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Assessing the ability of vegetation to enhance the hydromechanical performance of a capillary barrier

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ABSTRACT: A capillary barrier system (CBS) can help to regulate water fluctuations within the built environment and stabilise slopes that are vulnerable to rainfall-induced failures, such as those formed from high-plasticity clays. The barrier prevents water percolation into the underlying slope as a result of the unsaturated characteristics of the fine and coarse layers of the CBS. It also provides water storage, minimising run-off and acting as an effective element of a sustainable (urban) drainage system (SuDS). This paper will explore the effect of adding vegetation to improve the performance of such a system. The results of 1:1 full-scale physical models of a unit-cell within a vegetated CBS are presented to evaluate the ability of live vegetation to remove water from the barrier by evapotranspiration (ET) following saturation (e.g. from an extreme rainfall event), 're-setting' the beneficial hydraulic characteristics of the barrier and increasing resilience to subsequent events. The physical models are subsequently subjected to re-wetting after ET, to determine how quickly the positive engineering characteristics are regained. In conjunction with changes to fundamental physical characteristics induced by the vegetation (from element tests), including permeability and water storage capacity, the model testing demonstrates the potential for using live vegetation to create a nature-enhanced CBS that has significantly improved performance for the small cost of ongoing vegetation management.

1 INTRODUCTION

Cutting and embankment slopes formed from high plasticity clays are particularly vulnerable to seasonal changes in water content. Wetting and drying cycles generate small permanent deformations that accumulate, resulting in a 'ratchetting effect'. This has been shown to progressively reduce the stability of such a slope, limiting its usable life (Postill et al., 2021a). This damage mechanism is stronger for slopes that are steeper and/or taller, e.g. a 1:2 slope may have a time to failure (design life) greater than 120 years at 5 m tall, but less than 60 years at 10 m tall (Postill et al. 2021b). Furthermore, the effects of Climate Change have been shown to accelerate this process, by increasing the extremes of wet and dry conditions (Rouainia et al., 2020). The UK has many ageing slopes on the strategic rail network with geometries that mean that they are likely to shortly reach a marginal stability condition (Network Rail, 2018).

Conventional methods for strengthening such slopes typically involve increasing the slope's resistance to increase factor of safety, e.g. by installing soil nails. While this can extend life, it is expensive and yet does not change the underlying hydromechanical ratchetting mechanism as water can typically still infiltrate and evaporate from the surface.

A Capillary Barrier System (CBS) represents an alternative solution to protecting these vulnerable earthworks. A CBS consists of a thin two-layer soil veneer (a comparatively finer-grained layer (FL) above a coarser-grained layer (CL)) which is applied to the surface of the slope (Figure 1a). Although the fine layer saturates during infiltration, the coarse layer remains a hydraulic barrier, with unsaturated hydraulic conductivity orders of magnitude smaller than that of the fine layer (i.e. $k_{FL} > k_{CL}$). Water is then stored in and subsequently drained through the barrier, such that the slope is maintained under suction. This has a number of effects: the slope is maintained at a continuously high factor of safety (supressing large volume, deep

