University of Dundee

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Comparison of new *in situ* root-reinforcement measuring devices to existing techniques

Comparaison de nouveaux appareils de mesure *in situ* pour sols renforcés par des racines avec des techniques existantes

G.J. Meijer[1,2,3*], A.G. Bengough[1,2] , J.A. Knappett[1], K.W. Loades[2] and B.C. Nicoll[3]

[1] *University of Dundee, Division of Civil Engineering, Dundee, UK*
[2] *James Hutton Institute, Dundee, UK*
[3] *Forest Research, Roslin, UK*
[*] *Corresponding Author*

ABSTRACT Mechanical root-reinforcement is difficult to quantify. Existing in-situ methods are cumbersome, while modelling requires parameters which are difficult to acquire. In this paper, two new in-situ measurement devices are introduced (‘cork screw’ and ‘pin vane’) and their performance is compared to field vane and laboratory direct shear strength measurements in fallow and rooted soil. Both new methods show a close correlation with field vane readings in fallow soil. Tests in reinforced soil show that both new methods can be installed without significant root disturbance. The simplicity of both new methods allows for practical in-situ use and both can be used to study soil stress-strain behaviour, thus addressing some major limitations in existing methodologies for characterising rooted soil.

RÉSUMÉ Le renforcement mécanique des sols par les racines est difficile à quantifier. Les méthodes *in situ* existantes sont encombrantes tandis que la modélisation nécessite des paramètres qui sont difficile à acquérir. Dans cet article, deux nouveaux appareils de mesure *in situ* sont introduits («tire-bouchon» et «scissomètre a broches») et leurs performances sont comparées à des essais de cisaillement sur sols en jachère, aussi bien sur le terrain, par scissomètre, qu’en laboratoire, par mesure directe de la résistance au cisaillement. Les deux nouvelles méthodes montrent une forte corrélation avec les mesures de scissomètre classique. Certains essais en sol renforcé montrent que les deux nouvelles méthodes peuvent être installées sans perturbation significative de la racine. La simplicité de ces deux nouvelles méthodes permet une utilisation pratique in situ et autorise aussi l’étude des lois de comportement contrainte-déformation, elle permettent donc de franchir certaines des limitations des méthodes existantes.

1 INTRODUCTION

Soil reinforcement by roots can be a sustainable and cost-effective measure to stabilize slopes (Coppin & Richards 1990; Gray & Sotir 1996; Norris et al. 2008; Stokes et al. 2009). Reinforcement can be mechanical (fibre reinforcement, soil nailing) or hydrological (enhancing suctions, rainfall interception). However, because instabilities are often correlated with heavy or prolonged rainfall, resulting in (near) saturated conditions, mechanical reinforcement will often be more important (Pollen-Bankhead & Simon 2010). Thin roots, often classified as roots with diameters smaller than 2 mm (e.g. Stokes et al. 2009), are thought to be responsible for most of the mechanical reinforcement because of their large quantity and higher tensile strength compared with thicker roots (Coppin & Richards 1990).

Root-soil interactions are highly complicated. Not only is the interaction dependent on soil conditions (soil strength, elasticity, hydrological conditions such as water content and suctions), but also on root traits. Root traits can be mechanical (e.g. root strength, stiffness, root-soil interface friction), geometrical (length, diameter, orientation) or topological (root architecture, branching) (Mao et al. 2014). These parameters vary not only spatially, but also temporally because of root growth, decay or tissue development. Roots might reinforce soil by acting in tension, bending or even compression depending on these parameters and interactions. During soil shearing roots can fail in multiple ways, including breakage or slippage.

Two approaches are commonly adopted to quantify root-reinforcement. In the first, mechanical models are used to link soil and root parameters to reinforcement, often expressed as an increase in soil cohesion c_r, dubbed 'root cohesion' (e.g. Wu at al. 1979; Schwarz et al. 2010) with more complicated approaches involving the use of finite or discrete elements for modelling individual root-soil interactions (e.g. Dupuy et al. 2005; Mao et al. 2014). All models, however, heavily rely on input parameters which are difficult and time-consuming to quantify, such as root diameters, orientations or mechanical characteristics.

A second approach relies on in-situ measurements of reinforced soil strength, typically through the use of a large direct shear apparatus (DSA) in the field. These can be of varying design, e.g. Wu et al. 1979; Ekanayake et al. 1997. However, wide variations in size (generally with a shear plane between 30×30 and 60×60 cm), shear depth, shear rate, test control (force- or displacement controlled), hydrological condition (saturated or not) and overburden pressure are reported and no test standard exists. Field shear testing is time-consuming and typically requires heavy equipment, making it less suitable for use in difficult terrain.

