Deterioration of earthworks and the resultant implications for serviceability and increased occurrence of failures have a significant negative impact on transport networks both in the UK and internationally. There is evidence in the field that deterioration processes are occurring over the life of an asset, comprising cracking and loss of suction. These are weather-driven processes that occur in the absence of increased mechanical loads and can lead to failure many years after construction. To demonstrate the progressive loss in mechanical performance of clay fill due to a purely environmentally driven deterioration process, a programme of unsaturated triaxial testing was carried out. A new mechanism of soil deterioration driven by cyclic wetting and drying is proposed, based on an extensive laboratory and field experimental programme. The underlying cause for this is the micro-structural changes to the soil fabric leading to loss of suction generation capacity. In addition, cracking leads to changes in hydraulic conductivity and the movement of water into and out of the soil. The implications for slope stability assessment include the need for changeability of soil parameters and of the ground model, with changes occurring both seasonally and gradually over time.

KEYWORDS: fabric/structure of soils; field instrumentation; laboratory tests; partial saturation; slopes
STRENGTH REDUCTION

To investigate the progressive loss in mechanical performance of clay fill due to wetting and drying processes, a programme of unsaturated triaxial testing at constant water content was performed. The material studied in this work is a sandy clay derived from Durham Lower Boulder Clay (a glacial till referred to as Nafferton soil herein). This soil was used in the construction of the Bionics full-scale research embankment (Hughes et al., 2009; Glendinning et al., 2014), located at Nafferton in the north east of England, near Newcastle upon Tyne. The prepared material comprised 30% sand, 35% silt and 35% clay, with a liquid limit of 43.3% and a plastic limit of 23.7%, resulting in a plasticity index of 19.6%.

The material comprised 30% sand, 35% silt and 35% clay, with a liquid limit of 43.3% and a plastic limit of 23.7%, resulting in a plasticity index of 19.6%. The soil was used in the construction of the Bionics full-scale research embankment (Hughes et al., 2009; Glendinning et al., 2014), located at Nafferton in the north east of England, near Newcastle upon Tyne. The prepared material comprised 30% sand, 35% silt and 35% clay, with a liquid limit of 43.3% and a plastic limit of 23.7%, resulting in a plasticity index of 19.6%.

Samples were subjected to varying numbers of drying–wetting cycles in which they were dried to a water content of 15% and then wetted back to the initial water content of 22%. The dry–wet cycling was performed outside the triaxial cells by wetting inside a sealed chamber at high relative humidity and air drying 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 (negative pore water pressure) using high-suction tensiometers with a capacity of 1500 kPa (Toll et al., 2013). Testing was carried out at atmospheric pressure (not using the axis translation technique) so the suctions measured are matric suctions. In most cases, at these degrees of saturation, the pore water pressures were positive after the application of the confining stress.

Testing was carried out using a multi-stage procedure at different confining pressures (25, 50 and 100 kPa) for seven specimens, while three specimens (1, 18 and 19) were tested using a single-stage procedure (see Table 1). Multistage testing was used due to the long times necessary for preparing specimens that were subjected to up to six drying and wetting cycles. There were concerns that variability between specimens could affect the results, so testing at three stress levels on the same specimen was seen as the best option. While it is recognised that peak strengths measured in subsequent stages can be affected by the degree of straining to which the specimen has previously been subjected, it was felt this would not be as important in compacted soils as it might be for natural intact specimens (with chemical bonds that would be broken down by straining). The three tests carried out as a single stage are identified in Fig. 1. In all multistage tests, the same sequence of stages was followed (25 kPa, 50 kPa and 100 kPa). Therefore, the data for all tests at 25 kPa are for first-stage tests, and would not be affected by previous shearing. Tests at 50 kPa and 100 kPa were carried out after previous stages of shearing, and therefore might be expected to be affected in the same way. Therefore, the trends with the number of cycles would be consistent, as is seen in Fig. 1.

