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Investigating Water Holding Barriers for Climate Adaptation

Étude des barrières de rétention d'eau pour l'adaptation au climat

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ABSTRACT: CACTUS (Climate Adaptation Control Technologies for Urban Spaces) is an ongoing research project that is investigating the development of "climate adaptation composite barrier systems" capable of limiting the impact of a changing environment on buried geo-infrastructure, such as retaining walls and foundations. The project partners are investigating: (i) a range of potential soil types (with amendments) that will meet the desired requirements of climate adaptation engineered barriers (permeability and water holding capacity); (ii) the independent and combined impacts of wet-dry and freeze-thaw cycles on the volume change and strength characteristics of the potential barrier materials; (iii) appropriate species of vegetation that can promote removal of water from the water holding layer; (iv) experimental modelling of stress-deformation characteristics (lateral and axial) of the soil systems when subject to wetting and drying; (v) numerical modelling of the composite barrier systems to develop protocols for implementing the novel systems; (vi) trial implementation of the proposed technologies at field scale.

RÉSUMÉ : CACTUS (Climate Adaptation Control Technologies for Urban Spaces) est un projet de recherche en cours qui étudie le développement de «systèmes de barrière composite d'adaptation au climat» capables de limiter l'impact d'un environnement changeant sur les géo-infrastructures enterrées, telles que les murs de soutènement et les fondations. Les partenaires du projet étudient: (i) une gamme de types de sols potentiels (avec amendements) qui répondront aux exigences souhaitées des barrières artificielles d'adaptation au climat (perméabilité et capacité de rétention d'eau); (ii) les impacts indépendants et combinés des cycles humide-sec et gel-dégel sur le changement de volume et les caractéristiques de résistance des matériaux de barrière potentiels; (iii) des espèces végétales appropriées qui peuvent favoriser l'élimination de l'eau de la couche de rétention d'eau; (iv) la modélisation expérimentale des caractéristiques de déformation sous contrainte (latérale et axiale) des systèmes de sol soumis à un mouillage et à un séchage; (v) la modélisation numérique des systèmes de barrières composites pour développer des protocoles de mise en œuvre des nouveaux systèmes; (vi) la mise en œuvre expérimentale des technologies proposées à l'échelle du terrain.

KEYWORDS: Climate adaptation; Barriers; Water holding capacity; Soil water retention curves; Freeze-thaw.

1 INTRODUCTION

CACTUS (Climate Adaptation Control Technologies for Urban Spaces) is an ongoing research project investigating the development of "climate adaptation composite barrier systems" capable of limiting the impact of a changing environment on buried geo-infrastructure, such as retaining walls and foundations. The project is undertaking systematic experimental and numerical modelling studies to understand the response of composite barrier systems, when subjected to extreme weather events and long-term climatic processes.

The barriers comprise an upper water holding layer (engineered to hold water during storms and wet periods), a vegetation layer that can remove water during drying periods (by evapo-transpiration) and a capillary barrier system to prevent water from entering or leaving the deeper soil layers in order to maintain a constant water content at the level where the geo-infrastructure is constructed.

The project team is a consortium of UK Universities: Durham, Cardiff, Dundee, Queen's Belfast, Imperial College London and Newcastle. The project partners are investigating: (i) a range of potential soil types (with amendments) that will meet the desired requirements of the barriers (permeability and water holding capacity); (ii) the impacts of wet-dry and freeze-thaw cycles on the volume change and strength characteristics of the potential barrier materials; (iii) appropriate species of vegetation that can promote removal of water from the water holding layer; (iv) experimental modelling of stress-deformation characteristics (lateral and axial) of the soil systems when subject to wetting and drying; (v) numerical modelling of the composite barrier systems to develop protocols for implementing the novel systems; (vi) trial implementation of the proposed technologies at field scale.