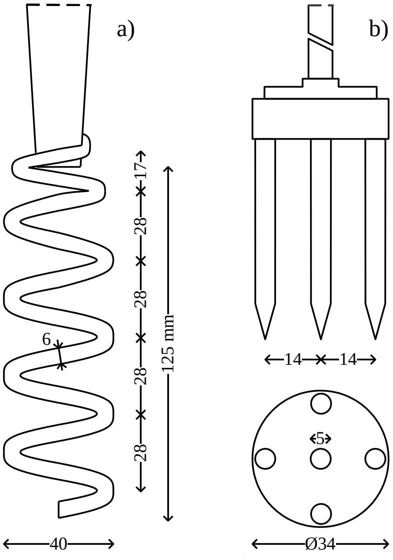

Figure 1. Schematization of (a) 3-D helical cork screw and (b) pin vane devices. All dimensions are in mm.

A major issue in quantifying root reinforced soil shear stress is spatial variability (Mao et al. 2014 for example). Often the value of c_r is locally determined and applied over large regions of the slope. However, a landslide will tend to localize in weaker zones necessitating identification of local weak zones.

There is a need for a quick, simple and robust method to measure the shear strength of vegetated soil. Thus, slope stability can be estimated rapidly. This paper introduces two potential new techniques for quantification of soil reinforcement. Results from each approach are compared to shear strength measurements (field vane and laboratory direct shear) in fallow and rooted field soil to study the measurement mechanism in more detail.

2 METHODS

2.1 Measurement devices

Soil disturbance during installation is a major problem when measuring the strength of rooted soil. With many conventional methods, roots will be displaced and cut, with the soil being heavily disturbed during insertion of a device. This may result in underestimation of rooted soil strength.

To avoid this, a first measuring technique is developed based on a cork screw. During rotational installation, the small tip only disturbs a small volume of soil with most roots avoided or pushed aside rather than cut. Once installed to the desired depth the screw is extracted vertically. During extraction the root-reinforced soil resistance is mobilized around the circumference of the cylinder of soil trapped within the helix. The reinforced shear strength can be estimated by:

$$\tau_{cs} = F / (h_{cyl} \cdot \pi \cdot d_{cyl}) \qquad (1)$$

where τ_{cs} is the root-reinforced shear resistance [kPa], F the measured extraction force [kN] and d_{cyl} and h_{cyl} the diameter and height of the displaced soil cylinder [m] respectively. Reinforcement acting on the bottom interface of the cylinder is neglected because of typical low or non-existing soil tensile strengths.

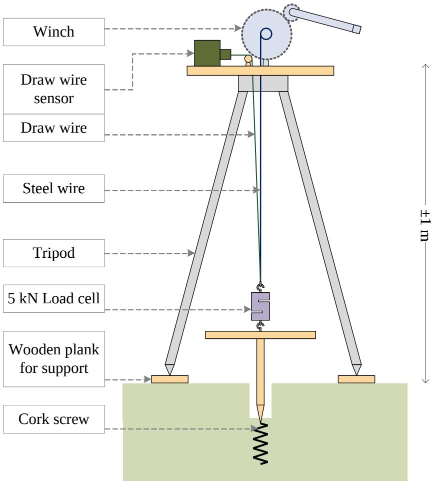

Figure 2. Schematic of cork screw test arrangement.

A second method is derived from the field shear vane test. Vane blades are replaced by vertical prongs (pins), of diameter d_{pr}, to again minimize root cutting and corresponding soil disturbance during installation. The prongs will act as a pile wall when loaded laterally in rotating the vane because of arching (Ito and Matsui 1975). The area ratio (ratio of prong volume over sheared soil volume) is equal to 10.8%. This is lower than the maximum value of 12% prescribed by the British Standard (BS 1377-9:1990) for cruciform vane blades. Therefore, any soil disturbance introduced during installation should be within acceptable limits. Similar to cork screw tests, the soil is excavated just above the desired test depth preventing root accumulation and soil compaction during installation. The pin vane shear strength τ_{pv} [kPa] is evaluated as:

$$\tau_{pv} = 12 \cdot \pi \cdot T / (6 \cdot h_{cyl} \cdot d_{cyl}^2 + d_{cyl}^3) \qquad (2)$$

where T [kNm] is the measured peak torque and h_{cyl} and d_{cyl} the height and diameter of the soil cylinder [m] respectively.

