Deterioration of geotechnical infrastructure: the influence of asset aging through environmental cycling

Détérioration des infrastructures géotechniques: les éffets du vieillissement des terrassements résultant des cycles de mouillage-séchage

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ABSTRACT: This paper sets out to establish the implication of weather driven deterioration processes on the long-term performance of infrastructure earthworks. With particular reference to UK transport network slopes, the work presented here centres on their sustainable management and assessment of resilience to climate change. An extensive campaign of investigation has been undertaken consisting of (1) field site monitoring and observation, (2) laboratory scale testing under wetting-drying conditions and (3) unsaturated finite element analysis. By cycling the unsaturated state of engineered fill samples, suction generation behaviour has been measured and assessed via the Soil-Water Retention Curve (SWRC). Full-scale investigation at a trial embankment and controlled laboratory testing has provided evidence of seasonal processes behind fundamental changes in soil-water retention behaviour e.g. due to the development of desiccation cracking, vegetative cover and evapotranspiration-recharge cycles. Lastly, the sensitivity of suction generation has been evaluated via input of in situ SWRCs into a coupled hydrological-mechanical model. The ability to accurately model these deterioration processes is crucial if we are to fully understand the implications of our changing climate on the long-term stability of our infrastructure.

RÉSUMÉ: La détérioration des sols a des implications à long terme pour la performance des terrassements d'infrastructure. Avec une attention particulière au réseau de transport du Royaume-Uni, ce travail concerne l'évaluation de sa résilience face au changement climatique. Un programme expérimental a été lancé sur des sols argileux, comprenant (1) des essais de laboratoire sous des conditions cycliques d'humectation et de séchage; (2) un programme de surveillance du terrain; (3) des simulations non-saturées en différence finie. Par la variation cyclique du comportement non-saturé, la génération des succions interstitielles a été évaluée en utilisant une courbe de rétention d'eau. Un remblai expérimental, conçu sur mesure, a permis de mettre en évidence les changements fondamentaux dans le comportement du matériel : le développement des fissures, l'influence de la végétation et des cycles d'évapotranspiration/recharge d'eau. La sensibilité de la génération des succions a été évaluée par l'introduction des données de terrain dans un modèle hydromécanique. La construction de modèles précis est essentielle pour la compréhension des implications des changements climatiques sur la stabilité à long terme des réseaux d'infrastructure.

KEYWORDS: Asset deterioration; Soil-water retention curve; Slope monitoring; Climate impacts; Transport infrastructure

1 INTRODUCTION

Geotechnical assets are fundamental to the delivery of critical services, such as roads, railways, pipelines and flood protection structures. These are typically relatively long in length and 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'.

The Soil Water Retention Curve (SWRC) is an important concept for understanding the behaviour of unsaturated soils and their property functions (Fredlund, 2002). A SWRC consists of a relationship between soil water content and suction, a typical hysteretic SWRC being shown in Figure 1. Starting with a saturated sample under drying conditions, air enters the soil as it begins to follow the primary drying curve down to residual suctions at low water contents. Initially, large voids desaturate leading to small increases in suction. As water contents decrease, more numerous smaller voids desaturate causing suctions to increase more rapidly. At low water contents, the curve flattens off to a residual state.

In practice, however, soils do not exclusively switch between saturated states with no suction and desaturated states with very low water contents and levels of suction approaching residual. Instead, soils may follow scanning curves, bridging between the extremes of the primary wetting and primary drying.