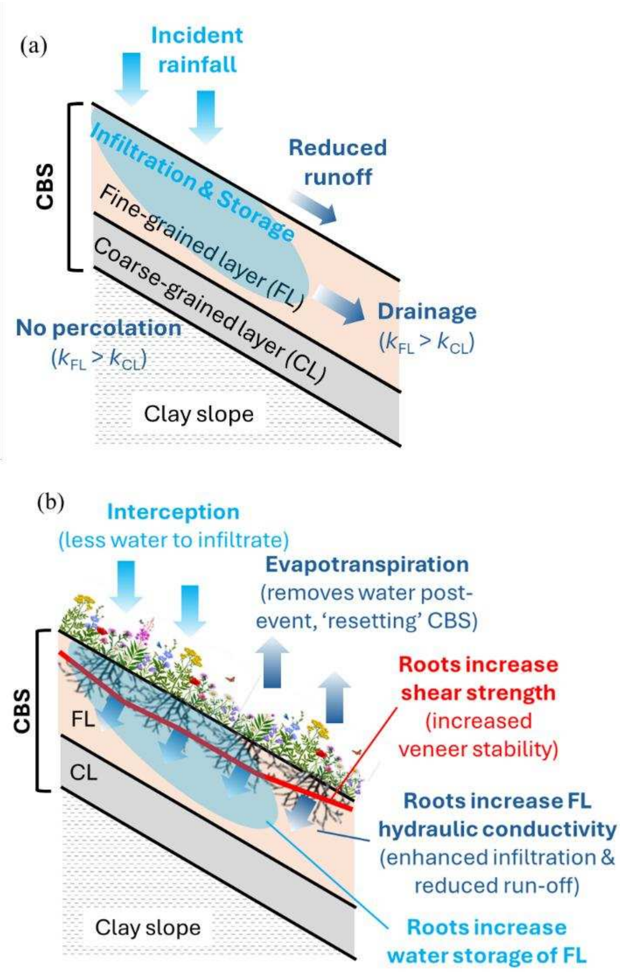

Figure 1. Capillary Barrier System (CBS) for slope protection: (a) principle of operation - standard CBS; (b) additional benefits of a nature-enhanced CBS.

slips), the cyclic wetting-drying/ratchetting mechanism is supressed, slowing deterioration, and the critical slip failure mechanism moves to within the (shallow) CBS veneer with a factor of safety higher than that of the fully saturated clay slope, were water allowed to infiltrate unimpeded (Scarfone et al. 2023). Run-off is also reduced, lowering the risk of flooding within a cutting.

Figure 1b shows the potential benefits to hydromechanical performance of adding surface vegetation. This paper presents the results of 1:1 physical model tests of a conventional and 'nature-enhanced' CBS (using vegetation), focussing on: (i) modification of basic hydraulic characteristics due to the plant roots; (ii) infiltration to the CBS in antecedent wet and dry conditions (representative of an extreme rainfall event occurring in winter or summer, respectively); (iii) the ability of vegetation to rapidly 'reset' the water storage of the CBS to improve its ability to deal with multiple events happening within a short period of time; and (iv) shear strength enhancement within the FL to increase the critical factor of safety against sliding with the barrier in place.

2 METHODOLOGY

2.1 Model CBS

A simple physical model of a one-dimensional column from within a CBS was developed, utilising a PVC pipe 100 mm in diameter and 0.5 m long to act as the container. This was coated internally in silicone grease and a thin sheet of polythene to facilitate extraction of the soil for post-test sampling, while preventing preferential water flow between the pipe and the sheet. The base of the pipe was covered with a nylon mesh of 1 mm aperture size. A layer of pea gravel, 50 mm thick, was firstly placed in the bottom of the pipe, above the mesh to act as the drainage layer (CL). Above this, a 0.4 m thick layer of compacted sandy silt (43.3% sand, 55.2% silt and 1.5% clay) was placed to represent the FL at 1:1 scale. The FL soil had a liquid limit of 32%, plastic limit of 24% and a plasticity index of 8%.

Soil was compacted in eight lifts of 50 mm thickness to a target dry density of 1400 kg/m3. This utilised a standard Procter hammer (2.4 kg) applying five blows per layer to a 100 mm diameter aluminium plate with a thin circumferential outer step on the underside to ensure that there was no preferentially low-density zone near the wall of the pipe, supressing preferential water flow and root growth along this interface.

2.2 Nature-enhancement with vegetation

Six UK-native herbaceous plant species were selected for testing representing species commonly found in European dry (three) and wet (three) meadows, such as might be suitable for dryer or wetter locations. These represented contrasting functional types (forbs – F; grasses – G; legumes – L), as shown in Table 1. Model CBS, prepared following the method in Section 2.1, had three pre-germinated seed sown at the upper surface of the FL at the three corners of an equilateral triangle of side 60 mm.

Table 1. Plant species used in nature-enhanced CBS tests.

