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Developing a novel geophysical tool to investigate the influence of vegetation on slope stability

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Abstract. Vegetation is important for managing shallow geotechnical assets. However, root water uptake-driven changes in slope hydrology and the near-surface (soil water content, matric suction, and hydraulic conductivity) are highly complex. Improved knowledge of these processes is increasingly important as society faces the threat of a greater prevalence of climate-driven extreme rainfall and drought events. Intrinsic factors affect slope stability, including geometry, soil properties, groundwater, and vegetation-driven matric suction. Field evidence shows that engineered slopes are susceptible to hydrometeorological instability mechanisms and pose a potential failure hazard to asset operation and public safety. This study considers the combination of a novel geophysical monitoring system and geotechnical point sensors for use in controlled laboratory conditions to assess the influence of vegetation on soil-water dynamics in the context of geotechnical infrastructure. The geophysical monitoring system, referred to here as PRIME (Proactive Infrastructure Monitoring and Evaluation system), uses electrical resistivity tomography (ERT) technology to non-invasively image changing subsurface moisture-driven processes. The PRIME system and point sensor arrays are being developed for near real-time data acquisition of transient soil moisture conditions in a suite of soil column experiments. Through addressing the challenges associated with designing integrated geophysical-geotechnical laboratory-scale monitoring experiments, this research aims to provide new tools and approaches to further our understanding of vegetation-driven soil moisture movement to better assess slope instability risk.

1 Introduction

Conventional approaches for predicting slope failure events typically rely on intrusive investigations, which can only directly sample a small proportion of the subsurface, or surface observations, which do not reveal the subsurface precursors to slope failure events. In addition, these approaches are often observed at low temporal and spatial resolutions, limiting opportunities to characterise processes driving slope failure. To complement conventional approaches, geophysical imaging is being developed for asset monitoring to enable non-invasive high spatiotemporal resolution monitoring of the subsurface. In this study, time-lapse electrical resistivity tomography (ERT) is developed for laboratory scale monitoring using the PRIME (Proactive Infrastructure Monitoring & Evaluation) system (Chambers et al., 2020). Traditionally, when ERT is deployed, one-off snapshots of subsurface conditions are acquired through manual surveys – an approach that is widely used for environmental and engineering investigation (Loke et al., 2013). However, the PRIME system uses ERT technology to provide near-real-time automated remote monitoring and visualisation of subsurface conditions - allowing for changing ground conditions to be accurately modelled and displayed in a four-dimensions. This advancement in the capabilities of ERT technology is highly novel, providing researchers with new insight into subsurface processes driving slope failure (e.g., Holmes et al., 2020). Since the PRIME system was developed, it has been deployed in regions of slope instability, including for monitoring engineered slopes (e.g. Holmes et al., 2022). However, the PRIME system has not been applied in small-scale laboratory experiments. This study aims to address some of the technical challenges (e.g. electrode materials and dimensions, measurement settings,

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geophysical modelling of columnar geometries etc.) associated with small-scale column experimental design to enable the impact of vegetation on the soil hydrological performance of engineered slope fill to be explored.

2 Methods and Materials

This work consists of laboratory experiments at the UK National Green Infrastructure Facility (NGIF), Newcastle. The influences of vegetation on soil hydrology and slope stability have been tested in a high plasticity clay, *Ampthill Clay*, used to construct linear infrastructure networks in southern England. Hydraulic conductivity, moisture content, suction and resistivity have been measured. Laboratory-scale experiments apply ERT and point sensors in a series of soil column experiments. Vegetated samples are analysed using a controlled environment chamber and subjected to extreme climatic conditions (wetting and drying cycles). A suite of petrophysical characterisation tests and root scans were also performed further to quantify vegetation's impact on the soil hydrological performance. Three cylindrical columns (550 mm high, 110 mm diameter) were constructed from PVC plastic piping. The growth chamber controls relative humidity and temperature, and lighting is kept constant, providing stable environmental conditions for growth. Figure 1 depicts three soil column experiments taking place in the Environmental Chamber. (1) Soil column one consists of the ERT electrode array. (2) The middle column does not use any sensors and is used to grow plants in the given material. Root scanning equipment will then be used to map and quantify the root systems of the plants. (3) the column on the right uses TEROS-12 soil moisture sensors and TEROS-31 tensiometers. The soil material profile is kept the same throughout.