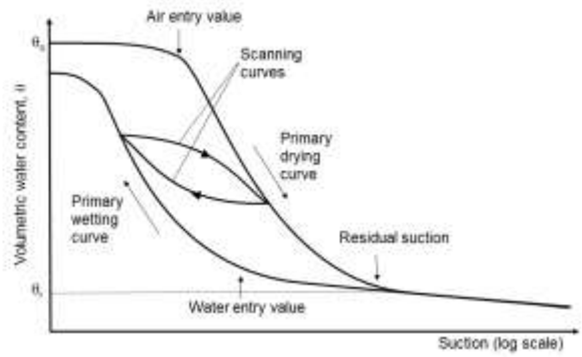

Figure 1. Typical Soil Water Retention Curve (after Toll, 2012)

SWRCs are commonly derived on remoulded samples under carefully controlled conditions. However, long-term field monitoring data has provided evidence for a shift in the SWR trend with seasonal cycling. This behaviour not only has implications for the generation of suctions for given fluctuations in water content but also for shifts in unsaturated hydraulic conductivity and shear strength. Furthermore, the implementation of an initial drying path into slope stability modelling is common place due to the complexity of incorporating hysteresis and laborious SWRC derivation. The implications of a residual/multi-cycled SWRC on modelled slope stability are explored using unsaturated FE analysis.

2 LONG-TERM FIELD MONITORING

The monitoring component of this work was undertaken at the BIONICS embankment, a purpose built full-scale research facility, comprising a 6 m high, 90 m long embankment with a 1 in 2 slope. The facility was built in 2006 using a Durham Lower Boulder Clay fill with extensive in-ground instrumentation (Hughes et al, 2009; Glendinning et al, 2014). The site is located in North East England and is currently being investigated as part of the iSMART project (www.ismartproject.org). For further details regarding embankment construction, please refer to Hughes et al, 2009.

2.1 Instrumentation and resulting time series

The data presented in this work were obtained using sensors manufactured by Decagon Devices, namely the EC-TM and MPS-1/2 models and installed soon after embankment construction. The EC-TM measures the dielectric permittivity of the soil to determine the volumetric water content while the MPS-1/2 measures permittivity across a ceramic disc in equilibrium with soil-water to determine the water potential. In the interests of brevity, technical specifications for these sensors may be accessed directly from the manufacture's literature.

These sensors have been positioned at two sites (Figure 2) on the south facing aspect of the westerly, poorly compacted panel. Installations were at 0.5 and 1.0 m depths within a spacing of no more than 150 mm.

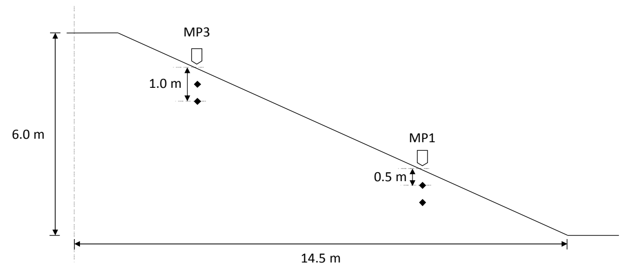

Figure 2. Slope schematic showing layout of sensor pairs.

Since 2008, a near-continuous data set has been compiled as illustrated by the time series presentedFigure in Figure 3. 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. The pore pressure response to precipitation and estimated recharge is further discussed in Glendinning et al. (2014) 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 summer period and so drying-wetting cycles may not be considered solely on an annual basis. Overall, a range of ultimate suction magnitudes are achieved throughout the monitored period while volumetric water content is observed to consistently fluctuate within the range 40 – 25%.

2.2 Drying event selection and SWRC construction

In order to produce SWRCs from the monitored data, a series of eight drying events were selected from the 2008-2015 period, as shown in Figure 3. These events are clearly identified by the generation of suction. The start of each event is consistently defined as the time at which an increase in suction from the instrument baseline (-10 kPa) occurs. Laboratory derived SWRCs indicates that suctions in the order of 100 kPa may exist prior to any noticeable change in water content for this material.

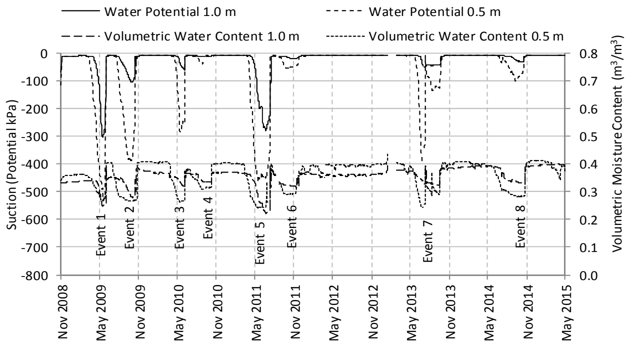

Figure 3. Volumetric water content and soil-water potential records from position MP1 at 0.5 and 1.0 m depth.