2 PRELIMINARY RESULTS

2.1. *Identifying soil materials for barrier layers*

The identification of an appropriate material for a composite barrier layer is based on a number of critical parameters which include water holding capacity, unsaturated and saturated hydraulic conductivity, soil water retention characteristics, volume change during wetting and drying, compaction characteristics and shear strength. The composite barrier must allow the rapid infiltration of water during wetting, hold this water until it can be removed by vegetation, whilst remaining structurally stable under saturated conditions. These parameters can be viewed holistically as a soil's 'flood holding capacity' (Kerr et al., 2016). Kerr et al. demonstrated that using water treatment residual (WTR) to amend soil has significant impact on the water retention and volume change properties, with most notable improvements in saturated hydraulic conductivity and shear strength. WTR is a non-hazardous waste material from the production of drinking water. In its raw format WTR contains ~20% total dissolved solids and has a texture that resembles wet sludge. In its dried format WTR is highly porous and brittle material with a particle density of 2.11 g/cm^3.

Four amendments have been selected for CACTUS testing to assess their ability to provide critical improvements to key 'flood holding' parameters for the composite barrier material: a control soil (sandy loam), 10% WTR, 5% WTR, 2% WTR, 10% co-amendment with compost (5% WTR and 5% compost), calculated by dry mass. The amended specimens have been characterized using the following methods: use of high capacity tensiometers (Toll et al., 2013) to produce soil water retention curves (Fig. 1), use of chilled mirror hygrometer WP4C to provide suction values at low water content, triaxial testing (unconsolidated unsaturated and saturated consolidated) for shear strength and saturated hydraulic conductivity. Additionally, specimens were prepared to measure volume change and water holding characteristics of amendments over many climatic cycles, mirroring data produced at Cardiff University (see 2.2).

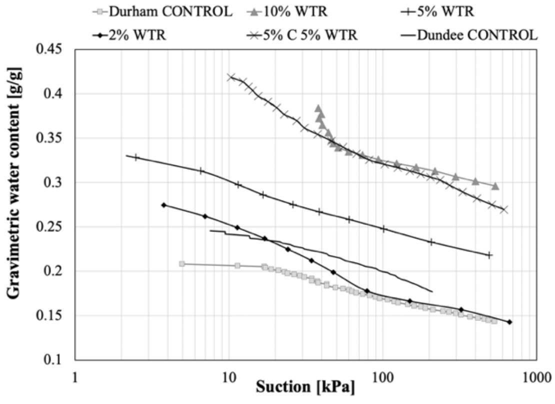

Figure 1. Soil water retention curve (drying only) derived using high capacity tensiometers of four amended specimens and two control specimens. Specimens have undergone four climatic cycles previous to testing.

The soil water retention curve shown in Fig. 1 indicates that the addition of WTR significantly changes the water retention characteristics, where higher water content is sustained for the same suction by amended specimens compared to the control soils from Durham and Dundee (sandy loams). This will be due to the change in fabric and the addition of clay size fine material, as 75% of WTR particles are <75μm. The gravimetric water content at 10kPa suction is highest for the 5/5% co-amended soil [0.42g/g] compared to 0.2g/g and 0.24g/g for Durham and Dundee control soils. Single WTR amendments also increase the gravimetric water content at the same suction, 2% WTR [0.30g/g] and 5% WTR [0.30].

Preliminary data suggests that the addition of WTR improves the water retention and shear properties of soils compared to the controls. Testing on hydraulic conductivity and consolidated undrained triaxial testing are ongoing and are required to make an assessment of the best proportion of amendment to improve the flood holding capacity of the composite barrier.

2.2. *Wet-dry and freeze-thaw cycles*

Seasonal climatic processes affect the engineering properties of soils and hence the stability of structures founded on soils. The volume change behaviour of soils subjected to wetting-drying and freezing-thawing cycles have been investigated previously but the combined response of soils to seasonal climatic processes involving all the four processes have not been explored in detail.

A low-plastic soil (sandy loam) from Dundee, UK (as used in 2.1 and 2.3) was used for studying the cyclic wet-freeze-thaw-dry behaviour. A column cell device (Al-Hussaini 2017; Tripathy et al. 2020) was used for carrying out the wet-freeze-thaw-dry tests on compacted specimens of the selected soil. The applied vertical pressure on the specimens was 2.0 kPa. The diameter and height of specimens tested were 103 and 80 mm, respectively. A vortex tube connected to the top chamber of the device controlled the freezing and drying temperatures in the soil specimens. The temperature at the top of the specimen was -15 °C (±1°C) and 37 °C (±1.5 °C) during freezing and drying cycles, respectively. The specimens underwent wetting and thawing cycles at ambient temperature of 22 ± 2.5 °C.