The decision to end one stage and move to the next was based on continual monitoring of the q/p’ ratio. When a peak in the q/p’ ratio was observed, this was taken to indicate that the stage had reached the failure envelope, before progressing

Table 1. Test details for constant water content triaxial tests

| No. of dry/wet cycles | Sample | Confining stress: kPa | Gravimetric water content: % | Degree of saturation, Sī | Initial mean effective stress, (p – u0): kPa | Initial pore water pressure, u0: kPa | Mean effective stress at failure, (p – u0): kPa | Deviator stress at failure, q: kPa |
|-----------------------|--------|------------------------|-----------------------------|--------------------------|------------------------------------------|---------------------------------|-----------------------------------|---------------------------------|
| 0 (as compacted)      | 1      | 25                     | 21.1                        | 0.93                     | 30                                       | –5                             | 36                                | 64                              |
| 0 (as compacted)      | 2      | 25                     | 21.1                        | 0.96                     | 41                                       | –16                            | 37                                | 66                              |
| 0 (as compacted)      | 2      | 50                     | 20.8                        | 0.99                     | 48                                       | 2                              | 58                                | 87                              |
| 1                     | 2      | 100                    | 20.8                        | 1.00                     | 60                                       | 40                             | 67                                | 99                              |
| 1                     | 5      | 25                     | 21.0                        | 0.92                     | 16                                       | 9                              | 15                                | 34                              |
| 1                     | 5      | 50                     | 21.0                        | 0.93                     | 13                                       | 8                              | 12                                | 31                              |
| 1                     | 5      | 100                    | 21.0                        | 0.95                     | 15                                       | 8                              | 11                                | 35                              |
| 1                     | 18     | 50                     | 21.0                        | 0.99                     | 22                                       | 28                             | 18                                | 42                              |
| 1                     | 19     | 100                    | 22.0                        | 0.97                     | 10                                       | 90                             | 5                                 | 22                              |
| 1                     | 11     | 25                     | 23.3                        | 1.00                     | 4                                        | 21                             | 3                                 | 8                               |
| 1                     | 11     | 50                     | 23.3                        | 1.00                     | 4                                        | 46                             | 3                                 | 13                              |
| 1                     | 11     | 100                    | 23.3                        | 1.00                     | 1                                        | 99                             | 3                                 | 8                               |
| 3                     | 6      | 25                     | 21.0                        | 0.97                     | 8                                        | 17                             | 4                                 | 14                              |
| 3                     | 6      | 50                     | 21.0                        | 0.98                     | 11                                       | 39                             | 8                                 | 18                              |
| 3                     | 6      | 100                    | 21.0                        | 0.99                     | 15                                       | 85                             | 13                                | 32                              |
| 4                     | 15     | 25                     | 22.6                        | 0.97                     | 4                                        | 21                             | 2                                 | 9                               |
| 4                     | 15     | 50                     | 22.6                        | 0.99                     | 4                                        | 45                             | 4                                 | 16                              |
| 4                     | 15     | 100                    | 22.6                        | 1.00                     | 5                                        | 95                             | 5                                 | 19                              |
| 5                     | 13     | 25                     | 21.7                        | 0.99                     | 3                                        | 22                             | 17                                | 15                              |
| 5                     | 13     | 50                     | 21.7                        | 0.99                     | 3                                        | 47                             | 1                                 | 17                              |
| 5                     | 13     | 100                    | 21.7                        | 0.99                     | 5                                        | 95                             | 5                                 | 28                              |
| 6                     | 9      | 25                     | 23.2                        | 1.00                     | 6                                        | 19                             | 6                                 | 13                              |
| 6                     | 9      | 50                     | 23.2                        | 1.00                     | 7                                        | 43                             | 7                                 | 14                              |
| 6                     | 9      | 100                    | 23.2                        | 1.00                     | 9                                        | 91                             | 9                                 | 14                              |
Fig. 1. Triaxial test results on unsaturated specimens subjected to cycles of drying and wetting

to the next stage. All samples were at or very near full saturation (S_r > 97%) at the beginning of the test.

For tests at high degrees of saturation (>90%), the results can be interpreted using a simple ‘Bishop stress’ approach, where Bishop’s r factor (Bishop, 1959) is taken as equal to the degree of saturation (as first used by Schrefler (1984) and justified as average soil skeleton stress by Jommi (2000)).

\[ p^* = p - [S_r u_w + (1 - S_r) u_a] \]

where \( p^* \) is the mean ‘Bishop stress’; \( p \) is the mean total stress; \( S_r \) is the degree of saturation; \( u_w \) is pore water pressure and \( u_a \) is pore air pressure.