Dimensions of both devices are presented in Figure 1.

2.2 Tests in fallow soil

The field site used was a agricultural field in rest near the James Hutton Institute (56°27’26”N, 3°3’59”W). No vegetation was present on or near the field. The soil was classified as low plasticity sandy clayey silt (57% sand, 32% silt, 11% clay). Four days prior to testing the site was irrigated.

Soil density and gravimetric water content were measured immediately after testing using 100 ml cores. Below 100 mm depth, the average dry bulk density (ρ_w) was 1.48 Mgm^{-3} and the average gravimetric water content (w) 20.9%, corresponding to 75% saturation. Near the surface, these values were lower (ρ_w = 1.23 to 1.48 Mg m^{-3}, w = 19.1 to 20.9%).

Field soil suction was determined using two field tensiometers (model SWT4, Delta-T) at 100, 200 and 300 mm depths. Below 100 mm, suction pressure (s) ranged from 6.1 to 7.4 kPa on the first and 7.3 to 7.7 kPa on the second day of testing. At 100 mm, suctions were higher (7.8 to 9.9 and 9.3 to 11.4 kPa respectively).

2.3 Test protocol and equipment

Tests were performed over two days on the central 2×2 m area of the irrigated plot, with two tests locations in each 1×1 m subplot to account for spatial and temporal variability.

The cork screw device was manually screwed into the soil. Once the desired depth was reached, a wooden tripod (model GST101, Leica Geosystems, selected for its rigidity, Nindl & Wiebking (2010)), was placed over the top to facilitate extraction. A manual winch was aligned vertically above the corkscrew on top of the tripod. The target extraction rate was 100 mm min^{-1}, in line with the displacement rates of landslides (Davies et al. 2010). A 3 mm diameter steel wire connected the winch to the cork screw via a 5 kN load cell (model RLT0500kg, RDP Group) with a linearity of ±0.03% of the full scale output. Displacement was measured with a draw wire sensor (model WDS-1500-P60-CR-P, Micro-Epsilon, linearity ±1.5 mm). Both force and displacement data was logged at a frequency of 100 Hz using a data logger (model CR3000 Micrologger, Campbell Scientific). A schematic of the test setup is presented in Figure 2.

Pin vane shear strength was measured using a digital torque wrench (Clarke PRO235 3-30 Nm) while an Edeco Pilcon hand vane was used to measure residual shear strength. Residual strengths were defined as the maximum measured strength between 360 and 720° rotation.

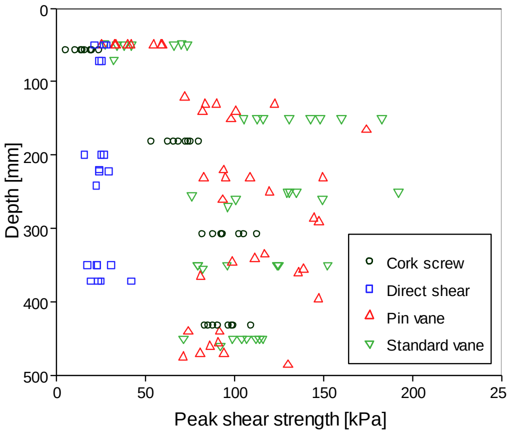

Figure 3. Peak strength measurements for all tests in fallow soil. For the cork screw, pin vane and standard vane tests, depth is defined as the average depth of the mobilized soil plug.

For comparison purposes, soil shear strength was also measured using a standard 34 mm diameter 50 mm high cruciform vane blade, using the same equipment as used for pin vane measurements. Each field shear test was replicated 8 times for each depth ranging from 0-500 mm.

100 mm diameter soil samples were collected for laboratory based direct shear tests. 130 mm high steel cores were driven into the soil using a hammer. Less destructive techniques could not easily be adopted because of high soil strength. Samples were subsequently dug up and stored for a maximum of 7 days at 4°C in sealed bags to prevent evaporation. Samples were extruded before testing using a hydraulic press and sheared in a custom laboratory DSA with the same diameter. The bottom (moving) part and top (fixed) part were 80 and 50 mm high respectively. Such a large shear box was adopted because similar or even larger devices are typically used to measure root-reinforcement as reported in the literature. All samples were subjected to similar overburden pressures as field samples by stacking small weights on top of a top cap. Force and displacement was measured using a 1 kN load cell (RLT0100kg, RDP Group) and a PD20 displacement sensor (Pioden Controls). Samples were sheared to 25 mm at a displacement rate of 2 mm min^{-1}, the fastest rate that could be adopted. Residual strengths were calculated as the average strength over the 20-25 mm displacement interval.