The specimens were subjected to five cycles of wetting-freezing-thawing-drying. Fig. 2 shows typical test results for specimen M3 (compacted on the dry side at 1.48 Mg/m^3).

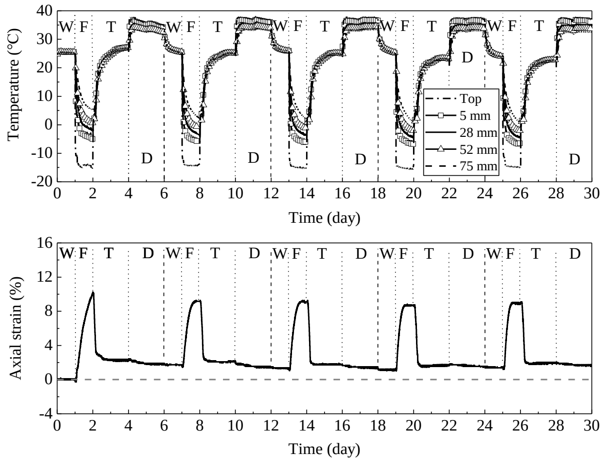

Figure 2. Typical temperature variations at predetermined heights of specimen M3 and axial strain with elapsed time (W-wetting, F-freezing, T-thawing and D-drying).

The temperatures recorded by the thermocouples at various depths from the top of the specimen were different; however, with an increasing number of cycles the values were similar for any given depth and process. The strain exhibited by the specimen was the greatest during the freezing cycles. The strains due to wetting and drying (partial) were found to be insignificant.

The axial strains of the specimens are presented in Fig. 3. Regardless of the initial compaction conditions, after about three cycles of wetting-freezing-thawing-drying, the volume change of all the four specimens became stable. An accumulation of strain was noted with an increasing number of cycles. At equilibrium cycles, the sum of strains due to wetting and freezing was found to be equal to sum of the strains due to thawing and drying.

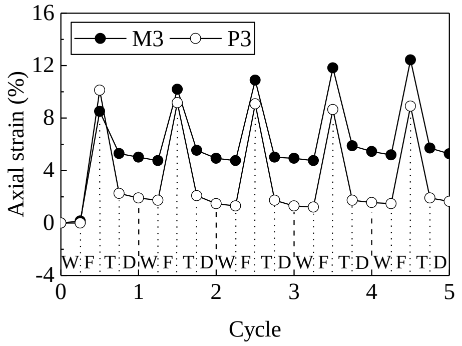

Figure 3. Impact of compaction conditions on vertical strain (M3 compacted on the dry side and P3 on the wet side).

2.3. *Plant-soil interactions*

Vegetation is a key driver of soil structure and hydrology (Bengough 2012; Gregory et al. 2010). Soil surrounding roots (rhizosphere) is one of the most hydrologically active regions of the biosphere, as approximately 40% of total terrestrial precipitation transits in it before being transpired to the atmosphere (Bengough 2012). In engineering solutions, rooted soil can represent a composite material with enhanced infiltration (Leung et al. 2018). In the urban environment, impermeable surfaces, and the removal of natural hydrological processes (e.g., transpiration) can exacerbate climate change effects and increase the risk of floods (Semadeni-Davies et al., 2008). Therefore, this research is needed to design new environmentally friendly multi-layer earthen barrier systems that can mimic the natural hydrological processes (e.g., plant-soil interactions) removed by urbanization.

This element of the project aims to identify hydro-mechanical effects induced by vegetation on the composite barrier system, by screening suitable plant species for enhancing barrier performance (e.g., removal of water from barrier). To select suitable species and plant types, contrasting herbaceous species (forbs, grasses and legumes) were selected and grown (Mar – Aug 2019) in compacted columns with barrier soil (sandy loam - 1.4 Mg/m^3 in dry density). Fallow soil columns were used as controls. After plant establishment, saturated hydraulic conductivity (k_{sat}) was tested for each soil column, followed by re-saturation and evapo-transpiration monitoring. Plant water uptake and soil strength (in terms of penetration resistance) were measured.

