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The impact of vegetation on the stability of loose fill slopes

T.C. Wistow[1], S.F. Slaughter[1], T.A. Elmrom[1], T.A.V. Gaspar[2], P.A. Crous[3]

[1]*School of Mechanical, Aerospace and Civil Engineering, University of Sheffield, UK*
[2]*Department of Civil & Environmental Engineering, Imperial College London, UK*
[3]*Department of Civil Engineering, University of Pretoria, South Africa*

ABSTRACT: This study investigates the stabilising effect of vegetation on loose fill slopes using centrifuge and numerical modelling by comparing two models prepared to similar initial conditions: one unvegetated, and one with vegetation at the toe. The vegetated slope exhibited soil suctions of 10–40 kPa between the toe and mid-section, compared with near-zero pore pressures in the unvegetated slope, indicating an increase in effective stress due to transpiration. When subjected to a rising water table, vegetation reduced the rate of pore pressure rise, reflecting lower hydraulic conductivity due to increased suctions. Numerical analyses demonstrated that introducing minimal vegetation at the toe increased the factor of safety (FoS) by over 7%. The vegetation allowed for the height of the upstream side of the phreatic surface to be increased by an additional 1.4 m before an FoS similar to that of the unvegetated case was reached. These results highlight that even localised vegetation at a slope's toe can substantially improve slope stability, offering a cost-effective and environmentally friendly alternative to conventional post-construction interventions.

Keywords: centrifuge modelling; finite element analysis; vegetation; nature-based solutions

1 INTRODUCTION

Tailings storage facilities (TSFs) are used worldwide to store waste produced during the mining of minerals. A 2010 study showed that over the past 100 years an estimated 1.2% of TSFs experienced instability, double than that of water storage dams (Azam & Liu, 2010).

The collapse of TSFs can be incredibly destructive, and recent failures such as the 2019 collapse of the Brumadinho TSF have led to increased focus and scrutiny on the actions of the global mining industry and the safety of tailings dams (Lamb, 2019). The collapse of the Feijão dam killed over 270 people and released 12 million m^3 of tailings into the local environment, including the region's main water course which led to increased levels of various toxic metals in the river (Parente et al., 2020).

Various methods can be used to stabilise tailings dams after construction if concerns about their stability arise. One of the most common and effective approaches is buttressing, which involves placing rockfill at the toe of a slope. However, this technique requires vast quantities of rock to be quarried, transported to site and placed, which has significant environmental and economic consequences. The escalating climate emergency underscores the need to minimise the environmental impact of construction. In this context, research into alternative methods of tailings dam stabilisation offers potential to reduce the mining industry's environmental footprint (Bolton, 2021).

Vegetation can be an effective method of slope stabilisation (Löbmann et al., 2020), but its use in tailings dam stabilisation is less well understood. Use of vegetation to stabilise existing tailings dams may provide a cheaper and less environmentally destructive alternative to traditional buttressing methods as it requires no quarried material and involves much lower volumes of transported material. To investigate this potential, the present study combines centrifuge modelling with finite element analyses to assess the effectiveness of a vegetation-based stabilisation strategy.

2 METHODOLOGY

2.1 Soil Properties

Due to the limited availability of tailings in the UK, a fine-grained silica sand (iCAIR sand) was used as an alternative. It was selected for its similar shear strength and hydraulic characteristics to gold tailings used in previous studies (Crous, 2022). Mechanical properties of the iCAIR sand and gold tailings were obtained from direct shear and consolidated undrained triaxial tests, respectively. Saturated permeabilities were determined using falling head tests for the iCAIR sand and Hazen's formula for the gold tailings. The particle size distribution of iCAIR sand and a comparison of basic soil properties are shown in Figure 1 and Table 1, respectively.

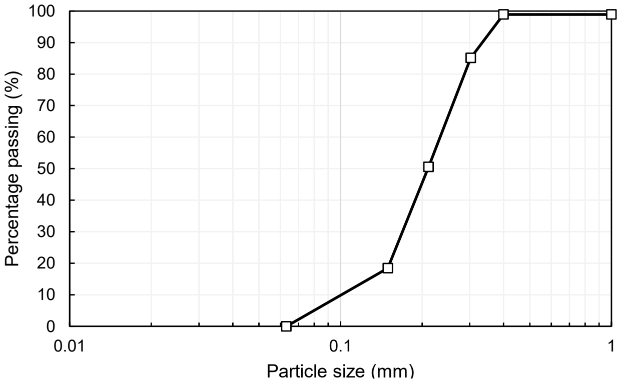


Figure 1. Particle size distribution curve of iCAIR sand

Table 1. Properties of iCAIR sand and typical gold tailings

Property	**iCAIR Sand**	**Gold Tailings**
Specific Gravity, $\mathbf{G_s}$ (-)	2.68	2.65
Critical Angle of Shearing Resistance, $\boldsymbol{\phi'}$ (°)	33	33
Effective Cohesion, $\boldsymbol{c'}$ (kPa)	1	0
Saturated Permeability, $\boldsymbol{k_s}$ (m/s)	1.5 x 10^{-6}	1.4 x 10^{-6}

