11TH INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

Long-term monitoring of long linear geotechnical infrastructure for a deeper understanding of deterioration processes

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Abstract

Long linear geotechnical infrastructure such as earth embankments and cuttings used for railways, highways and flood defence can progressively reduce in performance over time as a result of aging and deterioration principally driven by environmental cycles of wetting and drying. These include volumetric and fabric changes including desiccation cracking, accumulating downslope plastic strain and geo-chemical/mineralogical changes, influencing the strength, stiffness, permeability and water retention behaviour of the soils from which they are constructed. A deeper understanding of these processes is necessary to develop effective tools for assessing and forecasting the geotechnical condition of long linear infrastructure over the lifespan of the asset and in response to climate change. As part of a major research project called ACHILLES, three exemplar long linear geotechnical earthworks have been instrumented with state-of-the-art sensors for long-term monitoring of deterioration behaviour and condition. The monitored sites are a highway cutting slope, a constructed trial embankment and a flood embankment. The sites are also being extensively characterised using geophysical, geodetic, UAV and cone penetrometer approaches. Data from these exemplar assets is of fundamental importance to understanding deterioration processes and is being used to validate conceptual and numerical models of asset performance and enable rapid characterisation of their current condition.

Keywords: Slope Stability, field testing, monitoring, site investigation

1. Introduction

Infrastructure is fundamental to the UK economy and society and has been identified as a key ‘pillar’ of the UK’s Build Back Better strategy (HM Treasury, 2021). Long linear geotechnical assets (LLGA’s) such as earth embankments and cuttings used for railways, highways and flood defence are critical components of this infrastructure. There are currently 15,800 km of railway, 80,000 km of highways and 10,200 km of flood defences in Great Britain. Failure of these LLGA’s is fairly common with Network Rail reporting 1386 earthwork failures on their network from 2004 to 2019 of which 91 were described as ‘potentially high consequence’ and 18 attributed to derailments (Network Rail, 2018). The resulting financial and carbon costs associated with repair are significant. For example, Network Rail reported that emergency repairs cost ten times more than planned works, which cost 10 times more than regular maintenance.

LLGA’s progressively reduce in performance over time due to different modes of deterioration which are principally driven by environmental cycles of wetting and drying. These include volumetric and fabric changes including desiccation cracking, accumulating downslope plastic strain and geo-chemical/mineralogical changes, influencing the strength, stiffness, permeability and water retention behaviour of the soils from which they are constructed. These deterioration modes are poorly understood which makes loss of performance and ultimate failure difficult to predict. This problem is further exacerbated by projected climate change which will subject LLGA’s to increasingly extreme weather patterns altering the cycles of wetting and drying and likely increasing the rate of deterioration and likelihood of failure.

A deeper understanding of the deterioration modes is necessary to develop effective tools for assessing, mitigating, and forecasting the long-term condition of LLGA’s, including their response to climate change. As part of a major research programme called ACHILLES, three exemplar LLGA's have been instrumented with state-of-the-art sensors for long-term monitoring of deterioration and condition. The monitored sites are a highway cutting slope, a constructed trial embankment and a flood defence embankment. The sites are also being extensively characterised using both geophysical, geodetic and cone penetrometer approaches. This paper will describe the exemplar assets and explain how they are being used to understand deterioration processes, validate conceptual and numerical models of asset performance, and develop and test methods for rapid characterisation of their current condition.

2. The ACHILLES research programme

The research programme ACHILLES (Assessment, Costing and enHancement of Long-LIfe, Long-Linear AssEtS; www.achilles-grant.org.uk) is funded by the UK Engineering and Physical Sciences Research Council (EPSRC). The project is a collaboration between seven UK universities (University of Bath, Durham University, University of Leeds, Loughborough University, Newcastle University, University of Southampton, and University of Strathclyde) and the British Geological Survey, and a large number of industry and government stakeholders including the Environment Agency, Jacobs, National Highways and Network Rail. Together the group has wide experience of research and practice relating to LLGA's, with the research institutions providing unique expertise in field, laboratory and modelling/simulation methods. The overall aim of ACHILLES is to address the deterioration of LLGA's in order to create more reliable infrastructure by developing knowledge and tools for predicting and improving long-term performance of these assets at an affordable cost.