Species	Type	Community	ID
Lotus corniculatius	L	Dry	L-LC
Festuca ovina	G	Dry	G-FO
Daucus carota	F	Dry	F-DC
Lotus pedunculatus	L	Wet	L-LP
Deschamp. cespitosa	G	Wet	G-DC
Geum rivale	F	Wet	F-GR

Some models were prepared in monoculture, using three seeds of the same species, while others were planted with a community of one of each dry (CDM) or wet (CWM) meadow species. Immediately after sowing, each model was irrigated with 200 ml of water before being placed in an unheated glasshouse with no additional heat or light provided. Temperature and relative humidity were close to outdoor conditions at the James Hutton Institute (Dundee, Scotland) throughout the establishment/growth and testing period (April – September 2019). During establishment (three months; April – June), model barriers (planted and unplanted controls; see Section 2.3) were irrigated with 30-60 ml of water, three times per week.

2.3 Test programme

A total of forty-five model CBS columns were created following the procedures outlined in Sections 2.1 and 2.2. These consisted of five replicate conventional CBS (with no vegetation), five replicate columns of vegetated CBS of each of the species' monocultures as indicated in Table 1 ($5 \times 6 = 30$) and five replicate columns of each of the CDM and CWM community plantings ($5 \times 2 = 10$). All model CBS columns were then subjected to the same consecutive suite of hydraulic tests as detailed below.

2.3.1 Hydraulic performance

Following plant establishment (Figure 2) the columns were seated on a thin layer (10 mm) of sand and gravel within a large outer container and saturated bottom-up with water for 24 hours. Subsequently a constant head test was conducted under saturated conditions, applying 30 mm of head to the soil surface using a Mariotte bottle to characterise the hydraulic conductivity (test series 1).

Figure 2. CBS model columns after plant establishment.

While samples remained saturated, a single ring infiltrometer (55 mm diameter) was used to determine the infiltration rate for 75 ml of water in the fully saturated soil. This simulates intense rainfall occurring in a wet ('winter') season with wet antecedent soil conditions (test series 2).

Water was then drained from the outer container and the models were left to evapotranspire (vegetated CBS) or evaporate (conventional CBS) for 21 days under 'summer' weather conditions (July – August 2019). Water loss was measured by weight difference periodically. These tests simulated CBS 'reset' following an intense rainfall event (test series 3).

The infiltrometer tests, detailed above as test series 2, were repeated following the evaporation/ evapotranspiration stage. This simulates intense rainfall occurring in a dry ('summer') season with dry antecedent soil conditions (test series 4).

Finally, intact soil cores (50 mm diameter; 60 mm high) were sampled from the centre of the conventional and community (CDM; CWM) models to determine soil-water retention curves (SWRC; examining differences in water storage between conventional and nature-enhanced CBS systems). A ceramic suction plate was used for matric suctions up to 50 kPa and a pressure plate apparatus (Soilmoisture Equipment Corporation, USA) was used beyond this up to 1.5 MPa (test series 5).

2.3.2 Shear strength enhancement

Following the hydraulic testing described in Section 2.3.1 and exhumation of the root systems post-test, seven further model CBS columns were produced to examine root enhancement to mechanical shear strength for a critical slip plane passing through the FL of the CBS. The columns were slightly larger in diameter (150 mm) and had a horizontal split that was initially externally taped during model preparation. The diameter and split enabled the columns to be tested in direct shear at ~170 mm below the soil surface in the FL as a physical model of the CBS element undergoing a shallow translational soil slip. The apparatus for this is shown in Figure 3 and shearing was conducted at 0.05 mm/s (test series 6).

One column acted as a conventional CBS control; of the remainder, three columns were planted with F-DC and the other three with L-LC, due to the contrasting root morphologies observed from the preceding hydraulic testing. Due to the larger area of the tube, nine pre-germinated seeds were sown at the upper surface and plants were grown for four months.

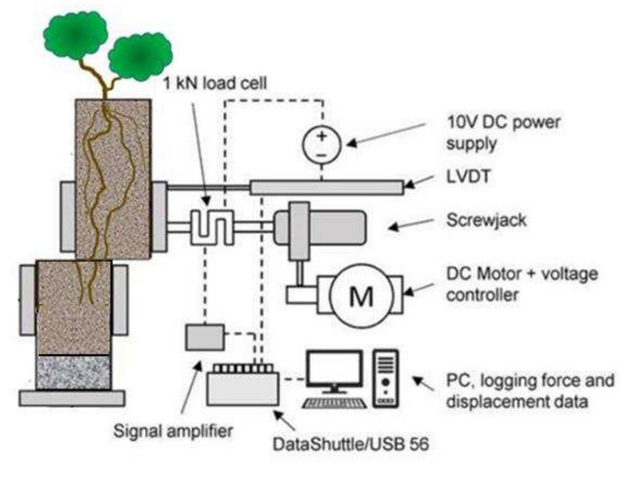

Figure 3. Direct shear apparaus for simulating landsliding in vegetated cores.