On average k_{sat} of vegetated soil was larger than that of control fallow soil (6.9e-6 ± 1.4e-6 m/s). However, the tested species differed in their effect on k_{sat}, ranging from 9.9e-6 ± 1.3e-6 m/s of *Festuca ovina* (grass) to 3.9e-5 ± 1.2e-6 m/s of *Lotus corniculatus* (legume; Fig. 4). In the vegetated soil, daily evapo-transpiration resulted in up to five times greater water loss compared to the fallow soil (Fig. 5). This soil drying strengthened the vegetated soil. For instance, soil vegetated with *L. corniculatus* had twenty-five times greater strength compared with control fallow soil.

Vegetation can have a notable effect on the soil-water relations of the barrier system. For example, the increase in soil hydraulic conductivity through root-induced channels and cracks in vegetated soil can allow more rapid transmission to drainage layers, mitigating flooding and erosion. However, large differences between species were found, with tap root systems (e.g., F-DC; L-LC) being more effective in increasing k_{sat} than fibrous roots (e.g., G-FO). Moreover, transpiration can restore the water holding capacity of barrier systems after heavy rainfall events and induce strengthening of soil. Therefore, vegetation should not be simply selected for aesthetically “greening” the barrier system, but instead for its engineering role. Indeed, there is a substantial scope of species selection to manipulate soil hydro-mechanical properties and hence to improve barrier performance during extreme climate events.

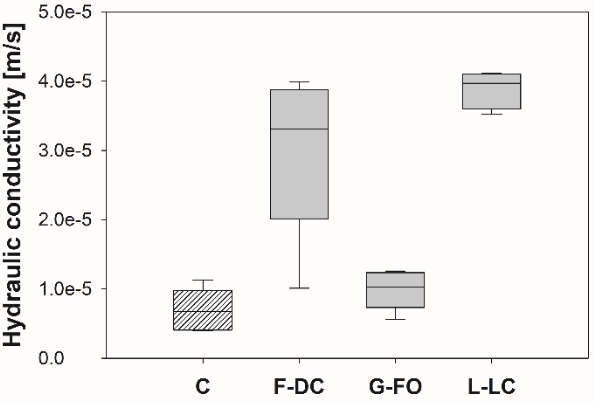

Figure 4. Saturated hydraulic conductivity measured in fallow soil and in soil columns vegetated with contrasting species. Acronyms: C (Control); F-DC (*Daucus carota*); G-FO (*Festuca ovina*) and L-LC (*Lotus corniculatus*).

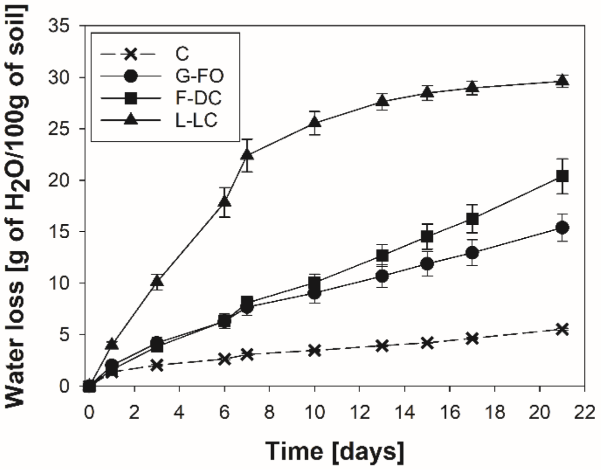

Figure 5. Water loss from fallow (control) and vegetated soil columns (30th July – 19th Aug 2019) normalized by dry soil weight. Means are reported ± standard error of mean (*n* = 5). Acronyms: C (Control); F-DC (Daucus carota); G-FO (*Festuca ovina*) and L-LC (*Lotus corniculatus*).

2.4. *Numerical modelling of barrier systems*

2-dimensional, axi-symmetric, hydro-mechanically coupled finite element analyses were performed to assess the performance of a generic engineered barrier, with the use of the Imperial College Finite Element Program (ICFEP; Potts and Zdravković, 1999 & 2001). The FEM mesh represents a 45-metre-deep soil column and the numerical analysis was performed in 3 Stages.