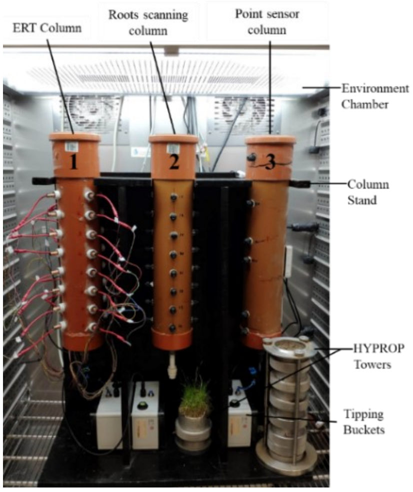

Fig. 1. Soil columns in the environment chamber at National Green Infrastructure Facility.

2.1 Plant Species Selection and Growing Conditions

Two grass species have been selected for this study - False Oat Grass *(Arrhenatherum elatius)* and Common Bent *(Agrostis capillaris).* Both Common Bent and False Oatgrass are hardy grass species native to and found in abundance across most of the UK. They have adventitious rooting ability (form roots during normal development and in response to stress conditions such as flooding) and coverage resistance (Norris et al., 2008) and tend to exhibit deep root systems that provide additional strength to surface soil layers. Their high tolerance to wet and dry conditions makes them an attractive plant choice for soil column experiments. The temperature of the growth chamber was kept at 16.6 degrees Celsius.

Table 1. Physical and Chemical Properties Measured of Engineered Fill.

	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	PI	Maximum Pd (Mg/m3)	Optimum WC (%)	CEC (meq/100g)
Ampthill Clay	0	1	4	95	44.84	1.48	20.8	18.2
Subsoil	0	50	20	30	na	1.68	17	10.7
Topsoil	15	83	2	0	na	1.58	17.9	10

2.2 Soil Column Material Profile

Figure 2 depicts the soil column set-up applied to the experiment. Three columns were filled with 500mm of soil. The top layer consisted of 50mm of topsoil; the middle layer consisted of 225 mm of subsoil overlying 225 mm of Ampthill Clay. Table 1 supplies the physical and chemical properties of the soil used in the column experiments. Experiments will be carried out at field capacity first, and later tests will explore different dry densities/ moisture contents.

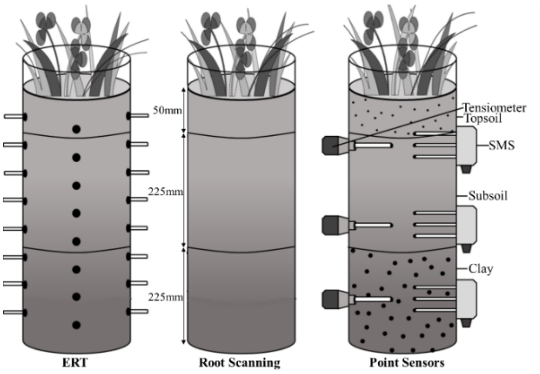

Fig. 2. Embankment soil column set up depicting the material profiles of the ERT, Root scanning and SMS/Tensiometer columns.

British Standards for topsoil requirements for use (BS 3882:2007), technical papers supplied by Network Rail (Birch and Evans, 2018), and borehole records from target regions of the UK were consulted when deciding the soil profile for the embankment column experiments. Given that the soil columns are limited to a material height of 500mm, a scaled approach was adopted for the soil columns to account for the three layers of soil comprising a typical railway embankment in the UK. Suitable (loosened) subsoil provided some rooting depth. The minimum rooting depth is usually 450 mm for grass. The length of the soil column is 500 mm, allowing soil depths to be scaled. However, grass rooting cannot be scaled. After experiments had concluded, it was found that grass did not penetrate deeply into the clay layer.