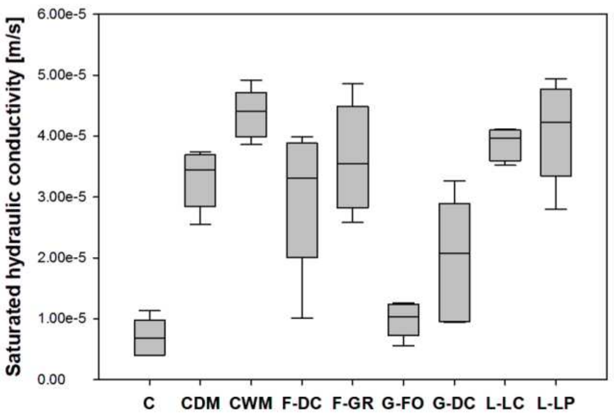

Figure 4. Saturated hydraulic conductivity of conventional ('C') and nature-enhanced CBS models (test series 1).

3 RESULTS

3.1 Saturated hydraulic conductivity

Figure 4 shows the results of the initial characterisation testing of the different cores. The shaded boxes show the interquartile range (25th to 75th percentiles), the lines in the shaded zone indicate the median and the whiskers indicate the 10th and 90th percentiles (n=5 in each case). The conventional CBS without vegetation is represented by 'C'; the other labels are as indicated in Table 1.

In most cases, the presence of plant roots increased the saturated hydraulic conductivity by a factor of approximately four. Across the monocultures, the effect was very variable, either exhibiting large variability or little effect compared to the conventional case. Only one monoculture exhibited strong and reliable beahviour (L-LC). In contrast, both community cases produced strong increase in conductivity and comparatively little variability. This suggests that planting a more diverse range of species can help provide more predictable modifications of fundamental engineering parameters for use in design. Such an approach would also provide benefits in terms of resilience to disease, biodiversity and overall soil health.

3.2 Infiltration (wet antecedent conditions)

Figure 5 shows the infiltration rate of surface water for the extreme groundwater condition when the FL soil is fully saturated (e.g. from an extended previous wet period). The bars indicate mean values, and the whiskers indicate one standard error of the mean. In all vegetated cases, infiltration rate is increased compared to the conventional CBS ('C') by a factor of four-to-

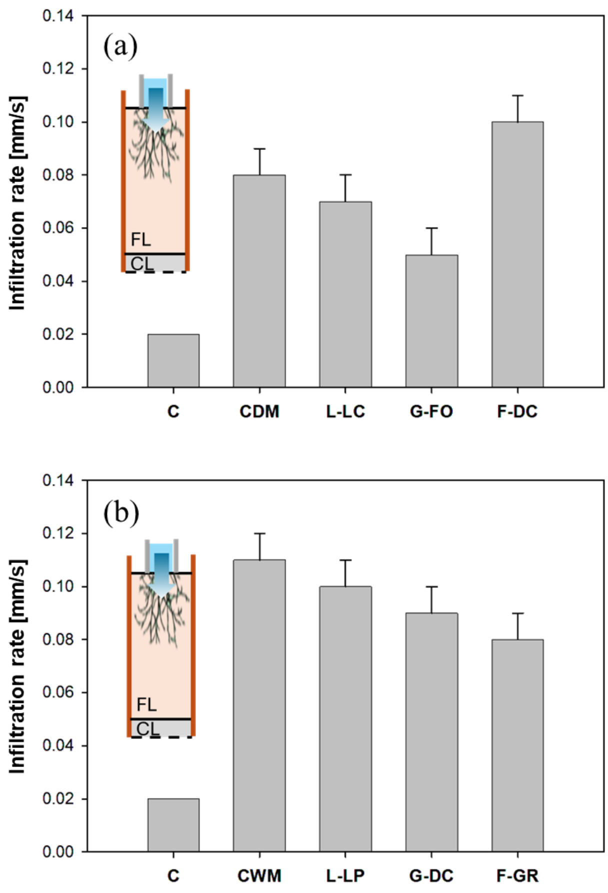

Figure 5. Comparison of surficial infiltration rate between conventional ('C') and nature-enhanced CBS when the FL is fully saturated (wet antecedent conditions; test series 2): (a) Dry meadow species; (b) Wet meadow species.