In this work the high degree of saturation (\( S_r \approx 1 \)) in the samples leads to \( u_a \) being negligible and the resultant equation being applied

\[ p^* = p - u_w \]

Figure 1 shows the stress paths in terms of mean Bishop stress, \( p^* \) plotted against deviatoric stress, \( q \). The figure shows the deviatoric stresses at failure for the initial ‘as compacted’ specimens were 60–100 kPa (equivalent to shear strengths of 30–50 kPa), for the range of confining stresses investigated. After one cycle of drying (to 15% water content) and wetting (back to 22%), the deviator stresses reduced to 30 kPa (equivalent to shear strengths of less than 15 kPa). After two or more cycles of drying and wetting, the deviator stresses reduced below 30 kPa (equivalent to shear strengths of less than 15 kPa).

The data have been plotted to show the decrease in deviatoric stress, \( q \), for each of the three confining stresses (25, 50 and 100 kPa) in Fig. 2. 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.

Mendes & Toll (2016) previously tested Nafferton soil, investigating the effects of drying back, or wetting up from an initial compacted state. They found that samples that are dried back to a particular water content had a higher strength than a sample compacted at that water content; conversely, a sample wetted to achieve that water content had a lower strength. The data presented here show that a full cycle of drying and wetting results in an overall loss of strength, which is exacerbated by further wet–dry cycles. This behaviour occurs up to a limiting number for cycles of a similar magnitude, the effect of exposure to larger cycles is discussed in the later section entitled ‘Development of SWRC under environmental cycling’.

The effect of dry–wet cycles on tensile strength is a crucial factor in desiccation crack initiation and crack network development in clay-rich fills. The development of tensile strength with dry–wet cycling has been investigated using a direct tensile strength test described by Stirling et al. (2015). Crack initiation is assumed to occur by induced tensile stress brought about by restrained shrinkage due to surface desiccation exceeding the soil tensile strength. The development of tensile strength in clay soils with changing water content is related to (but not solely a result of) an inherent increase in matrix suction. A cracking analysis on this basis indicates that crack initiation will occur at a given tensile strength, which exists at a specific water content. However, it has been found that reduced tensile strength is achieved upon cyclic wetting and drying, meaning the use of a single, initial drying relationship will result in an underestimation of subsequent crack network development. The relationship between tensile strength and water content established along an initial drying path has been considered as a main influence on the temporal and spatial distribution of cracking during progressive soil drying.

A programme of testing was conducted to investigate the tensile strength change with dry–wet cycles in Nafferton soil. This behaviour is presented in Fig. 3 for samples undergoing initial drying, wetting and subsequent re-drying. The initial drying path shows a trend of exponentially increasing tensile strength with decreasing water content. This path is fitted with the highest \( R^2 \) value; the confidence of fit is noted to reduce with each subsequent path. Upon wetting, a similarly exponential trend may be fitted. However, the wetting relationship follows much lower strength values and at water contents > 20%, negligible tensile stress is maintained. The second drying path exhibits higher tensile strengths than that of the wetting trend, yet is considerably weaker than the initial drying curve.
The reduction in tensile strength produced by cycling water content is evident, in addition to the hysteric relationship between matric suction and water content, which is familiar in the study of soil wetting. In other words, in the context of soil-water retention, upon wetting, lower suction is developed at a given water content than would be generated upon drying. This effect may well contribute to the reduced strength shown along the wetting path, but cannot be the sole cause because of the continued reduction in tensile strength with cycles of water content.

In order to explain the reduction in strength with wet–dry cycles, a model of soil fabric deterioration is proposed, in which micro-cracks are developed during the initial desiccation stage that reduce the tensile strength that leads to crack initiation. This leads to irrecoverable deterioration of the structure of the compacted clay. This in turn causes stress concentrations in the intact clay fabric under further wet–dry cycles, which may reach the tensile limiting stress and cause crack propagation ultimately manifesting as an interconnected network of cracks with progressive cycles. This phenomenon, as documented by Tang et al. (2011) and Wang et al. (2017), has been further investigated herein using scanning electron microscopy (SEM), the results of which are described in the following section.

In summary, significant losses in shear and tensile strength are observed after each drying–wetting cycle, consistent with the reduced ability of the soil to generate a consistent level of suction. The underlying mechanism by which suction generation is reduced is proposed as the development of a matrix of cracking throughout the soil.

**MICROSTRUCTURAL CHANGE**

To investigate the presence of microstructural changes upon repeated drying, imaging at the nano/micrometre scale was carried out using an environmental scanning electron microscope (E-SEM). Specimens were prepared at water contents equivalent to the liquid limit and allowed to come to water content equalisation (sealed for 24 h) before being statically compacted into 10 mm dia. circular steel specimen holders to a depth of 5 mm. A drying environment was promoted by a reduction in pressure within the imaging chamber.