The saturation of the soil columns took two weeks. The columns were drained to reach field capacity. Once field capacity was achieved, the columns were planted with 0.28 g of Common Bent and False Oat grass. It is recommended, in the field, that seeds are watered twice a day. However, given the poor drainage, and small surface area of the soil within the confines of the columns, the grass received 50 ml of water twice a week for one month until the grass reached maturity. Once the grass fully matured, it was subjected to an extreme rainfall event. A one-in-100-year storm event was chosen. 400 ml of water was dispensed over one hour at equal intervals. A one-month summer drought was then simulated where the soil columns received no water. Data using ERT and point sensors were acquired over the duration of the experiment, with root scans taken once the grass reached maturity and, at the end of the experiment, after the drought phase.

3 Results and Discussion

3.1 Electrical Resistivity Tomography Soil Column

The ERT soil column was drilled with thirty-two holes, each 10 mm in diameter, consisting of four vertical rows of electrodes. Each row consists of eight electrodes, as seen in Figure 3. Holes drilled into the column for the electrodes were fitted with a plastic sealant used to support the weight of the electrodes, keeping them level over time and providing a watertight seal around the electrodes. Two iterations of the ERT soil column were developed to adapt the PRIME instrument for column experiments (Figure 3). The first design (A) used electrodes cut from stainless steel with pointed tips that could protrude into the sample. Glands were fitted to the column so the electrodes could be removed easily between experiments, and the depth that the electrodes extended into the soil could be adjusted. The second column (B) used electrodes cut from carbon graphite coated in copper foil. These electrodes are sealed into a position flush to the inside of the column with blunted tips. Before filling the columns with soil, the ERT column's ability to model resistivity was evaluated in both designs. Measurements with the PRIME system were taken every half an hour, allowing 15 minutes for the forward measurement and 15 minutes for the reciprocal. This was the shortest measurement interval achievable, given the number of electrodes in the column.

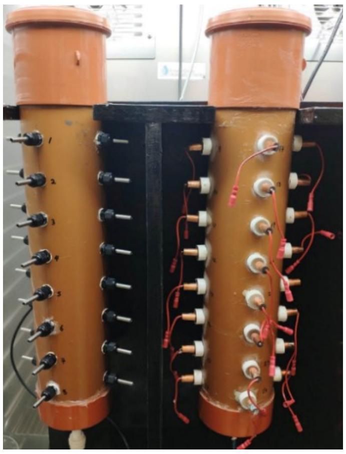

Fig. 3. Photograph of the first iteration of the ERT soil column (Column A, left) next to the second iteration of the ERT soil column (Column B, right).

The soil columns were filled with CAT 5 water (with a measured resistivity of 40.18 Ω.m), providing a homogenous medium to analyse the material's resistivity. Diagnostic data from the PRIME system comparing the two soil columns indicated a slight uptick in the number of measurements with lower reciprocal errors (error estimation by reciprocal measurements) and electrode contact resistances in column B, compared to column A, suggesting that carbon graphite was a more effective electrode design to steel. Early assessments indicated that both columns outputted highly irregular resistivity measurements. Figure 4 depicts the resistivity profile of water from columns A and B produced using ResIPy, a Python wrapper providing a graphical interface to process resistivity data from ERT sources. The inversion of column A depicts regions of high resistivity surrounding the electrodes. It was assumed that the glands fitted to the column surrounding the electrodes and the length of the electrodes were creating a layer of complexity in the geoelectrical models. A finite element modelling mesh was developed to physically model the glands and electrodes in the 3D volume of the cylinder. This approach helped slightly to achieve a more homogenous resistivity volume as it enabled ResIPy to account for the existence of the glands during processing; however, when column B was filled with water, and the resistivity profile was examined, the same problem persisted for column B, despite the more simplified geometries.