3. The ACHILLES exemplar long-term monitoring sites

3.1 Newbury site

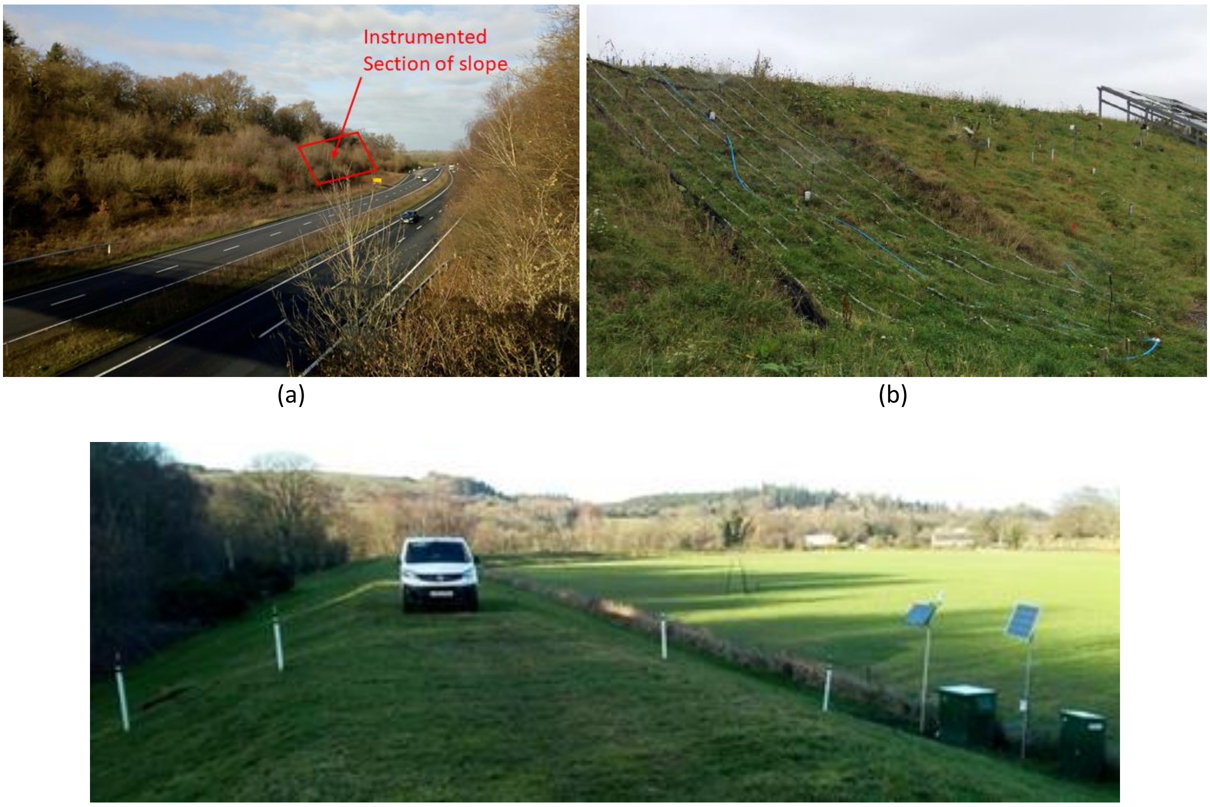
The highway cutting (Figure 1a) is located on the A34 Newbury bypass in Berkshire, United Kingdom (Ordnance Survey GB grid reference SU455652). The cutting was constructed in 1997 and is entirely within London Clay, east facing, 8 m high and 28 m long with a gradient of 1 vertical:3.5 horizontal. The London Clay is highly weathered to a depth of about 2.5 m below original ground level. Following excavation up to 0.4 m of topsoil was placed over the cut to facilitate the planting of vegetation. The London Clay at the site is predominantly a stiff grey clay containing several bands of silty clay up to 50 mm thick and bands of flint. The weathered London Clay is spatially very variable changing from a stiff orange brown clay to a clayey silt over small distances and depths. The plasticity index, I_D, of the Grey London Clay and weathered London Clay are I_D = 34.8% and 31.7% respectively. When the slope was instrumented in 2002 the vegetation cover comprised grass, herbs and some small trees and shrubs less than 1 m in height. From 2002 to 2008, the trees and shrubs within the instrumented area were maintained to no more than 1.5 m height by heavy pruning. From 2008 onwards, vegetation was unmanaged resulting in development of a thick vegetation cover with trees and shrubs up to 6 m in height. The site, and its instrumentation and monitoring, are described in detail by Smethurst *et al* (2006; 2012; 2021).