Values for gold tailings from Crous (2022)

2.2 Centrifuge set up and model preparation

The physical modelling was conducted in the 50 g-ton geotechnical beam centrifuge at the University of Sheffield. The centrifuge package for each test consisted of a strongbox, a groundwater control system, the model slopes, and monitoring equipment including tensiometers and cameras. The model layout and tensiometer locations are shown in Figure 2. The models were prepared by moist tamping a profile in 6 layers, which was then cut to a slope at an angle of 35°. All tests were conducted at $35g$.

Water levels in the slopes were controlled by an upstream inlet, which filled the water well after reaching the targeted acceleration. The well was separated from the sand filter by a perforated sheet. The sand filter and upstream angles, introduced following the work of Crous (2022), prevented preferential flow paths forming around the sides of the container, reducing the risk of piping. In-house tensiometers, (based on a design by Jacobsz (2018)) were used to measure both positive and negative pore water pressures.

For the vegetated test, millet seeds, selected for their rapid growth, tolerance to poor soils, and low cost (Kheya et al., 2013), were sown at the slope toe. Seeds were planted about 25 mm deep and 40 mm upstream of the toe to minimise disturbance during planting. Once planted, the toe was lightly watered, and the strongbox sealed for 10 days to allow growth, unlike other models tested immediately after preparation. Notably, subsurface portions of the roots reached lengths of between 110-150 mm (Figure 3).

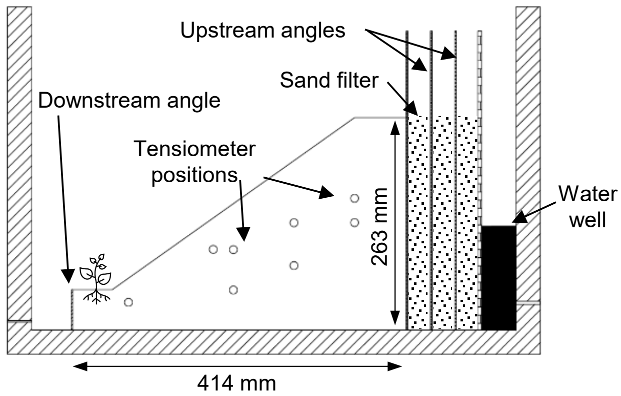


Figure 2. Model container layout and PPT locations

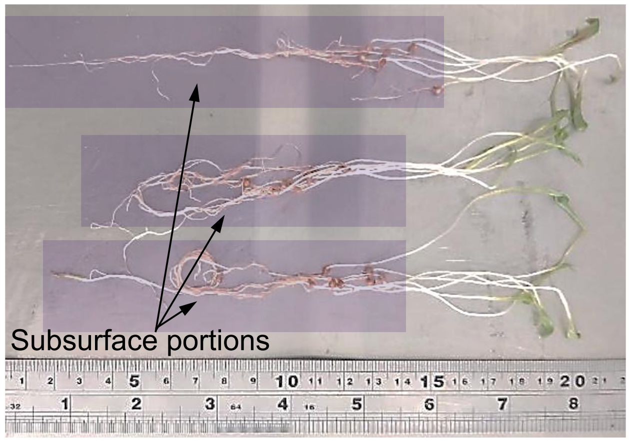


Figure 3. Root geometry following excavation from Test 4

2.3 Testing Procedure

The experimental programme comprised four centrifuge tests. The first three were *unvegetated* and designed to examine how the initial state affected slope failure mechanisms by varying the initial void ratio (e_0=0.9, 1.1, 1.2). These tests highlighted contrasting behaviours, ranging from progressive (dense slope) to brittle (loose slope) failures for Tests 1 and 2 respectively. Based on the brittle response observed for Test 2 ($e_0 = 1.1$) a final test (Test 4) was prepared at the same initial void ratio but with vegetation, to assess whether root reinforcement could mitigate such behaviour. The discussion in this paper focuses on Tests 2 and 4, while further details of the initial series are provided by Slaughter et al. (2025).