At Stage 1, the column consisted of 3 m of Weathered London Clay (WLC) and 42 m of London Clay (LC). This column was subjected to a long duration (4 years) of soil-atmosphere interaction analysis, to estimate the stable seasonal pore water pressure profile. Rainfall was simulated with the use of the precipitation boundary condition (Smith et al, 2008), while evaporation and transpiration were simulated using the vegetation boundary condition in ICFEP (Nyambayo and Potts, 2010). The input precipitation rate was based on weather simulation data for central London, obtained via the history+ database of meteoblue.com.

At Stage 2, the top 1 m of the column was excavated and a 1 m thick engineered barrier was constructed, consisting of a 0.2 m thick Drainage Layer (DL) at the base, and a 0.8 m thick Compacted Soil layer reaching the original ground surface. One additional year of barrier-atmosphere-vegetation interaction, with daily average precipitation and evapotranspiration data, was performed for higher accuracy of the initial suction profile before the storm application.

Finally, at Stage 3, an intense rainfall event was applied, with 15 mm/h intensity and 300 minutes duration, representing a return period of T=10 years for the London area, based on simulation weather data from Prodanovic and Simonovic (2007). The rainfall event initiated during the “dry” summer period (July). The water runoff initiation, the infiltration and run-off rates and the accumulated runoff water were examined both for the treated soil column with an engineered barrier and an untreated one consisting solely of in-situ London Clay to benchmark the effectiveness of the engineered barrier in reducing the risk of fast flooding and in preventing excessive deformations during wetting and drying cycles.

A variable permeability model for London clay was employed as a function of mean effective stress (Potts and Zdravković, 1999). A second variable permeability model, that accounts for the effect of desiccation crack opening (drying) and closing (wetting), was employed for weathered London clay. A suction dependent variable permeability was used for the compacted soil. Finally, a non-hysteretic soil-water retention curve model, presented in Tsiampousi (2013) was employed for the compacted soil.

Fig. 6 illustrates the infiltration (full squares) and runoff (empty squares) rates, for the treated (black lines) and untreated (grey lines) cases, for the 300 minutes rainfall event. In the case of the treated soil column, the infiltration rate equals the applied rainfall rate for the whole duration, meaning that the infiltration capacity of the barrier is not exceeded, and the runoff rate remains zero. On the other hand, in the untreated soil column, although the infiltration rate was initially equal to the rainfall rate, the water holding capacity of the soil was exceeded and runoff was initiated at 125 minutes. Thereafter, the infiltration rate progressively decreases while runoff rate progressively increases.

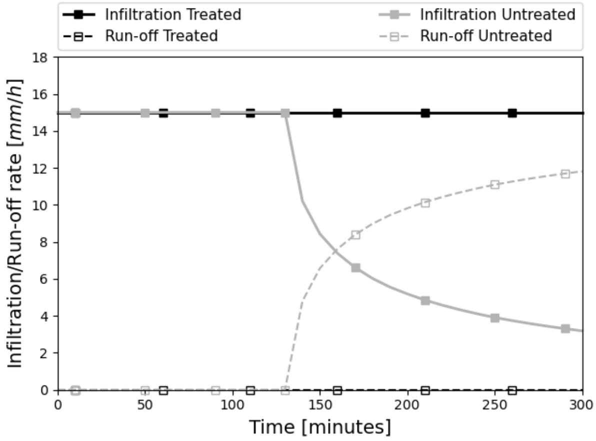

Figure 6. Infiltration and run-off rates during an intense rainfall event. Comparison between the treated (Barrier) and untreated (London Clay) cases.

Fig. 7 presents the surface heave with time during the rainfall event. It can be observed that the engineered barrier significantly reduces the large surface heave that is observed in the untreated soil column (grey dashed line). The numerical performance of the barrier during rainfall events of varying intensity and a parametric analysis for the critical properties of the barrier's materials, affecting its performance, is presented in Petalas et al. (2021).

The results demonstrate the potential of the engineered barrier to control runoff and reduce surface settlements during an intense rainfall event (Stage 3).