3.2 BIONICS site

The BIONICS trial embankment (Figure 1b) is situated at Nafferton Farm, Stocksfield, Northumberland, United Kingdom (Ordnance Survey GB grid reference NZ064657). It was purpose built in 2005 to study the biological engineering impacts of climate change on slopes. The embankment is 90 m long, 29 m wide, 6 m high and with a 5 m wide crest forming side slopes at a gradient of 1 vertical:2 horizonal, giving dimensions representative of UK transport earthworks. The embankment was separated into four compaction zones, two compacted to the current Highway specification and two compacted to a lower specification representative of old Victorian railway embankments. The embankment was constructed from Durham lower boulder clay which is of intermediate plasticity (I_D = 18.5%). Following construction 0.3 m of topsoil was placed on the embankment and seeded with a grasslands/highways mixture, which has been periodically mowed. Hughes *et al* (2009) and Glendinning *et al* (2014) provide a more in-depth description of the embankment's construction and properties, and the instrumentation and monitoring at the site. Longer-term monitoring data are given by Stirling *et al* (2021).

3.3 Warden site

The flood defence embankment (Figure 1c) is located on the river South Tyne at Warden, Northumberland, United Kingdom (Ordnance Survey GB grid reference NY907660) and is approximately 600 m long. Its crest is elevated approximately 2.5 to 3 m above the flood plain and 6 to 7 m above the lowest point of the riverbed, with side slopes of varying gradients from 1:3 to 1:2.5 (vertical: horizontal). The landward slope and riverside slopes are north and south facing respectively. The embankment was reconstructed in 2009 from a low to intermediate stony clay fill, after a section of it failed in 2005. It is primarily covered in grass which is periodically mowed.



(a) (b)

(c)

Figure 1: ACHILLES earthwork monitoring sites: (a) Newbury; (b) BIONICS; and (c) Warden.

3.4 Instrumentation and long-term monitoring

Monitoring has been taking place at the Newbury and BIONICS sites since 2003 and 2007 respectively, and began at Warden in October 2021 with a further phase starting in April 2022. All three sites have been extensively instrumented to monitor soil pore water pressure and suction, soil water content, soil temperature, soil lateral deformation, rainfall, surface runoff and interflow (flow of water through the topsoil), atmospheric pressure and the parameters required to estimate evapotranspiration (wind speed, air temperature, relative humidity, and solar radiation). The instruments include time-domain reflectometry (TDR) and heat capacity probes (for measuring soil water content and suction), water filled tensiometers, flushable piezometers, shape accelerometer arrays, and tipping bucket rain and flow gauges (Table 1). Extensometers were installed to measure soil vertical deformation at BIONICS (magnetic type) and Warden (vibrating wire type). Geophysical monitoring systems based on electrical resistivity tomography (ERT) (e.g. Loke *et al*, 2013; Holmes *et al*, 2020) have been installed at BIONICS and Warden to image spatial and temporal variations in subsurface resistivity, which is related to soil composition and water content. At each site, the sensors were connected to a data logger with a GSM modem connection, powered by a car battery recharged by a solar panel. The data were typically measured at 10-minute intervals and recorded as sub-hourly or hourly averages. Smethurst *et al* (2017) provide a thorough description and assessment of the instrumentation and monitoring technologies listed above.