Therefore, the onset of drying is based on suction to capture the true start of each event. The end of each event is characterised by a loss of suction associated with the rapid increase in water content due to the onset of precipitation.

The initialisation and duration of these events varies between instrumented position and depth. Typically, the monitored position toward the shoulder of the slope showed an earlier onset of drying than at the toe, 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. This is attributed to the shallower region being closer to the slope-atmosphere interaction processes and being more densely rooted, hence subject to a greater effect of water uptake driven by transpiration.

Wetting events are not presented herein, although it may be noted that the high rate at which suction is lost upon wetting (see Figure 3) reduces the number of data points with which to populate a credible wetting curve. This is a function of the hourly logging interval.

2.3 Compiled in situ SWRCs

The assembled SWRCs produced by the above method are presented in Figure 4. It can be seen that not every drying event is present – this is primarily due to hardware malfunction. However, event 4 is not present at MP1 1 m depth due to drying not being sufficient to generate a measurable suction by the potential sensor (see Figure 3).

In the time between each drying event, the slope is noted to have reached full saturation at the monitored depths. During construction, samples were taken at each lift enabling 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). On this basis, the recorded volumetric water contents are considered sufficient to negate the risk of drawing comparison between scanning curves.

The initial, as constructed drying curve (darkest) is consistently found to exhibit sustained saturation over a greater suction range, a higher AEV. Subsequent drying events (sequentially paler) are characterised by desaturation at lower suction values i.e. a reduced suction generation for a given magnitude of drying. It is believed that this change in behaviour is in some part related to micro scale soil fabric changes due to extremes in shrink-swell experienced by the soil between drying events. Reduced AEVs are associated with larger pore spaces. The formation of micro cracks (enlarged void spaces and increased pore connectivity) may be responsible; however, dual air entry curve forms are inconsistent in the in situ responses.

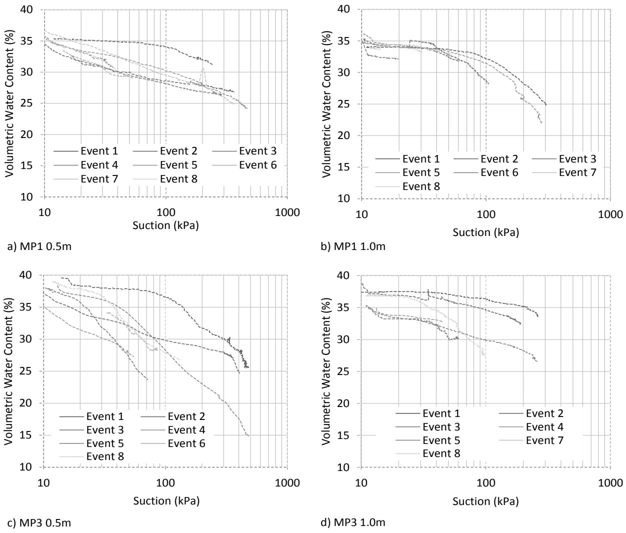

Figure 4. In situ SWRCs as measured at (a-b) slope toe and (c-d) slope shoulder at 0.5 and 1.0 m depth.