The testing procedure for all four centrifuge tests followed a standardised approach. After reaching the targeted centrifugal acceleration of $35g$, the phreatic surface was established by raising the water level in the upstream water well, allowing seepage through the model. This process continued until failure was observed, after which the water inlet valve was closed. Water was then allowed to drain from a downstream outlet, resulting in drawdown of the water table (WT) before the centrifuge was stopped. Throughout testing, pore pressure measurements were logged at a frequency of 1 Hz, with photographs taken every 0.5 seconds.

2.4 Numerical Modelling Procedure

Finite element (FE) back-analyses of Tests 2 and 4 were conducted using PLAXIS 2D to investigate the stability and failure mechanisms observed in the centrifuge tests. The analyses used the prototype-scale dimensions and a fine two-dimensional mesh with triangular 15-node elements with stress and deformation degrees of freedom. Left and right boundaries were roller connections, with the bottom boundary fixed. The slope face and toe were modelled as seepage boundaries, with bottom and downstream boundaries set as impervious. For the back analysis of Test 4, a region near the toe was assigned an increased strength to represent the effects of vegetation. An illustration of the FE model is provided in Figure 4.

A Mohr-Coulomb failure criterion was implemented with a friction angle (ϕ') of 33° and an effective cohesion (c') of 0.25 kPa, to ensure numerical stability and convergence. Vertical and horizontal saturated hydraulic conductivities were set to 0.130 and 0.648 m/day respectively to represent anisotropy induced when the slope was compacted (in layers). A soil water retention curve was implemented using the Van Genuchten (1980) equation, using the parameters in Figure 4. In the back-analysis of Test 4, apparent root cohesion (c_r) was assigned following work by Chok et al. (2015), adopting lower-bound values of 5 kPa and 2 kPa for the top and bottom layers respectively.

Analyses followed a staged approach similar to that of Ng et al. (2023). Initial conditions were established with gravity loading. A hydraulic head of 3.6 m and 5.0 m for Tests 2 and 4 respectively, was applied at the upstream boundary in a fully coupled flow-deformation analysis, gradually raising the WT until it resembled that observed in the centrifuge tests. Once the WT had been established, the strength reduction method was used to determine the factors of safety against slope failure.

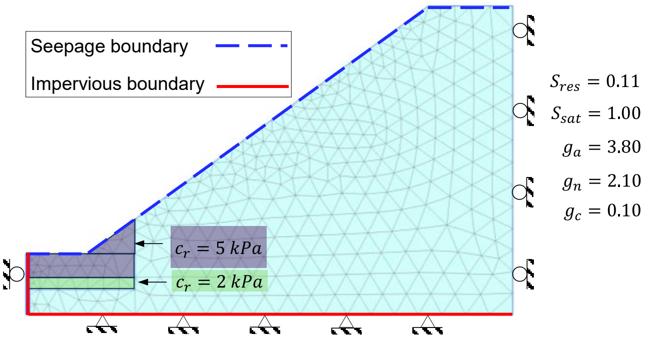


Figure 4. Numerical model layout

3 RESULTS

3.1 Centrifuge test results

Although the models in Tests 2 and 4 were prepared to similar initial states, the responses of each slope to the imposed rising WT were markedly different. In Test 2, a brittle/abrupt failure occurred as soon as the phreatic surface reached the toe of the slope. In contrast, no such behaviour was observed in Test 4, where vegetation was included, even after the WT had risen to considerably higher levels (Figure 5). In Test 4, only minor erosion/very shallow slip surfaces were observed (indicated by the more 'jagged' face). To investigate the improved stability more closely, Figure 6 presents pore pressure measurements for the two tests.

From Figure 6 it can be seen that at the start of testing (prior to and during centrifuge acceleration), pore water pressures measured by tensiometers were close to zero throughout the unvegetated model. In contrast, the vegetated slope exhibited soil suctions of 10-40 kPa between the toe and mid-section of the slope, decreasing to zero towards the upstream face (Tensiometer 3). While some drying of the slope (evaporation) may have occurred during the 10-day growth period, it can be stated that establishment of this pore pressure profile was largely governed by transpiration due to

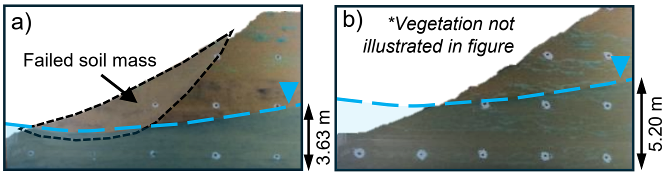


Figure 5. Centrifuge models at end of test for a) unvegetated and b) vegetated slopes