While some measurements of soil water content and pore water pressure/suction have been made deeper within the slopes, probes were installed specifically to understand the seasonal changes taking place within the near surface (less than 1.5 m depth) zone influenced by weather and vegetation. The measurements of rainfall, surface runoff and interflow, and evapotranspiration has enabled a full water balance to be established for the sites (e.g. see Smethurst *et al*, 2012).

Measurement	**Instrument**	**Newbury**	**BIONICS**	**Warden**
Soil pore water suction	Tensiometer	Yes	Yes	Yes
Soil pore water pressure/suction	Flushable piezometer	Yes	Yes	Yes
Soil pore water suction	TDR and heat capacity probes	Yes	Yes	Yes
Soil water content	TDR probes	Yes	Yes	Yes
Soil deformation (lateral)	Shape accelerometer array	Yes	Yes	Yes
Soil deformation (vertical)	Extensometer	No	Yes	Yes
Rainfall	Tipping bucket gauge	Yes	Yes	Yes
Surface flow and interflow	Tipping bucket flow gauge	Yes	Yes	Yes
Wind speed, air temperature, relative humidity, solar radiation, atmospheric pressure and soil temperature	Climate station	Yes	Yes	Yes
Electrical Resistivity	ERT arrays (PRIME & ALERT systems)	No	Yes	Yes

Table 1: Summary of measurements and instruments at the monitoring sites.

3.5 *In situ* ground investigation

Each site is being thoroughly investigated and characterised *in situ* using cone penetrometer testing (CPT) methods including piezocone, CPTu (standard and dissipation), and full displacement pressuremeter (cone pressuremeter) to determine the mechanical (strength and stiffness parameters) and hydraulic (permeability and porewater pressure) properties of the earthworks. Numerous piezocone tests have been or are shortly to be carried out across the BIONICS and Warden sites to enable the spatial variability (vertical and horizontal) of soil properties within these earthworks to be determined.

Geophysical reconnaissance campaigns are also being carried out across all three sites to characterise the ground, improve understanding of the subsurface and the distribution, condition and integrity of the earthworks. Geophysical methods being applied at the sites include: Ground Penetrating Radar (GPR) using a relatively low frequency antennae such as 100 MHz to potentially differentiate between the soil types at the base of the earthworks; Multi-channel Surface Wave (MASW) surveys using a towed streamer with closely spaced shot centres to potentially map the shallow shear wave velocity (and estimated stiffness) variation along the earthworks; Electrical Resistivity Tomography (ERT) surveys along the surface of the earthworks to aid discrimination of water saturation or compositional variations in the fill and underlying materials; and Electromagnetic (EM) surveys using portable boom mounted coils that enable rapid walk-over mapping of near surface electrical conductivity. Ground and UAV-based LiDAR and photogrammetry surveys are also being undertaken to establish robust digital elevation models (DEMs) for the sites.

In situ observations have been supported by laboratory measurements on soil samples (from extracted borehole cores) of plasticity, particle size distribution, soil strength and stiffness, soil water retention behaviour, permeability, and resistivity. There has also been a substantial campaign of field measurements of surface infiltration/permeability, which is described further below.

4. Applications of the long-term monitoring data

The field monitoring data at the Newbury and BIONICS slopes have been used to understand changes in soil water content, pore water pressure/suction and lateral displacement and how these are influenced by the weather received at each site (see Smethurst *et al*, 2012 and 2021; Glendinning *et al*, 2014; Stirling *et al*, 2021). In addition, the sites have been used to specifically investigate several measures of variability and deterioration, and to provide critical validation for numerical simulations designed to understand future slope performance. These are described in more detail in the sections that follow.