3 DETERMINATION OF SWRC UNDER CONTROLED WETTING-DRYING CYCLES

The Durham Soil Water Retention Apparatus allows for the continuous measurement of suction and water content, based on the work by Lourenco et al. (2008; 2011) and modified by Noguchi et al. (2012) and Liu et al. (2015). The equipment consists of a frame placed on a balance for measuring the water deficit during drying and wetting, shown in Figure 5. A sample sits on a platform through which a high capacity tensiometer (Lourenco et al., 2006) measures the suction on the samples underside. Volume change measurements are made, for determination of density and volumetric water content, using six LVDTs; four measuring radially and two vertically. The instruments are then monitored wirelessly

3.1 Sample preparation and testing

Samples were prepared using remoulded Durham lower boulder clay sourced from the BIONICS embankment described in Section 2. This was compacted at 24% gravimetric water content using a 100 mm diameter mould. A modified method was used to apply the same compaction effort as the standard Proctor test, but for a 200 mm tall sample, from which 100 mm diameter, 30 mm tall samples were cut. This resulted in samples with a high degree of saturation (Sr>0.95) and densities near field density.

The sample was placed on the SWRC apparatus firmly, in contact with the high capacity tensiometer and LVDTs. A shroud was placed around the sample to limit the rate of evaporation and maintain confidence in representative suction readings. The shroud was left open minimally at all times to prevent build-up of condensation affecting the mass readings. The sample was then cycled between 0 kPa and 500 kPa, wetting using a syringe pump to apply water droplets to the top surface of the sample. This range was selected to be representative of the maximum suction range recorded at the embankment (Figure 3).

3.2 Laboratory derived cyclic SWRCs

The continuous soil water retention data presented in Figure 6 clearly shows there is a significant change in behaviour over consecutive wetting and drying cycles, with a shift towards lower suctions for the same water content.

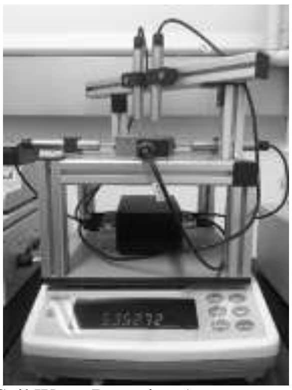

Figure 5. Durham Soil Water Retention Apparatus

For the same sample, Figure 7 shows that the lower suction for a given same water content is due to changes in void ratio, hence a trend for increasing dry density over repeated cycles. It can also be seen that with repeated cycles, for a given suction and wetting/drying phase, the increase in dry density and decrease in voids is progressively less substantial. This suggests when changing between two fixed suctions, in this case 0 kPa and 500 kPa, there is a trend towards steady state cycles.

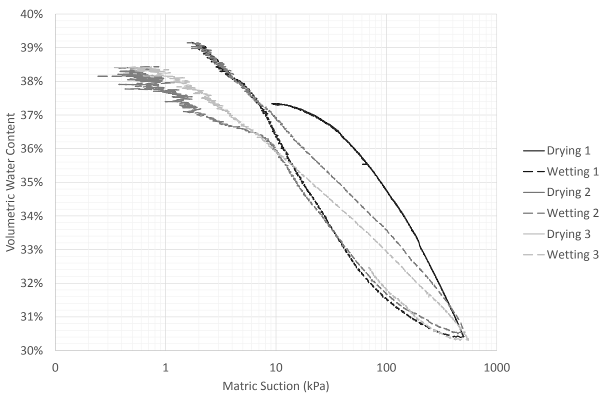

Figure 6. Soil Water Retention Curve Cycling between 0 and 500 kPa

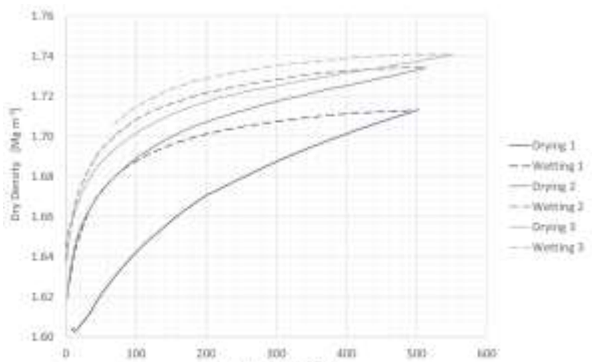

Figure 7. SWRC Dry Density Variation Cycling Between 0 and 500 kPa

4 MODELLING EFFECT OF VARIABLE SWRC

To illustrate the implications of the variability in SWRC on slope behaviour, the changes in pore water suctions within a trial embankment were modelled within the finite element code PLAXIS.