five in the CDM and CWM cases. Infiltration rates are relatively small, so the improvement is unlikely to significantly change run-off in a very large event or for a long duration storm when the ground is saturated. However, it may be significant enough to mitigate run-off in smaller events, reducing surface erosion and flooding. It is also notable that in the wet antecedent conditions tested in this phase, the wet meadow community (CWM) performs results in higher infiltration than the dry community (CDM) by approximately 40%.

There is, however, a balance to strike; although run-off can be reduced by enhanced infiltration, flow through the FL will be higher than in the control case due to the increased permeability (Figure 3), such that water will reach the FL-CL boundary more rapidly and potentially promote breakthrough earlier. This would need to be weighed against the other benefits the vegetation provides. However, recent numerical simulation work by Petalas et al. (2022) has demonstrated that an increase in FL permeability by a factor of approximately three from the control value considered in this study did not significantly increase percolation into the CL for a 10-year return period event with wet antecedent conditions. Further investigation into this effect under more extreme rainfall conditions would provide further guidance on this for design.

3.3 CBS 'reset' after rainfall event

Figure 6 shows the loss of water (regeneration of storage capacity) with time during the evaporation/evapotranspiration stage. The datapoints indicate mean values and the whiskers indicate ± one standard error of the mean. In all cases, vegetated columns (nature-enhanced barriers) lose water significantly more rapidly than the conventional CBS ('C'; which cannot lose water by transpiration). Wet meadow species performed significantly more consistently than dry meadow cases (where there was a larger species effect). Both communities, however, also perform well suggesting that significantly improved hydraulic regime can be achieved through mixed communities while making use of the smaller variability in other parameters that they exhibit (c.f. Figure 4).

In Figure 7, the soil water content at the start and end of the evaporation/evapotranspiration period is compared. Water contents at full saturation and residual water content from the SWRC (see Section 3.5) are also shown. It can be seen that, except in a few cases of monoculture (F-DC and G-FO), all of the vegetated CBS models are able to completely reset the water storage capacity of the FL after 21 days (3