4.1 Cracking and permeability

In clay slopes, desiccation cracking caused by soil shrinkage during dry summers significantly increases the permeability of the near surface zone. In the autumn, the high-permeability near-surface cracked zone can allow rapid infiltration of rainfall, having an important effect on the magnitude and duration of seasonal changes in water content and pore water pressures deeper within the slope. Large numbers of field measurements of saturated permeability at the Newbury and BIONICS site using double-ring and Guelph permeameters have been considered within the context of the monitored changes in runoff, soil water content and pore water pressures/ suctions (Dixon *et al*, 2019). Both Stirling *et al* (2021) and Yu *et al* (2021) monitored changes in crack morphology at the BIONICS site, again in the context of other soil observations (Figure 2 (a) and (b)). Collectively these studies have demonstrated how macro-scale cracks grow during soil drying in summer and increase the permeability of the near-surface zone by up to five orders of magnitude, and close again during swelling in autumn and winter. The results have been particularly important for the implementation of appropriate values for permeability within numerical simulations of slope deterioration in ACHILLES, which are described further in Section 4.3.

4.2 Soil water retention curves

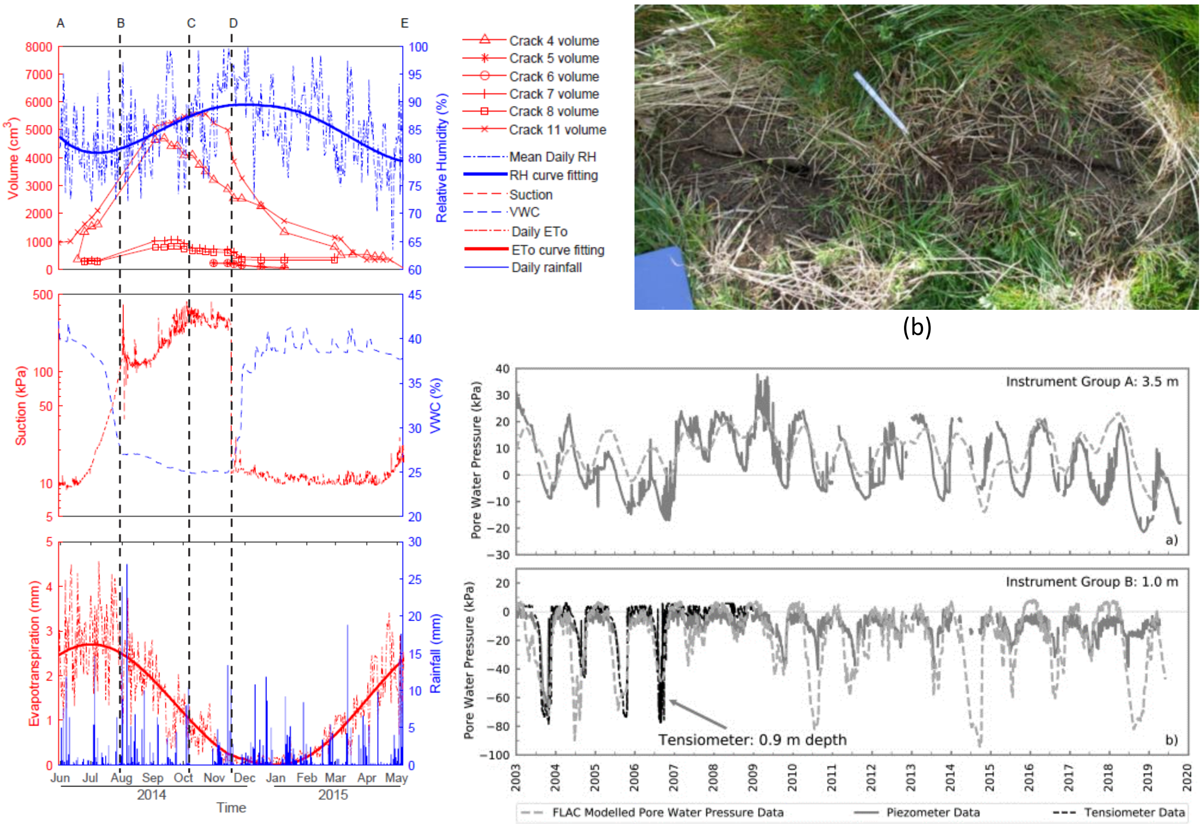
Soil water retention curves (SWRC's) define the relationship between soil suction and soil water content and provide a proxy for the mechanical and hydraulic properties of the soil within the unsaturated zone of the slope. Long-term and continuous *in situ* measurements of SWRC's are important because the soil water retention behaviour changes over time as a result of hysteretic wetting and drying cycles that cause volumetric and fabric changes to the soil structure including the formation of micro-cracks. In clay fill soils, the change in the soil structure causes progressively smaller suctions for the same change in soil in soil water content (Hen-Jones *et al*, 2017; Stirling *et al*, 2021). Soil suction (tensiometers and TDR/heat capacity probes) and soil water (TDR) sensors at each monitoring site have been co-located at the same depths to allow field SWRC's to be determined; Stirling *et al* (2021) present field observed changes in SWRC's for the BIONICS site. This enables the long-term influence of seasonal cycles of wetting and drying on the SWRC's and in-turn slope stability to be investigated at each site. As part of ACHILLES, these have been used, along with laboratory observations, to develop new constitutive model of soil behaviour that incorporates the progressive change in soil water retention behaviour.