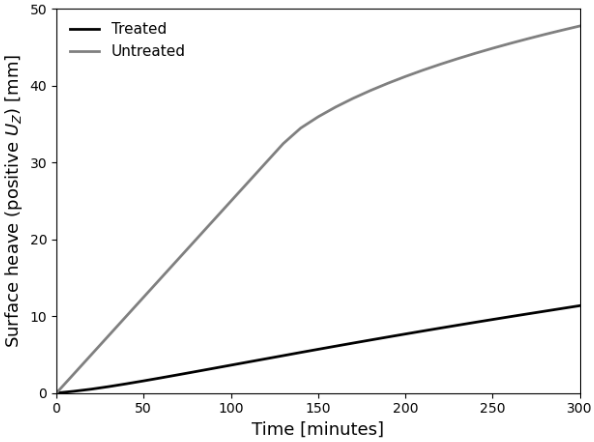

Figure 7: Surface settlement during an intense rainfall event. Comparison between the treated (Barrier) and untreated (London Clay) cases.

2.5. *Physical modelling of retaining walls*

The engineered barriers aim to protect geo-infrastructure (such as retaining walls and foundations) from variations in water content. Retaining walls can suffer as a result of swelling of clay fills producing high lateral stress, thus overstressing the wall. Lateral stress within the soil mass behind a retaining structure can significantly evolve during the post-compaction wetting (Sivakumar et al., 2015) and in some cases the earth pressure coefficient ($K_o = (\sigma_h - u_a)/(\sigma_v - u_a)$) can reach as high as 4.0 in high plasticity clays. The research undertaken at the Queen's University Belfast (QUB) will investigate the impact of stress regime on retaining structures during extreme environmental cycles (i.e., wetting and drying) by exploring 3 novel approaches (i) 1:10 physical scale model study, representing a 10 m retaining structure; (ii) Full-scale investigation through centrifuge testing and (iii) Element testing using a novel stress path system combined with various sensors to monitor stress and strain parameters. Some early findings from the element testing are presented here.

Kaolin clay prepared at a loose state (optimum water content of 28.0%) was compressed to a 50 kPa of vertical pressure in a split mould. A trimmed sample was subjected to a gradual increase of vertical pressure to a target value of 1300 kPa and then unloaded to 25 kPa. The lateral deformation was restrained by increasing or reducing the confining pressure using a computer control system. The maximum dry density achieved using this approach was approximately equivalent to that obtained using Standard Proctor compaction.

The next stage of the investigation was to model the post-construction performance, whereby the fill was subjected to wetting and drying cycles. To do so, a novel experimental system was developed. Fig. 8 represents a schematic view of this system which accommodates a sample of 100 mm height and 100 mm length. The system is equipped with four high capacity tensiometers, radial and axial strain gauges. The sample prepared using static compaction to a vertical pressure of 1300 kPa was assembled in the system.

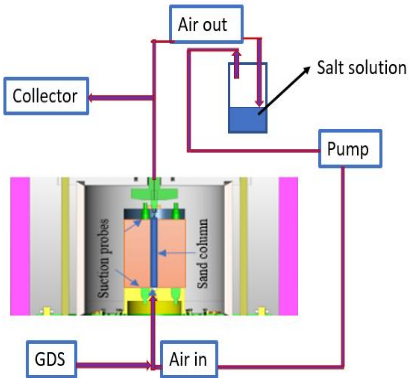

Figure 8. Schematic representation of stress path system fully equipped and a slender hole at the centre

A small slender hole of 7 mm diameter was drilled at the centre of the sample and filled with fine sand. The sample was then subjected to the current stress state (σ_v-u_a =200 kPa; σ_h-u_a =225 kPa). High capacity tensiometers located on the top and bottom of the sample yielded the suction value within the sample under this loading conditions. The sample was initially subjected to wetting by injecting water into the sample at a rate of 0.25 cm^3 per hour. The sample was then subjected to drying by circulating low humidity air (air above a salt solution) through the slender sand column. The wetting and drying cycle was repeated several times. Each cycle lasted about 20 days. During the entire testing, the vertical pressure was maintained at 200 kPa, however the horizontal pressure was changed to maintain zero lateral strain conditions.