The samples were analysed using an FEI Company Quanta 600 ESEM equipped with an Oxford Instruments Inca Energy-dispersive X-ray microanalysis (EDXA) system using a 50 mm² Peltier-cooled silicon drift X-ray detector (SDD). The samples were analysed without application of an electrically conductive coating. To control the sample moisture content and mitigate surface charging they were analysed under variable pressure conditions using a water vapour atmosphere and a Peltier-cooled stage. Drying was instigated by modifying chamber pressure, with the sample being held at 2°C (±0.01°C) and adjusting the pressure to below the water liquidus (5.3 Torr). Wetting was conducted by removing the specimen from the chamber, and applying four droplets of deionised water before being resealed for re-equilibration. Electron beam conditions were: accelerating voltage 10–20 kV, spot sizes 5 (nominal beam current range of 0.95–1.2 nA), working distance of 9.5–12 mm. SEM photomicrographs were obtained using backscattered electrons. Fig. 4 shows a single specimen subjected to a succession of three drying cycles and the crack pattern resulting from each drying stage. The images presented represent the end of drying – a chamber relative humidity of 100%. Figs 4(a)–4(c) illustrate the development of an increasingly interconnected and propagating network of cracks. Figs 4(d)–4(f) show the disaggregation of the clay structure with each successive cycle.

**DEVELOPMENT OF SWRC UNDER ENVIRONMENTAL CYCLING**

**Laboratory determination of cyclic SWRCs**

Soil-water retention curves define the relationship between water content and suction and represent a key aspect of understanding the unsaturated behaviour of soils. The SWRC testing apparatus developed by Toll et al. (2015) and Liu et al. (2020) was used because it allows continuous measurements of water content, suction and volume change. The measurement set-up consists of an electronic balance to determine the change in weight, and in turn gravimetric measurements and a high-capacity tensiometer to measure suction. However, other techniques were also used, including pressure plate, filter paper and dew point potentiometer.

Laboratory testing of soil-water retention behaviour was performed on specimens of the Nafferton soil. Specimens were prepared by air drying and sieving to < 2.8 mm in order to improve homogeneity and consistency between specimens (Mendes, 2011), and compacted at 22% water content into a 100 mm dia. mould using the equivalent effort of the standard 2.5 kg Proctor test. Specimens were trimmed to a diameter of 75 mm and a thickness of 20 mm for testing.

Figure 5 shows a suite of SWRCs expressed in both gravimetric and volumetric water content, as well as degree of
saturation terms. Good agreement can be seen between the differing test methodologies, defining an initial drying path SWRC envelope (see figure). Specimens compacted wet of optimum (near saturation) influence the upper bound of this envelope, whereas specimens compacted nearer the optimum water content (20% gravimetric water content)
show a flatter response, narrowing the envelope as suction increases.

To investigate the influence of wet–dry cycles, drying paths were imposed by allowing specimens to dry slowly in a controlled environment, in which the temperature was maintained between 22.5°C and 23.5°C and the recorded relative humidity fluctuated from 46.5% to 51.1% during the tests. Wetting paths were imposed either manually or by applying a constant rate of water droplets through an automated wetting system. Specimens were positioned on a low-friction surface during the test; combined with the slow rate of drying, this reduced the potential for the formation of large (>0.5 mm) cracks during water content cycling, although micro-scale cracks as observed in Fig. 4 could still develop.

Figure 6 shows a test where the soil was initially prepared at 23.3% gravimetric water content. It was allowed to dry until reaching a matric suction of 500 kPa. It was then wetted to 24.1%, before drying again to achieve a suction of 500 kPa. It was wetted again to a water content of 23.6% before a final drying stage back to 500 kPa. The test shows a progressive shift to lower suction at the same water content with each cycle of drying and wetting. If comparisons are made at a gravimetric water content of 22.0%, the first drying cycle shows a suction of 58 kPa, the second drying cycle shows 14 kPa and the third drying cycle shows 7 kPa. This demonstrates a significant loss of suction (at the same water content) with each wet–dry cycle.

Additional SWRC test results under further wet–dry cycles were conducted between two fixed water contents, namely 20% and 15% (Liu et al., 2020), and showed the same trend of a loss of suction with each cycle. The largest shifts are observed to occur in the first four cycles, with a smaller reduction in suction produced between the fourth and sixth cycles. These results corroborate the proposed mechanism behind the reduction in shear strength demonstrated in Fig. 1 whereby a change in fabric (as demonstrated in Fig. 4) brought about by successive wet–dry cycles reduces the ability to generate and retain suction.