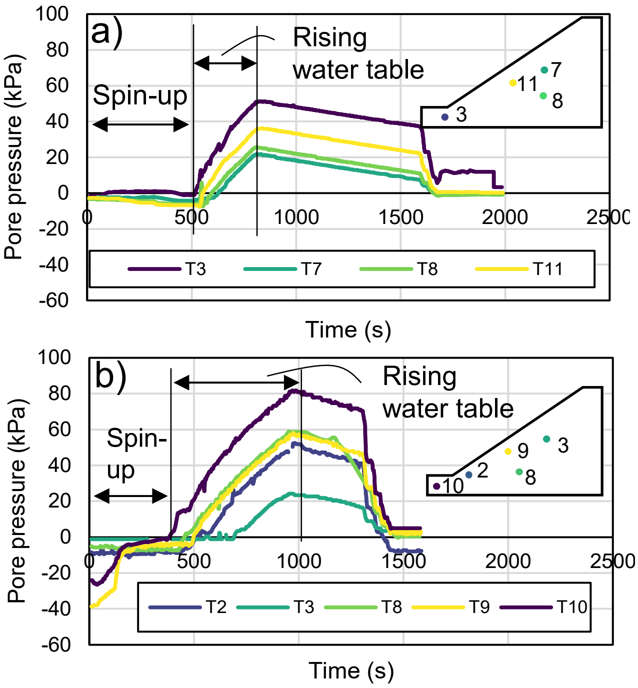
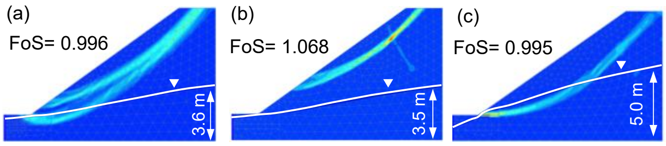


Figure 6. Pore pressure measurements for a) unvegetated and b) vegetated slopes (time in model scale)

the vegetation, given that the maximum root length extended to approximately one third of the model width. Notably, the unvegetated slope illustrated a slightly more rapid increase in pore pressure (~9 kPa/min) in comparison to the vegetated slope (~7 kPa/min) as the WT rose. Such behaviour can be attributed to the reduction in hydraulic conductivity brought about by increased soil suctions in the vegetated slope.

3.2 Numerical modelling results

The factors of safety (FoS) presented in Figure 7 illustrate: a) the unvegetated case, b) the vegetated slope with the WT at the position that induced failure in the benchmark case, and c) the vegetated slope with the WT at a position which produced a FoS approximately equal to that observed in the benchmark case.



Total deviatoric strain, γ_s (scaled up 5 times)

Figure 7. Numerical results for a) benchmark case, b) vegetated case for low WT, c) vegetated case for high WT

From Figure 7 it can be seen that inclusion of vegetation in a relatively confined region around the toe increased the FoS by over 7%. Although arguably not a large increase, this increased stability could prevent slope failure if subjected to certain instability triggers. Furthermore, to achieve approximately the same FoS of the benchmark case, the phreatic surface had to be raised by an additional 1.4 m. It should be noted that due to the simplified failure criterion and constitutive relationships used, the minor erosion/very shallow slip surfaces would not have been captured. Nevertheless, the simplified approach illustrates the significant improvements in stability achievable through the incorporation of a relatively modest amount of vegetation at the toe of a slope.

4 CONCLUSIONS

Given the current climate crisis, the need to develop sustainable construction practices is paramount. In this study, the effect of vegetation at the toe of loose fill slopes is investigated using centrifuge and numerical modelling. The inclusion of vegetation allowed suctions of 10-40 kPa to develop between the slope's toe and mid-section, in contrast to near-zero pore pressures for an unvegetated slope. The presence of vegetation also slowed the rate of pore pressure increase (~7 kPa/min compared with ~9 kPa/min in the unvegetated slope) as the phreatic surface was raised, reflecting a reduction in hydraulic conductivity. Numerical analyses further indicated that incorporating vegetation around the toe increased the factor of safety by over 7%, and allowed the WT to be raised by an additional 1.4 m before an FoS equivalent to the unvegetated case was achieved.

These results highlight that even localised vegetation can substantially improve slope stability, providing a cost-effective and environmentally friendly alternative to conventional interventions (e.g. buttressing).

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