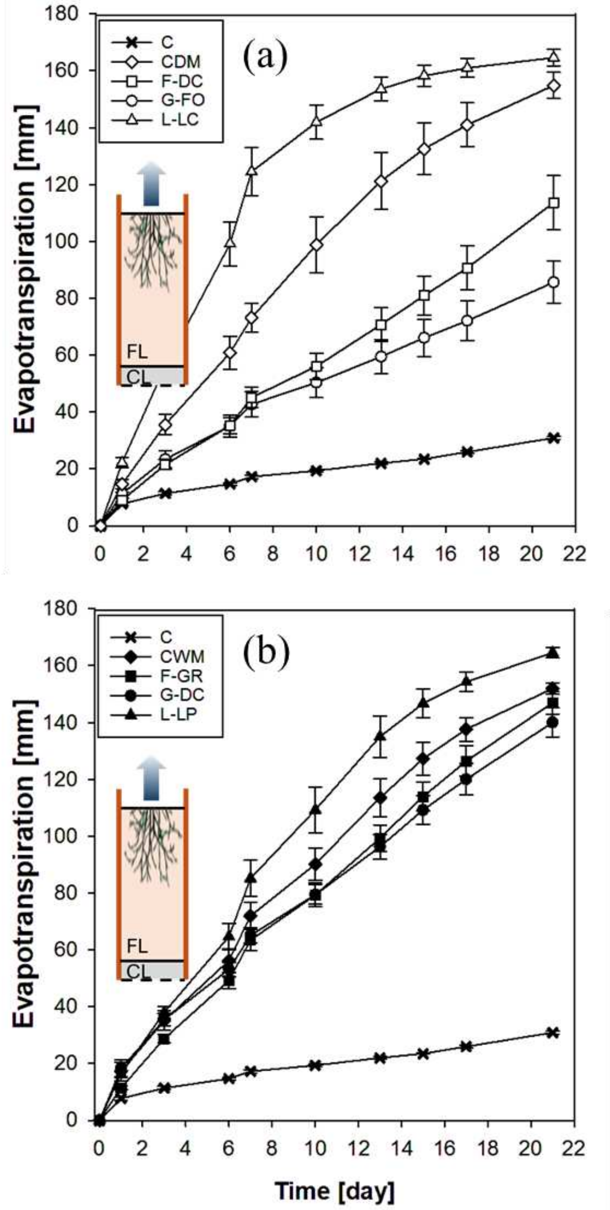

Figure 6 Comparison of water loss (increase in storage capacity) between conventional ('C') and nature-enhanced CBS (test series 3): (a) Dry meadow species; (b) Wet meadow species.

weeks) during ambient summer conditions in Scotland. In warmer and less humid conditions, this full reset may happen faster; In wetter, winter conditions, reset may be slower. Further research would be necessary in a different location or at a different time of year to quantify this, or further testing within an environmentally controlled glasshouse. Nevertheless, these initial results are promising. The conventional CBS ('C') performed significantly worse than the nature-enhanced CBS models, losing less total water more slowly by the end of the testing period. This suggests that such a system may have limited storage capacity against extreme events in wet

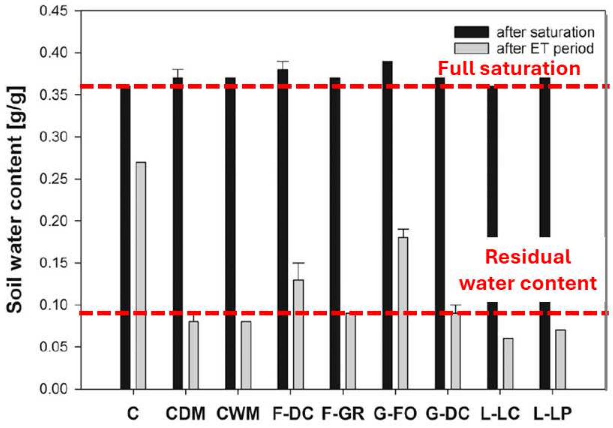

Figure 7 Soil water content in column at the start and end of the evaporation/evapotranspiration period.

antecedent conditions, increasing run-off and flood risk.

3.4 Infiltration (dry antecedent conditions)

Figure 8 shows the infiltration rate of surface water for the FL groundwater condition at the end of the evaporation/evapotranspiration period. The bars indicate mean values, and the whiskers indicate one standard error of the mean. This represents the infiltration performance of the CBS designs to a subsequent rainfall event in summer conditions. In all vegetated cases except G-FO, infiltration is increased compared to the conventional CBS ('C'). Infiltration rates are much larger than in the previous similar test phase (wet antecedent conditions; Section 3.2 and Figure 5. Unlike in Section 3.2, in the dry antecedent conditions tested in this phase, the dry meadow community (CDM) outperforms the wet community (CWM) by approximately 100%, i.e. there is a stronger species effect. Further research could explore a wider range of species under a similar test protocol to explore this further and optimise design of a nature-enhanced CBS.

3.5 Physical changes in water storage capacity

Figure 9 shows soil water retention curves for the conventional and community (CDM/CWM) nature-enhanced CBS models. For clarity, the curve shown in each case is based on a least-squares fit of the Van Genuchten equation (Equation 1) to datapoints for the five replicate cores sampled from each CBS model after testing:

$$w = w_r + \frac{w_s - w_r}{(1+|\alpha s|^n)^m} \quad (1)$$

where w (-) is the water content, w_r (-) is the residual water content at 1.5 MPa, w_s (-) is the saturated water content, s (kPa) is the soil matric suction and α, n, m are fitting parameters (with $m = 1 - (1/n)$).