Dry–wet cycles cause a shift in the SWRCs, as demonstrated in Fig. 6, but if cycling continues over the same suction range, then the movement in the curves stops after 3–4 cycles (Alonso et al., 2005; Liu et al., 2020). The soil-water retention behaviour then becomes quite repeatable. However, Fig. 7 shows that if a sample is subject to wet–dry cycles where the suction is increased beyond that which has been experienced before, the wetting/drying loop (scanning curve) shifts downwards because of progressing further down the main drying curve before being subject to wetting. This means that each time drying progresses beyond the prior maximum suction value that an asset has been subject to, due to a more extreme drying event than has occurred in its past history, an additional deterioration in performance due to the effect of suction loss can be expected (i.e. for a given water content, lower suction magnitudes are generated). As such, the same mechanism can cause progressively greater deterioration over the life of an asset, each time it is subject to an extreme event. UKCP18 projections (Lowe et al., 2018) suggest that a future climate is likely to include hotter, dryer summers, and as such it is possible that this mechanism may become more important in the future.

**Long-term field determination of SWRCs**

Testing of homogenised specimens in the laboratory has demonstrated clearly the potential shift in SWRC due to wet–dry cycling. To establish the influence of this

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**Fig. 6.** Soil-water retention behaviour showing three cycles of drying/wetting in terms of: (a) gravimetric water content; (b) volumetric water content; (c) degree of saturation. Note that part (a) is modified from Stirling et al. (2017)

**Fig. 7.** Drying/wetting cycles where suction is increased with each drying cycle. Fitted curve was derived from the van Genuchten (1980) equation in terms of gravimetric water content.
The estimated recharge is further discussed in Glendinning (Fig. 8(a)). The pore pressure response to precipitation and wet periods given (predominantly) summer period. This highlights that monitored depths. The time series shown in Fig. 8 are from the lower monitored position at 0·5 and 1·0 m vertically below the ground surface, with a spacing of no more than 150 mm between the water content and suction sensors. Given the measurement range of the sensor (–10 to –600 kPa), only negative pore pressures have been recorded leaving positive pore pressure data uncaptured during ‘wet’ conditions (seen as near zero in Fig. 8(a)). The pore pressure response to precipitation and estimated recharge is further discussed in Glendinning et al. (2014).

The results show, over the period 2009 to 2015, eight major drying events. Maximum generated suctions of 300 kPa and 535 kPa were recorded at 1·0 and 0·5 m depths, respectively, comfortably within the instrument sensitivity range. In comparison, the extended period of high precipitation experienced in the UK during the summer of 2012 is shown to have inhibited the generation of summer suctions at both monitored depths.

Multiple drying events have been recorded within a given (predominantly) summer period. This highlights that wet–dry cycles cannot be assumed to have annual periodicity and are instead potentially more frequent. Overall, a range of maximum drying event suction magnitudes are achieved throughout the monitored period while volumetric water content is observed to consistently fluctuate within the range 25–40%.

The start and duration of these events varies between instrumented position and depth. Typically, the upper monitored position toward the shoulder showed an earlier onset of drying than the lower position, which is likely to be due to greater wind exposure, although a similar wetting up time was experienced at both positions. In terms of depth, drying at 0·5 m was observed to begin 10–25 days earlier than at 1·0 m depth. This is due to the shallower region being closer to the atmospheric boundary and the greater effect of root-water uptake in the more densely rooted zone.

The start of each drying event is consistently defined as the time at which an increase in suction from the instrument baseline of 10 kPa occurs. This is because the laboratory-derived SWRCs indicate that suctions of the order of 100 kPa may exist prior to any noticeable change in water content for this material. Therefore, the onset of drying is based on suction (rather than water content) in order to capture the true start of each event. The end of each event is characterised by a loss of suction due to the onset of precipitation and also associated with a rapid increase in water content. The corresponding volumetric water content and suction data from these eight events have been compiled to produce in situ SWRCs at an upper and lower slope position (Stirling et al., 2017). The resulting SWRCs are presented in Fig. 9. The envelope of drying data derived from the laboratory testing is illustrated in grey for comparison. It was not possible to include event 4 in the plot of values from the lower slope at 1·0 m depth due to insufficient drying to generate a measurable suction. Values for event 7 from the upper slope at both 0·5 m and 1·0 m depth are not present due to hardware malfunction.