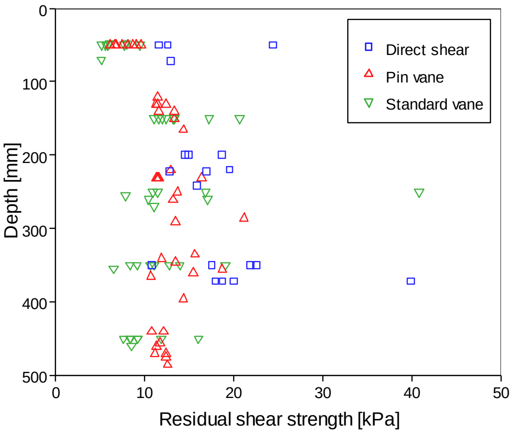

Figure 4. Residual shear strength results in fallow soil.

2.4 *Tests in rooted soil*

Cork screw and vane tests were also performed in a nearby rooted plot overgrown with grass, at 1 m distance from a row of mature Scots pines. Because of different soil densities and moisture conditions, direct comparison between rooted and non-rooted soil was not attempted.

The top 50 mm was heavily occupied with roots (~5% volume fraction; roots with diameters < 0.4 mm contributed half of the total root length), with a dry density (ρ_d ~ 0.75 Mgm^{-3}). Below this layer, densities ranged from 1.0 to 1.5 Mgm^{-3} with lower root quantities. Saturation levels ranged between 19 and 48% with no clear depth trend.

3 RESULTS

Peak measured shear strength for fallow soil are presented in Figure 3. Below ~250 mm depth, the pin vane, standard vane and cork screw methods all produced comparable results. Near the soil surface, cork screw results were lower in comparison. Peak strengths measured using the DSA were much lower than other measurements.

Residual pin and standard vane strengths were similar to measured residual strengths in direct shear (Figure 4). There is no clear way to interpret residual strengths within cork screw tests, and these therefore are not described.

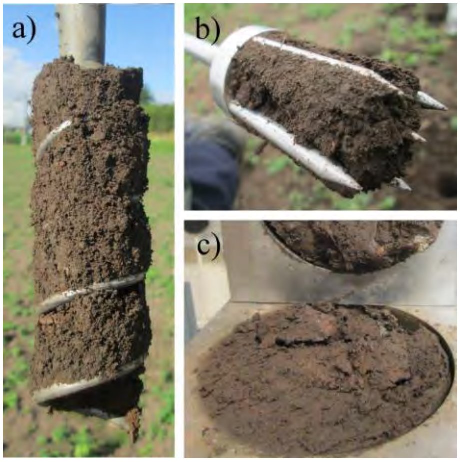

Figure 5. Shear surfaces after cork screw (a), pin vane (b) and laboratory direct shear test (c) in fallow soil.

Table 1. Comparison of pin and standard vane readings (mean ± standard error) for both peak and residual strength in rooted soil. *N* denotes number of tests and *p* the t-test result (i.e. chance that the means of the pin and standard vane data do *not* reflect a 'real' difference between the two groups of data).

	Depth [mm]	Pin vane [kPa]	Std. vane [kPa]	*N* [-]	*p* [-]
Peak	25	26.3 ± 1.3	18.4 ± 1.4	12	0.0005
	50	58.4 ± 5.0	63.1 ± 6.2	8	0.5603
	150	111.5 ± 6.3	112.9 ± 11.6	8	0.9205
Res.	25	5.4 ± 0.4	4.4 ± 0.2	12	0.0174
	50	7.5 ± 0.4	6.2 ± 0.4	8	0.0296
	150	9.5 ± 0.4	10.8 ± 0.6	8	0.1111

Typical failure mechanisms observed during tests in the fallow soil (Figure 5) suggest that the assumed cylindrical failure for both cork screw and pin vane tests (Equation 1 and 2) is valid.

Independent two-sample t-tests were performed to compare standard and pin vane results for both mean peak and residual strengths in rooted soil (Table 1). Only in the heavily fine rooted top soil mean peak strengths were significantly different. In this top layer, the pin vane failure mechanism was similar to fallow tests, in contrast to standard vane test where large voids were opening up behind the blades during shearing. During installation of the standard vane, roots holding the soil in the four vane quadrants together by tension are being cut, resulting in a different failure mechanism and lower measured strengths.