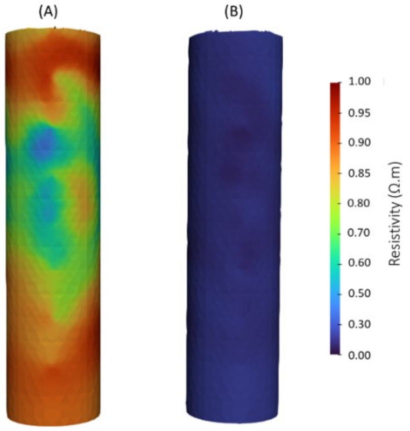

Fig. 4. Inversions of columns (A) and (B) filled with water.

Subsequent examination of the PRIME ERT column setup revealed that minor inconsistencies in the geometries of the electrodes and voltage clipping were at fault. When modelling the positions of the electrodes in the column, it is imperative that their locations are as accurate as possible. The PRIME system has yet to be applied in such small-scale experiments before, and it was discovered that the system did not allow for much tolerance for these discrepancies. Column B was handmade, accounting for these electrode position inaccuracies. The column was remade with machine capabilities, removing the risk of human error. Measurements collected by the PRIME instrument with high geometric factors were being voltage-clipped, causing inaccuracies in the returned transfer resistances. Geometric factors are physical entities that need to be accounted for when modelling ERT resistivity data. The more complex the geometries of that model become, the harder it is to portray the data accurately. Voltage clipping occurs when the PRIME system supplies the electrodes with too much electrical electric pressure resulting in the voltage transfer between electrodes exceeding its reference voltage level. A reference voltage level was not predetermined before commencing the experiment. Column B, presented in Figure 4, demonstrates that changing the PRIME measurement configuration to reduce the voltage output of the system helped to reduce the high resistances observed in Figure 4. The bulk resistivity of the column is now within a sensible order of magnitude.

3.2 Point Sensor Soil Column.

This column consists of three TEROS 12 soil moisture sensors and three TEROS 31 tensiometers. TEROS 12 sensors can measure the soil's volumetric water content, temperature, and electrical conductivity. TEROS 31 tensiometers measure water potential and temperature. A generic calibration was applied as the soils used in the experiments had an electrical conductivity lower than 8000 μS/cm. These sensors are well suited for laboratory work on soil columns, given that the sensor shaft can be installed from outside the column into the material and fitted into place using a gland. This minimises the site's disturbance level and can be easily removed during soil refills and maintenance. Transient soil moisture conditions are captured over time by time-lapse monitoring of soil-water-plant interactions using ERT and point sensors. Figure 5 provides moisture content data collected by point sensors over the duration of the experiment. The graph provides evidence of the system's poor drainage at each stage of the experiment. After the column was fully saturated and drained to reach field capacity, moisture content was significantly higher at the bottom (in the Ampthill clay) of the column, with moisture conditions being significantly lower at the top (topsoil) and middle (subsoil) of the column. Point sensor data will be used in tandem with future ERT resistivity plots to validate the reliability of PRIME technology for small-scale laboratory experiments.

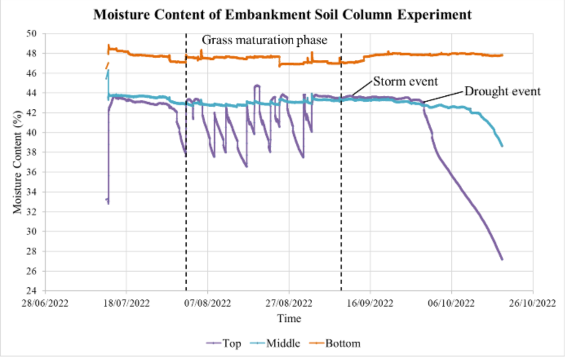

Fig. 5. The moisture content of embankment fill at the soil column's top, middle and bottom.