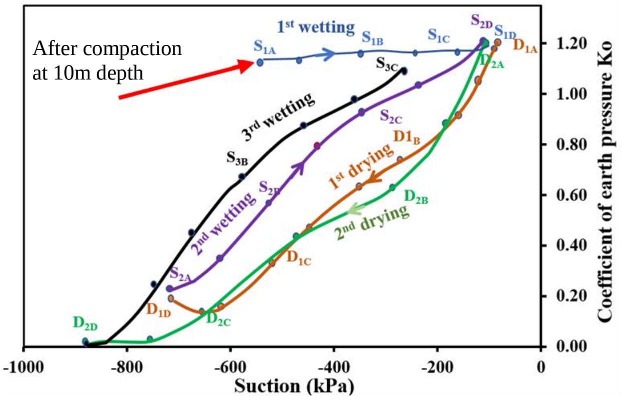

Figure 9. Variation of K_o during wetting and drying cyclic events

Fig. 9 shows the variation of K_o during the cycles of wetting and drying process. The starting point (S_{1A}) represents conditions after the placement of fill at which point the value of K_o was 1.12. This value increased to just over 1.20 during the first wetting process (Path S_{1A} - S_{1D}). During the subsequent 1st drying (to a suction of 650 kPa) the K_o value reduced to approximately 0.2. Surprisingly, the second wetting (S_{2A}- S_{2D}) resulted in a K_o value that was equal to that obtained during the first wetting. The second drying to a suction value of 700 kPa resulted in a K_o value of just over zero representing a formation of tension crack. The sample was dried further, to higher suction value (at D_{2D}), however a K_o condition could not be achieved as the system cannot apply lateral stress less than zero. At this stage, the lateral strain condition was seriously violated, representing a formation of a tension crack. The subsequent wetting (S_{3A} - S_{3C}) mimicked the case where the tension crack became filled with debris before wetting. Observations shows that the above scenario can exert more lateral pressure than otherwise, causing the K_o value to increase progressively. The state examined here is contemporaneous with 10 m depth, however, there can be a significant change in stress regime at shallow depths, which will be studied in further tests.

2.6. *Field-scale testing of barriers*

Field-scale testing of composite barrier systems will utilise a large-scale lysimeter (2 m x 1 m x 4.5 m) at the National Green Infrastructure Facility (NGIF), Newcastle University, UK. The lysimeter is fabricated from stainless steel and timber-clad to fit within the urban landscape. As outlined in Section 2.1, the composite barrier will consist of a water retention layer comprised of a sandy loam with an addition of 5% WTR. This will overlay a drainage layer comprised of recycled concrete that is 5 times coarser than the water retention layer to promote a capillary barrier effect at the interface (Jason and John, 2001). A geotextile will be installed at the boundary between these layers to prevent wash-through of fines into the coarse-grained layer and maintain the required contrasting hydraulic properties. A fibreglass liner installed in the lysimeter will separate the barrier into two equally sized cells. In each compartment, the thickness of the water retention layer will be varied such that the impact of geometry on the effectiveness of composite barriers can be assessed: A 0.6 m retention layer with large water-holding capacity will be compared with a more cost-effective 0.3 m retention layer. The drainage layer in each case will be kept a constant thickness of 0.2 m. Following from work presented in Section 2.3, each barrier will be planted with a biodiverse mixture of native flora including *Lotus corniculatus, Festuca ovina, Daucus carota, Lotus pedunculatus, Deschampsia cespitosa*, and *Geum rivale*. Besides the aesthetic and biodiverse appeal of such a community, it is intended that this range of species will provide maximum evapotranspiration throughout the year, as some species are adapted to wet conditions, and some are adapted to dry conditions.

Data will be acquired from the lysimeter experiment across a two-year monitoring period, during which the composite barrier will be subjected to natural and simulated rainfall events. The lysimeter will be instrumented with volumetric moisture content probes (Teros 12 and EC-5 (MeterGroup)) and soil suction probes (Teros 21 (MeterGroup) and TensioMark (ecoTech)) positioned at a range of depths below the surface (0.1, 0.2, 0.4, and 0.58 m in the 0.6 m retention layer case, and 0.1, 0.2, and 0.28 m in the 0.3 m retention layer case, plus 2 additional Teros 12 probes within the drainage layer in both experiments), as shown in Fig. 10. Drainage channels at the side and in the base of each lysimeter cell will allow for runoff and breakthrough to be measured using tipping counter flow gauges (MeterGroup), as shown.