The SWRCs from wetting events are not presented in Fig. 9 because the temporal resolution of the long-running data logger is insufficient to capture data points to credibly derive a wetting curve due to the high rate at which suction is dissipated following precipitation (see Fig. 8). In the time between each drying event, the ground is noted to have reached full saturation at the monitored depths. During construction of the test embankment, samples taken after each successive lift enabled porosity conditions at the time of construction to be determined. These ranged between 0·395 and 0·354, decreasing with depth (Glendinning et al., 2014). The return to full saturation indicates that the varying field drying curves represent changes to the primary curves due to wet–dry cycles. As such they are potentially a function of the deterioration mechanisms outlined previously, rather than representing scanning lines between fixed wetting and drying curves, which is how they may have been interpreted prior to the evidence for deterioration in the water-retention capacity due to wet–dry cycles.

The drying curves derived from the field data show a pronounced shift in the first three cycles of significant wetting and drying summarised as events 1, 2 and 3, which in all cases exceed 300 kPa suction at 0·5 m depth and 50 kPa suction at 1 m, with reduced variation in subsequent cycles. The initial, as-constructed drying curve (see event 1 curves in Fig. 9) consistently exhibits sustained saturation over a greater suction range and a higher interpreted air entry value (AEV) where desaturation is initiated. Subsequent drying events (sequentially lighter shading) display lower AEVs – that is a reduced capacity to maintain a suction at both full saturation and for a given magnitude of drying, as seen in laboratory controlled testing. It is believed that this change in behaviour is in some part related to the increased...
proportion of larger pore space, as these pores are less able to sustain suction. This shift in pore geometry distribution is a result of micro-scale soil fabric changes probably attributable to extremes in shrink–swell experienced by the soil between drying events. The formation of enlarged void spaces and increased pore connectivity can also be seen to have resulted in non-uniform drying paths where the sudden changes in the gradient of the drying curves are thought to represent dual or multiple air entry stages resulting from the development of a heterogeneous pore system (see e.g. Durner (1994)).

It is important to note that the Bionics embankment was constructed in 2005, with the instrumentation used for in situ SWRC analysis installed in 2008. Although the greatest change is observed in the early monitored cycles, as discussed in the earlier section ‘Laboratory determination of cyclic SWRCs’, the variability of weather determines the extent to which permanent deterioration is caused, with ever more extreme drying (i.e. progression along the bounding drying curve) governing the reduction in suction generation capability.

DETERIORATION AT THE MACRO-SCALE

It is proposed that, when subjected to wet–dry cycles, the soil microstructural deterioration (highlighted previously) progresses to the extent that, with sufficient drying, macro-scale surface cracking is initiated. These features are an indicator of the deterioration of an infrastructure slope. It is also proposed that these cracks are a means through which weather-driven slope deterioration penetrates deeper into the soil subsurface, developing a ‘deterioration front’.

The mechanism driving the progression of the deterioration front is that, as cracks propagate, they provide an enhanced pathway for water infiltration and removal at greater depths. This in turn causes shrink–swell cycles at depth that would not otherwise have occurred, driving
further crack development and propagation of the crack network. As the near-surface permeability increases due to increasing porosity, the ability to generate and maintain suctions decreases. The resultant reduction in tensile stresses acts to limit crack formation. This in combination with the higher confining stresses at greater depth leads to an increase in tensile strength, which in turn limits the depth to which further crack-driven deterioration can propagate.

To understand the behaviour of desiccation cracks at full scale on grass vegetated slopes, three linear transducers were installed across an active crack site on the south-facing 1 in 2 slope at the Bionics embankment. Volumetric water content and matric suction adjacent to the cracks, and rainfall together with the presence of run-off, were used as indicators of the impact of cracking on the depth of deterioration. The monitoring equipment and the approximate location of the cracks on the embankment can be seen in Fig. 10.

Monitored crack aperture data recorded between May 2015 and November 2016 are presented in terms of transducer displacement in Fig. 11. The corresponding volumetric water content and matric suctions are presented from a monitoring profile 1·6 m away from the crack site. Rainfall and reference evapotranspiration (ETo) data are also presented for the same period, as well as directly measured run-off.