3.3 Root Scanning Soil Column

The roots of the plants will be analysed at different stages of the experiment: (1) once the grasses have reached maturity; (2) after the grass has been subjected to prolonged heavy rainfall; (3) after a prolonged drought period. Root scans indicate root morphology changes during drought and water inundation periods, providing information on how roots influence soil moisture dynamics. ERT-developed 3D modelling of moisture conditions in near-real-time is used to assess the internal conditions of the column assets, alongside root morphology data from the root scans, to highlight the evolution of soil moisture in extreme weather conditions in clay. Two methods of root scanning are assessed. (1) WinRHIZO is an image analysis system for quantifying root morphology. It can analyse the length, area, and volume of roots and, through colour analysis, group areas of roots dependent on these features. (2) Computed Tomography scanning (CT scan) of root systems. They are typically used in medical imaging to obtain detailed internal images of the body, adapted for non-medical applications to examine plant root structures in situ (Lafond et al., 2015).

Root morphology data collected with WinRHIZO was determined to be unreliable as the roots had to be procured through destructive techniques resulting in some of the roots being lost during procurement and washing of the soil. Figure 6 depicts a high-resolution photo scan of the roots procured at the end of the experiment alongside digitally processed imagery colour categorising roots dependent on their width. The roots procured from the grass were found to be exceptionally fine and dense, making both their procurement from the column and data processing difficult. The software failed to capture all the roots for processing due to how dense and tangled they were. The time taken to procure and process the root data varied, taking several hours, depending on how dense the roots were and how difficult it was to extrude the soil core from the column. Scanning using CT capabilities is currently being explored. However, accessing a scanner large enough to analyse soil core samples has proven difficult. Core cuttings have been taken from the soil column for analysis. If effective, it should be a less destructive method of analysing the roots without needing to extrude them from the column and wash them.

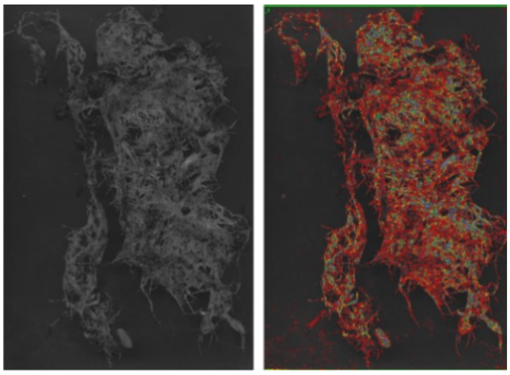

Fig. 6. Root scans of grass procured from soil column experiment. Processed using WinRHIZO.

3.4 Petrophysical Characterisation Tests

To better interpret PRIME resistivity models of soil columns, further analysis of the relationship between moisture content and electrical resistivity is required (Holmes et al., 2022). A modified HYPROP2 is used in combination with the soil column experiments (Figure 7). The modified HYPROP2 utilises a HYPROP2 instrument to produce soil-water retention curves (SWRC), which provide soil suction and moisture content data and ES2 conductivity sensors. The modified HYPROP2 measures electrical resistivity, soil suction and moisture content. Both resistivity and suction depend highly on moisture content. Therefore, it is possible to develop a quantitative relationship between these two parameters using a modified HYPROP2 system. This method was developed by Holmes et al. (2022), enabling resistivity to be measured in tandem with soil suction and moisture content. Non-vegetated samples are tested at maximum dry density. A limitation of the Modified HYPROP2 is that it is not possible to test vegetated samples directly at the start of the experiment. Once the experiment has commenced, grass would need to be grown for 8 weeks, at which point, the experiment has likely concluded, or the tensiometers have cavitated and the soil sample has shrunk, reducing contact with the electrodes. In order to overcome this limitation, a method for analysing the relationship between gravimetric water content and electrical resistivity was developed for vegetated soils. A HYPROP Tower was constructed from six 250 cm^3 HYRPOP2 rings. The HYPROP Tower was filled with 50 mm of topsoil overlying 225mm of subsoil and 25 mm of clay. The tower was planted with grass seed, and once matured, the rings were separated and tested on the modified HYPROP setup.