In the rooted soil, cork screw peak strengths were 27.3 ± 1.74 kPa at depth level 0 to 125 mm and 74.4 ± 3.4 kPa at 125 to 250 mm (mean ± SE, N = 8). Example cork screw extraction traces (Figure 6) show that root-reinforcement occur at higher displacements than peak strength displacement.

Both the pin vane and cork screw methods yielded soil cylinders containing exposed root ends (Figure 7). This suggests that both methods are suitable for use in root-reinforced soil because many roots will still be intact after installation.

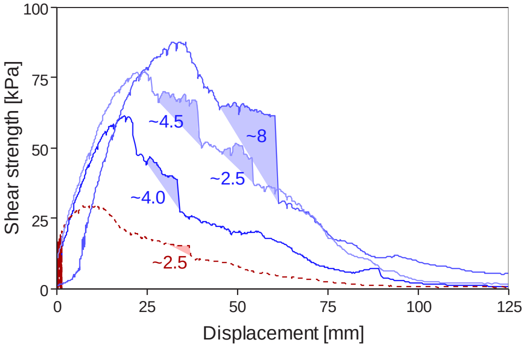

Figure 6. Example cork screw extraction traces in rooted soil at 0-125 mm depth (dashed line) and 125-250 mm (solid lines). Root reinforcement thought to be introduced by large diameter (>2 mm) roots which eventually broke is shaded and the corresponding diameter [mm], determined from field observations, given. Reinforcement gradually built up while displacing the root until breakage occurs, observable as a sudden drop in shear strength.

4 DISCUSSION

In fallow soil, measured direct shear peak shear strength was lower than vane and cork screw readings. This is likely to be caused by soil disturbance introduced during the core collection process. This hypothesis is supported by comparable residual strengths in direct shear and vane testing.

Soil heave was observed during cork screw tests in the surface layer in both soil types, providing an explanation for lower measured peak strengths near the surface compared with vane readings.

For both soils, the relatively large scatter in pin and standard vane peak shear strength could not be explained by spatial shear strength variation (comparing nearby pin vane and standard vane tests) or variations in soil bulk density and water content. Variations in shear strength are therefore likely to be caused by local variations in soil strength, especially through the presence of small (<20 mm diameter) stones. In some tests, scraping noises were heard during vane rotation and stones were observed in extracted soil plugs.

The cork screw results in rooted soil show that root-reinforcement is mobilized at higher displacements than soil peak strength. This explains the similarity between pin vane and standard vane peak strengths in all but the very surface layer of rooted soil. In the rooted surface layer, the standard vane severed the roots during installation, resulting in a similar failure mechanism during shearing as observed by Landva (1980) in peats, with large voids opening up behind the vane blades. This explains the lower measured strength compared to pin vane readings in this layer.

In the interpretation of cork screw and vane tests (Equation 1 and 2), the shear band thickness is assumed to be negligible as d_{cyl} is assumed to be equal to the diameter of the device. No large soil disturbance was observed around the cylinders indicating that this effect was likely to be small in the tested soil. However, this effect needs to be studied in more detail across a wider range of soils, and especially in rooted soils, as observed failure surfaces in peat expanded with increasing fibrousness (Landva, 1980).

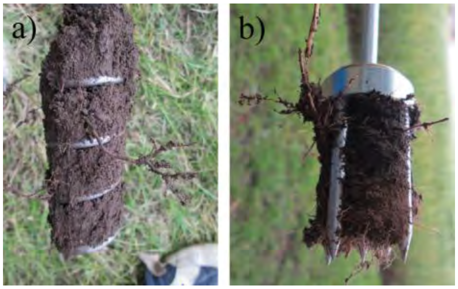

Figure 7. Typical extracted rooted soil in cork screw (a) and pin vane (b) tests.

5 CONCLUSION

Both cork screw and pin vane methods appear to be suitable for use in quantifying root-reinforcement of soil. Peak and residual strength readings were similar to standard vane readings in fallow soil. In addition, both devices yielded valuable insight into soil stress-strain behavior as force-displacement information and both peak and residual strengths were recorded. The two new approaches provide a quick, simple and easy to transport (e.g. by a single operator on foot) method for quantifying soil strength, making them suitable for use in remote areas.

6 ACKNOWLEDGEMENTS

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