The measurements indicate the onset of crack opening at the start of June. This is concurrent with the onset of suction generation as measured at 0·5 m depth and follows a period of limited rainfall and high ETo. Once open, a series of rainfall events partially dissipate suction and cause a rapid reduction in crack aperture (highlighted). Continued high levels of ETo during this period maintain suctions between 200 and 320 kPa, enabling the crack to re-open between the three major rainfall events. Following the fourth highlighted rainfall event, total ETo reduces and rainfall dominates. Crack aperture reduces consistently from October to mid-November 2015, with closure (return to original displacement in transducers 1 and 2) concurrent with suction dissipation.

During the 2015–2016 winter, little displacement is evident on the monitored crack. High water content suggesting saturated conditions results in run-off following high rainfall (see January 2016). In 2016, the crack aperture is shown to open in May during a period of sustained high ETo and low rainfall. The rapid response of crack displacement to rainfall events is repeated, although unlike the previous year, a wet period during late June to July limited the development of deeper suctions and resulted in measurable run-off.

There exists a clear connectivity between cracking, near-surface (<1 m) saturation and run-off. Taking the period May 2015–May 2016, despite relatively high rainfall during the active crack season, no run-off is measured. Conversely, once the crack is closed (mid-November 2015 onwards), run-off is produced from similar magnitude rainfall events. The occurrence of run-off is a function of surface saturation and the presence of open cracks on the slope surface. These cracks enhance surface hydraulic conductivity and intercept run-off; this in turn increases the potential for greater magnitude of pore pressure fluctuation.

In situ, near-surface (<1·5 m) saturated hydraulic conductivity measurements were carried out at the Bionics embankment to investigate variability due to environmental cycling (Dixon et al., 2019). This study is based on 85 individual measurements made in summer months (June to August) over the period 2009–2014. Large variability in hydraulic conductivity in the uppermost 1·0 m was observed, with values in the top 0·8 m having a range from $1 \times 10^{-2}$ to $5 \times 10^{-10}$ m/s (i.e. over five orders of magnitude) and a marked reduction in hydraulic conductivity with depth. Therefore, the near-surface zone is evidently affected by exposure to weather-driven deterioration and the resultant development of macro-scale, crack features.

**DISCUSSION: A PROPOSED WEATHER-DRIVEN SOIL DETERIORATION MODEL FOR EMBANKMENT SLOPES**

The work presented in this paper provides the evidence for the existence of a process of weather-driven deterioration of compacted clay fills and is summarised in Fig. 12. Post compaction, the action of successive wetting and drying, caused by both seasonal and higher frequency weather cycles, result in the soil at the near surface undergoing irreversible changes in microstructure caused by repeated shrinkage and swelling. This manifests as a matrix of micro-cracks that increase in aperture and interconnectivity, leading to a greater porosity of the soil micro-fabric with increasing numbers of wet–dry cycles.

The increasingly porous soil loses the ability to generate the same magnitude of suction at a given water content, as observed in the SWRCs at both laboratory and field scale. This causes the inferred AEV (where rapid desaturation is initiated) to decrease with increasing numbers of wet–dry cycles. This in turn influences the movement of water into and out of the slope by controlling the rate of evapotranspiration and infiltration. The progressive rates of change observed in soil-water retention, driven by wetting and drying, are non-linear, with the greatest change being observed after the initial, primary drying. However, further changes continue, albeit at a slower rate, as a result of continuous cycling. An extreme event (i.e. a longer, more intense drying
event than any previously experienced) causes a renewed increase in the rate of deterioration. Therefore, if climate change causes an increase in both magnitude and severity of these events (as included in future UKCP18 scenarios, see Lowe et al. (2018)), then it is possible that increased deterioration of soil-water retention properties will occur in the future.

Changes in the capacity to generate soil suction also result in loss of shear strength, which is most pronounced following the initial cycles, consistent with the loss of suction observed in SWRCs, and the reduction in shear strength seen in triaxial testing. This loss of strength can result in the shallow surface failures observed in engineered slopes post construction (Briggs et al., 2017). Any change in the ability of a soil to...
Maintain suctions will also have implications for the stability of cut slopes, which rely partly on construction-induced negative pore pressures, the dissipation of which can influence stability (Vaughan & Walbancke, 1973). Continued cycles can cause additional reduction in strength following extreme drying events that force suctions past the previous maximum. As described for the soil-water retention behaviour, this mechanism may become more significant in future.