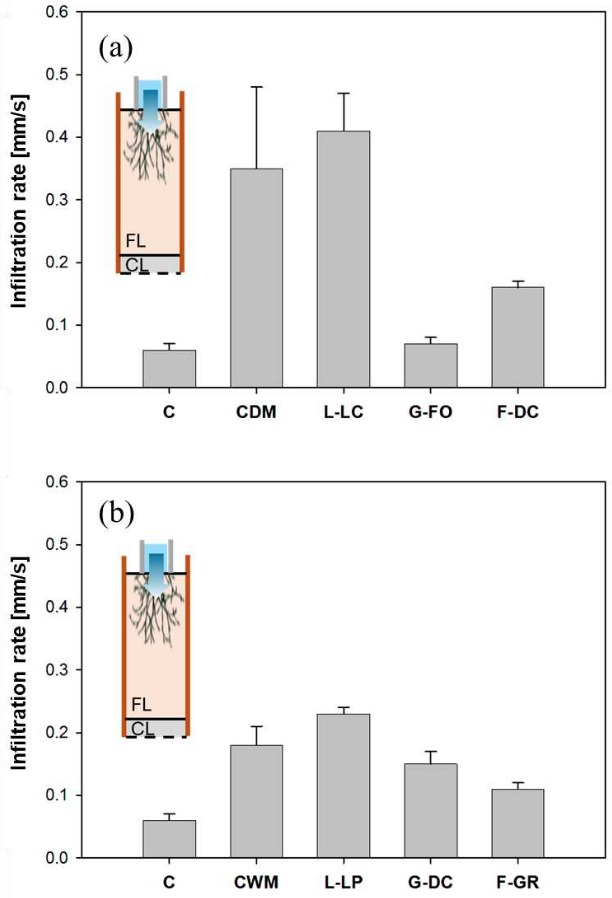

Figure 8. Comparison of surficial infiltration rate between conventional ('C') and nature-enhanced CBS following evaporation/evapotranspiration (test series 4): (a) Dry meadow species; (b) Wet meadow species.

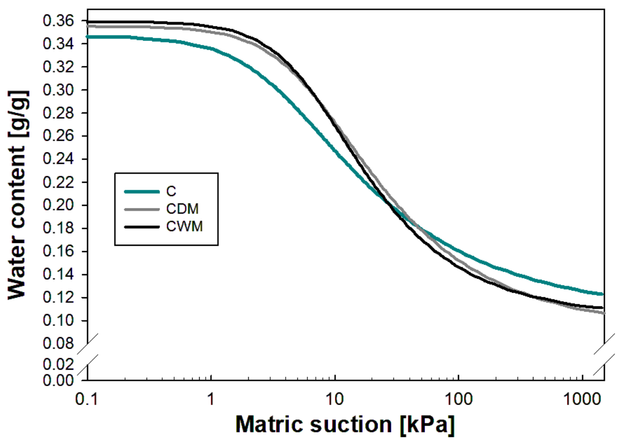

Figure 9 Soil water retention curves measured post-test on sampled cores for conventional ('C') and nature-enhanced CBS (community planting shown only; test series 5).

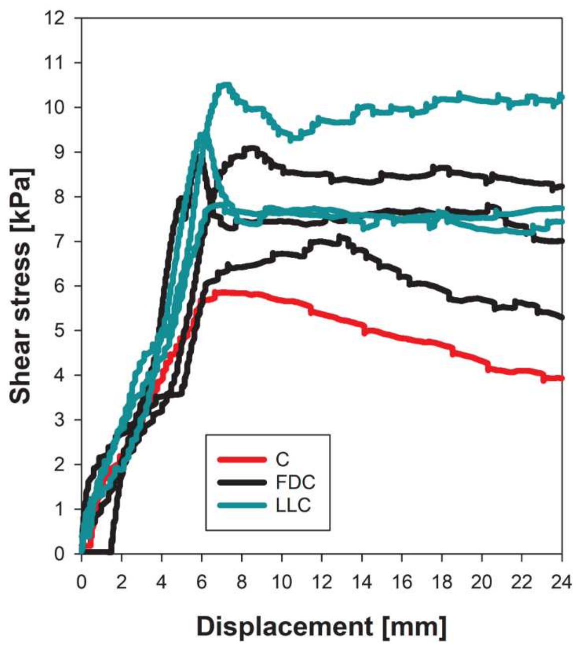

Figure 10. Shear strength of FL soil in conventional (C) and nature-enhanced CBS veneers (test series 6).