Vegetation will be monitored throughout the experiment, including a radiometer to estimate evapotranspiration, detection of Leaf Area Index and measurements of stomatal conductance. Infiltration rates will also be measured using a mini disk infiltrometer (MeterGroup) and a SATURO (MeterGroup), which will also provide measurements of saturated hydraulic conductivity. Weather conditions will be recorded by an onsite weather station consisting of a WXT536 (Campbell Scientific) which provides measurements of wind speed and direction, precipitation, barometric pressure, temperature and relative humidity.

3 CONCLUSIONS

The CACTUS project is researching novel composite barriers capable of limiting the impact of a changing environment on buried geo-infrastructure. The barriers comprise an upper water holding layer, vegetation to remove water during drying periods and a capillary barrier system to prevent water from entering or leaving the deeper soil layers in order to maintain a constant water content at the level of the buried geo-infrastructure.

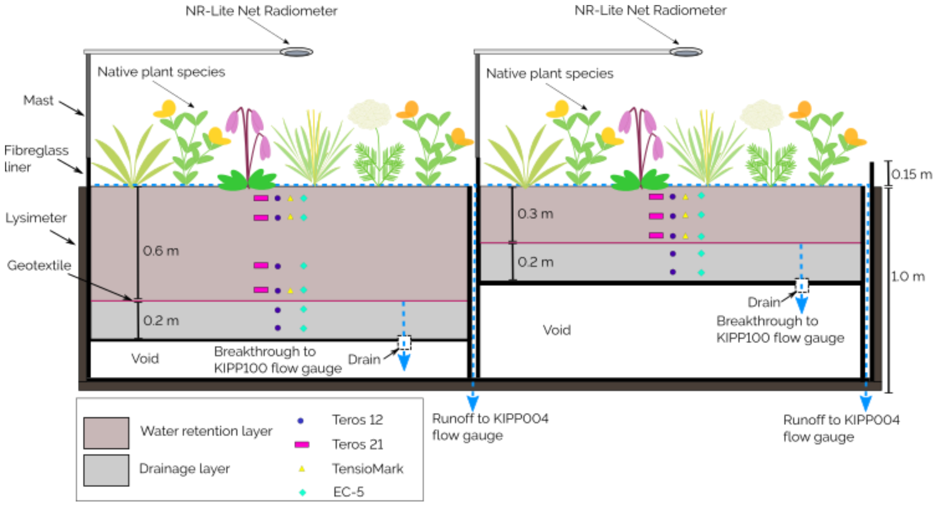

Figure 10. Schematic of lysimeters with annotation of instrumentation, construction material and soil profile.

Water treatment residual (WTR) has been identified as an amendment for a sandy loam soil to be used as potential barrier material and significantly enhances the water retention properties. Studies of combined wetting-freezing-thawing-drying of potential barrier material show that volume changes are greatest during the freezing cycles. After about three cycles, the volume changes become stable.

Herbaceous species (forbs, grasses and legumes) have been investigated for enhancing evapo-transpiration. The vegetation improves the hydraulic conductivity of the soil and results in daily evapo-transpiration producing up to five times greater water loss compared to the fallow soil.

Studies of post-compaction wetting and drying show that the lateral stresses that would act on retaining walls change significantly. They can reduce to zero as a result of tension crack formation during drying but recover to close to previous values on wetting.

Numerical modelling through hydro-mechanically coupled finite element analyses were performed to assess the performance of a generic engineered barrier. These show that for a typical barrier the infiltration capacity of the barrier would not exceeded during an intense rainfall event, whereas runoff would have been initiated if the barrier was not present.

The field-scale implementation will provide insight into engineered soil-plant-atmosphere interactions and their influence on the performance of barriers using differing geometries under a range of typical and extreme weather conditions, ultimately informing recommendations for the construction of urban composite barrier systems.

4 ACKNOWLEDGEMENTS

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