Loss of suction also results in a progressive reduction in tensile strength, which leads to the propagation of desiccation cracks. The micro-scale effects described previously also have implications at the macro scale, where, for example, the increasing crack network will expose previously unaffected soil to the effects of wetting and drying, thus perpetuating the deterioration process and increasing the depth to which deterioration penetrates. There is evidence that cracks in slopes can penetrate to a depth of approximately 1 m (Anderson et al., 1982; Dyer et al., 2009) and that a hydrologically distinct layer exists in the top 1·5 m of a clay slope (Ng et al., 2003). An increase in permeability has been observed to vary by up to five orders of magnitude at the near-surface (<0·6 m) permeability (Dixon et al., 2019).

The progressive failure described by Leroueil (2001) requires changes in the soil properties, which are attributed in part to weathering. The weathering process in clay is in part a combination of cracking (and the resultant enhanced surface hydraulic conductivity) and loss of strength due to a reduced ability to generate and maintain suction. This reduction in shear strength can cause downslope movements which, if large enough, can result in strain softening and the redistribution of load. Ultimately, changes in loading or further weather-driven deterioration could lead to slope failure.

It is postulated that cracking due to the action of wetting and drying and the resultant loss of strength and water retention capacity, along with increased permeability, is a pre-cursor to the initiation of progressive failure. This causes the soil at the near surface of an engineered clay slope to reduce in strength due to meteorological cycling without any change in external load.

The implications of this work are several fold. The first is that engineered clay slopes are likely to deteriorate as a result of wetting and drying action alone, which could result in failure as some critical reduction in strength is reached. The second is that, when assessing the long-term stability of an engineered slope, the result should not be viewed as static: the soil properties are changing gradually due to seasonal cycling as a result of shrinking and swelling; superimposed on this is the response to discrete extreme events, which can cause sudden progression of deterioration, and which may act as failure triggers if a critical magnitude of deterioration is surpassed. Third, any assessment should consider a range of parameters and ground models reflecting the time-dependent nature of the material properties. Modelling weather and climate impacts on slope stability requires the ability to model soil-atmosphere interaction, yet current hydro-mechanical coupled models are still unable to account for many deterioration mechanisms – for example, elevated, transient hydraulic conductivity due to cracking at the slope scale, shifting SWRCs both temporally and spatially, and the resultant effects on suctions and therefore to soil strength. New constitutive models for engineered soils are required that can capture these phenomena if the long-term stability of infrastructure slopes are to be assessed.

CONCLUSIONS

A new mechanism of soil deterioration driven by cyclic wetting and drying is proposed, based on an extensive laboratory and field experimental programme. The underlying cause for this deterioration is the microstructural changes to the soil fabric that lead to a loss in the ability to generate and maintain suction, causing a loss of strength. These changes in turn result in macrostructural features, such as cracking. Coupled together, these alterations in the fabric lead to changes in hydraulic conductivity, as well as significant reductions in shear strength which will have implications for seasonal ratcheting deformations, strength reduction and ultimately failure.

The rate of deterioration is non-linear, with the greatest observed change occurring after the initial, primary drying of newly compacted soil. However, further changes continue to develop with continuous cycling, additional changes occur suddenly, with the occurrence of discrete extreme weather events. The current evidence from UKCP09 and UKCP18 suggests that these events will increase in frequency due to climate change in the future. The above has implications for slope stability assessment, including the need for

Fig. 12. Conceptual model of weather-driven clay fill deterioration
changeability of soil parameters and ground model due to the time-dependent nature of the deterioration processes proposed. There is a need for new constitutive soil model(s) that can account for soil deterioration due to wetting and drying in order to assess properly the impacts of weather and climate change on the long-term stability of engineered clay slopes. This work develops a conceptual framework and it is intended that the results presented will enable the formulation, calibration and validation of such constitutive models capable of capturing the deterioration mechanism.

The improved understanding of these mechanisms, as provided by this work, has the potential to more effectively forecast the conditions that cause deterioration and lead to failure, permitting asset owners to invest in more effective pro-active remediation, reducing the number of unanticipated failures, improving the resilience of the asset to climate change and substantially reducing the economic impact.

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NOTATION

\[ \begin{align*}
\rho^s & \text{ mean total stress} \\
\rho^s' & \text{ mean 'Bishop stress'} \\
q & \text{ deviator stress at failure} \\
\phi_s & \text{ degree of saturation} \\
\Delta p & \text{ pore air pressure} \\
\Delta w & \text{ pore water pressure} \\
\Delta o & \text{ initial pore water pressure} \\
w & \text{ gravimetric water content} \\
\theta & \text{ volumetric water content}
\end{align*} \]

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