4.2 Model Geometry

The model geometry was specified to represent the BIONICS embankment (Section 2). The model has symmetry about the crest centreline and assumes plane strain.

The van Genuchten-Maulem model (van Genuchten, 1980) is used within Plaxis to simulate the suction-water content-unsaturated conductivity behaviour. The parameters for the fill material were derived by fitting the van Genuchten model to the in-situ and laboratory SWRC data. The parameters are shown in table 1.

Table 1. van Genuchten parameters fitted to the field and laboratory soil water retention data.

Parameter	Cycle 1 Laboratory SWRC	Cycle 1 SWRC	Cycle 3 SWRC
K_h (mday^{-1})	8.64 × 10-5		
α (m^{-3})	0.014	0.028	1.233
VG “n”	1.59	1.43	1.08
θ_s (m^{3}m^{-3})	0.38	0.35	0.35
θ_r (m^{3}m^{-3})	0.04	0.02	0.01

4.2 Weather Data and Model Surface Recharge

The precipitation surface boundary condition in Plaxis was used to simulate meteorological input. It can accept rainfall and evapotranspiration parameters. To generate the weather, the UKCP09 weather generator (Jones et al, 2009) was used to produce present climate data for a 5km grid square including the embankment. The surface recharge boundary was derived simply as the sum of rainfall minus evapotranspiration.

4.2 Model Results

Histories of PWP at differing points within the modelled embankment were recorded to allow a comparison between SWRCs to be made (Figure 8). Factor of safety (FoS) calculations steps were also undertaken at selected points and the history recorded to visualise the influence of changing the SWRC on embankment stability (Figure 9).

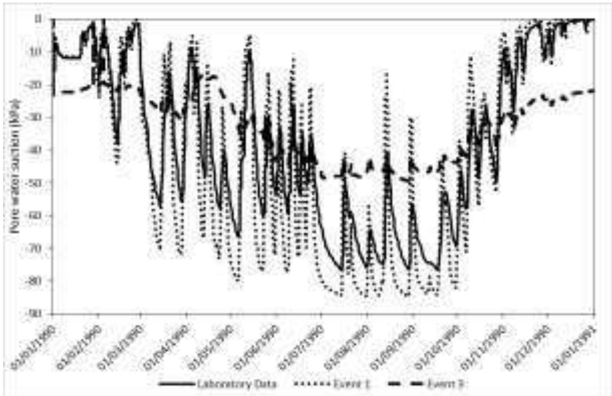

Figure 8. Pore-water suctions at the slope toe for the differing soil water retention curves.

5 CONCLUSIONS

Soil-water retention behaviour has been demonstrated to change with wetting and drying cycles leading to a lower AEV and lower SWRC drying gradient both in the laboratory and as recorded in the field. This has an impact on the magnitude of suction generation for a given reduction of moisture content under environmental conditions and in turn on unsaturated shear strength and hydraulic conductivity. The presented numerical modelling has demonstrated the implications of this by simulating the change in suction generation and hence transient shear strength due to the changing SWRC. The consequences of this cyclic variability has been shown to have a dramatic effect on the slope factor of safety.

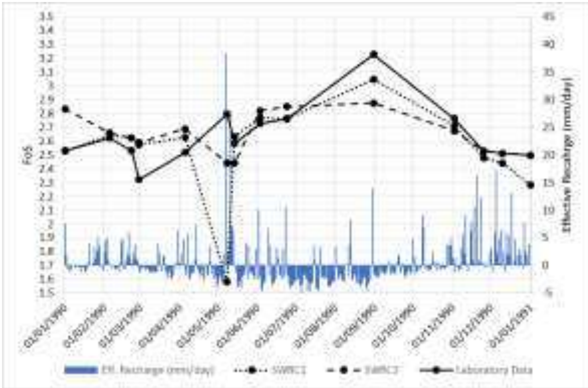

Figure 9. FoS changes within slopes with differing SWRCs.

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