be sufficient to create a further loss in suction.

3. Conclusions – Implications for resilience

The important findings of the work undertaken in the ACHILLES project are to demonstrate a weather-induced deterioration process that has significant implications for resilience to climate change. Results are presented for cycles of drying and wetting on a glacial till (Durham Lower Boulder Clay), an intermediate plasticity sandy clay, typical of fill materials that might be used in embankment construction in the North of England. It is observed that with cycles of drying and wetting, the values of suction progressively reduce, even at the same value of water content. This can lead to a significant loss in strength, sufficient to reduce the shear strength to below 50% of the initial, as-compacted strength. Such loss of strength is likely to lead to slope failures on embankments. As climate change is anticipated to produce greater amplitude of wetting and drying cycles, with wetter winters and drier summers, this deterioration effect could become even more significant in the future.

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