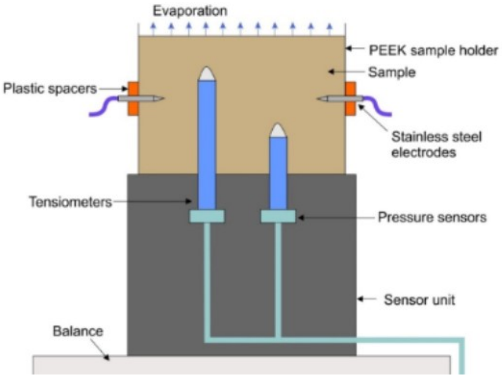

Fig. 7. Cross-sectional view of modified HYPROP experimental set-up (Holmes et al.2022).

During testing, a GP2 data logger was used, enabling multiple modified HYPROP2 experiments to be run congruently whilst using only one data logger. A calibration experiment was performed in order to process data transferred from the ES2 conductivity sensors to the GP2 logger. Preliminary experiments on soil samples were successful. However, subsequent testing revealed that raw data produced by the ES2 sensors had been corrupted. It is not yet known how this occurred, although it is suspected that the GP2 logger is at fault. A ZL6 data logger will be used in future experiments and assessed for its applicability for modified HYPROP2 experiments.

A set of data was procured from the modified HYPROP2 experiment from a non-vegetated sample of Amended Topsoil, a material used in a separate project occurring at the NGIF. Results of the electrical resistivity-moisture content relationship are shown in Figure 8 for the Amended Topsoil fitted with the Waxman-Smits model, labelled pGMC (Waxman and Smits, 1968). The Waxman-Smits models were fitted to the data to convert electrical resistivity to gravimetric moisture content (Holmes et al., 2022). The relationship demonstrates a clear decrease in resistivity as moisture content increases. When the same plot is produced for the embankment experiment, the resulting models can be used to calibrate ERT models generated by the PRIME system in the column experiments to convert resistivity into moisture content. Methods for examining the relationships between moisture content, soil suction and electrical resistivity in vegetated samples are still being developed and, if proven effective, will enable PRIME soil column models to be examined with respect to changes in moisture content and soil suction in the presence of vegetation.

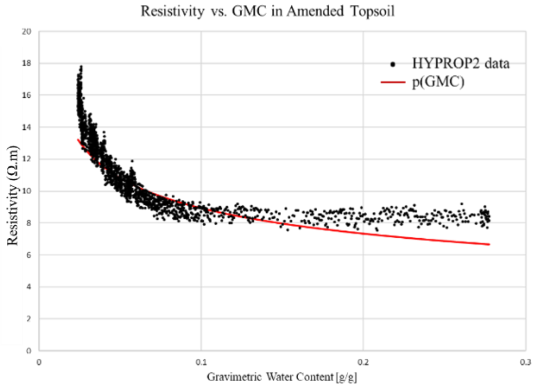

Fig. 8. Relationship between electrical resistivity and gravimetric water content in Amended Topsoil, fitted with Waxman-Smits model.

4 Conclusion

Using ERT in correlation with destructive root architecture imaging and point sensor data, this research investigates tools to understand better how to manage and mitigate slope failure risk. Developing a method for adapting the PRIME system for small-scale lab experiments has the potential to provide a unique insight into vegetation-driven soil moisture movement induced by the roots of plants during drought and extreme wetting events. This research aims to better inform slope management in response to climate change through real-time automated remote monitoring and visualisation of subsurface conditions.

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