Of principal interest for the design of a CBS is that the maximum water storage in fully saturated conditions (i.e. w_s) is increased due to the presence of the vegetation. This is important as the most critical design events are likely to be those that occur in wet antecedent conditions (winter), where the available storage for new rainfall is smaller. Although the increase is relatively small (~5% increase), it will still help to postpone the onset of runoff and reduce run-off volumes. This acts in combination with other benefits shown in the preceding sections (e.g. starting at a lower water content due to evapotranspiration) to have a compound effect.

3.6 FL shear strength enhancement

Figure 10 shows shear stress – displacement curves for the FL soil at 170 mm depth, with and without vegetation. Both types of vegetation tested increased the shear strength of the FL at the test depth by a significant proportion, between 20-75% across the three replicates of each species and on average, by approximately 30%. This represents a direct increase to the resistance of the FL which was demonstrated by Scarfone et al. (2023) to be the critical mechanism in a CBS-protected slope, where deep slips in the underlying slope are mitigated through maintained suction thanks to the CBS.

4 CONCLUSIONS

This paper has presented a programme of model testing on 1:1 scale columns from a capillary barrier system (CBS) to assess the potential benefits of adding surface vegetation, creating a nature-enhanced CBS. It was shown that vegetation increases the rate of surface water infiltration in both wet and dry antecedent groundwater conditions and increases the overall water storage capacity of the soil. This can be used to minimise surface water run-off and consequent flooding in cuttings. Furthermore, by enabling evapotranspiration via roots acting as hydraulic sinks, rather than just evaporation, vegetation can rapidly remove water from throughout the fine (storage) layer of the barrier after intense rainfall, increasing the resilience of the CBS to periods where multiple heavy rainfall events occur in a short period of time. Planting communities of species, rather than monocultures, was shown to provide comparable or better performance while providing other benefits (e.g. biodiversity, disease resilience, soil health). Finally, the roots of the vegetation provide mechanical strengthening of the soil in the fine layer, where the critical slip surface is typically located in a CBS, increasing resistance to shallow translational sliding (in addition to the suppression of deep rotational slips from the suction maintained by the barrier). The results are a useful first step towards practical nature-enhanced design of capillary barriers and the benefits this can bring to infrastructure.

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REFERENCES

Network Rail (2018). *Earthworks Technical Strategy*, Network Rail Limited.

Petalas, A. L., Tsiampousi, A., Zdravkovic, L. and Potts, D. M. (2022). Numerical investigation of the performance of engineered barriers in controlling stormwater runoff. *Geomechanics for Energy and the Environment*, 32: 100401. https://doi.org/10.1016/j.gete.2022.100401

Postill, H., Helm, P. R., Dixon, N., Glendinning, S., Smethurst, J. A., Rouainia, M., Briggs, K. M., El-Hamalawi, A. and Blake, A. P. (2021a). Forecasting the long-term deterioration of a cut slope in high-plasticity clay using a numerical model. *Engineering Geology*, 280: 105912. https://doi.org/10.1016/j.enggeo.2020.105912

Postill, H., Helm, P. R., Dixon, N., El-Hamalawi, A., Glendinning, S. and Take, W. A. (2021b). Strength parameter selection framework for evaluating the design life of clay cut slopes. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering*, 176(3): 254-273. https://doi.org/10.1680/jgeen.21.00125

Rouainia, M., Helm, P. R., Davies, O. and Glendinning, S. (2020). Deterioration of an infrastructure cutting subjected to climate change. *Acta Geotechnica*, 15: 2997-3016. https://doi.org/10.1007/s11440-020-00965-1

Scarfone, R., Wheeler, S. J. and Smith, C. C. (2023) Numerical modelling of the application of capillary barrier systems for prevention of rainfall- induced slope instability. *Acta Geotechnica*, 18(1), pp. 355-378. https://doi.org/10.1007/s11440-022-01582-w