4.3 Validation of conceptual and numerical models

Data from the exemplar long-term monitoring sites are being used to inform and validate conceptual and numerical models in-development within the ACHILLES research programme. For example, 16 years of soil pore water pressure and over 9 years of weather data measured by the piezometers and climate station installed at the Newbury site have been used by Postill *et al* (2021) to validate a novel numerical model of progressive failure that is being used to forecast the long-term performance of cut slopes formed in high plasticity clay (Figure 2c). The numerical model couples surface hydrology, unsaturated flow and soil mechanical behaviour to investigate the combined influence of dissipation of excavation-generated excess pore water pressures and seasonal weather-driven near-surface cyclic pore water pressures. The models being developed are essential to understand the effects that climate change will have on the rate of deterioration of the slopes (as demonstrated by Rouainia *et al*, 2020), and are being used to generate a set of deterioration curves for clay earthworks. The BIONICS field dataset is currently being used to validate a parallel set of models investigating deterioration in embankments.

4.4 Reconnaissance of condition and spatial variability

Earthworks can be heterogeneous at a range of scales due to the soil materials and methods used in their construction. The condition of an earthwork can also vary along its length, with sections that have changed or deteriorated more rapidly, leaving for example softened zones of lower strength. Ways of determining both heterogeneity and assessing condition (and the parameters associated with these) are important in trying to identify lengths of earthwork that may be more vulnerable to a reduction in performance and/or failure. For example, the vertical and horizontal spatial variability of soil strength can be considered in probabilistic assessment methods but these tend to over-estimate failure probabilities when only discrete measurements of soil strength parameters are used. The extensive characterisation of the BIONICS and Warden sites using both cone penetrometer tests (CPT) and the geophysical methods described above (see Section 3.5) is being used to explore heterogeneity and test whether the methods employed could assess condition or changes in condition. The CPT and geophysical information will be considered alongside the field monitoring data from the instrumented sections of the earthworks, to help assess a range of conceptual and numerical approaches for the above.



(b)

(a)

(c)

Figure 2: Use of field monitoring data to: (a) and (b) investigate crack opening and closing at the BIONICS site with changes in weather, soil water content and suction (redrawn from Yue *et al*, 2021); (c) validate numerical simulation results using field measured pore water pressures/suctions for several locations at the Newbury site (redrawn from Postill *et al*, 2021)

5. Conclusions

This paper has provided an overview of three exemplar long-term monitoring sites being used within the ACHILLES research programme: a highway cutting in London Clay (Newbury site); a purpose-built trial embankment constructed from Durham lower boulder clay (BIONICS site); and a flood defence embankment constructed from low to intermediate plasticity clay (Warden site). On-going instrumentation, long-term monitoring and ground investigation activities at these sites are described together with some applications of the long-term monitoring and ground investigation data. The observations from the field sites have proved invaluable in helping to understand real asset-scale performance, including changes in soil water content and ground movements due to seasonal cycles of wetting and drying, and seasonally driven deterioration in the near-surface including cracking and changes in permeability and water retention. The field data have played a critical role in validating both laboratory scale observations and novel numerical models of clay slope deterioration. The sites are also being used to investigate and test methods of assessing heterogeneity and condition.

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