On the dilatancy of root-permeated soils under partially saturated conditions

Authors:

1. Anil Yildiz, Dr .Sc.

Research associate, National Green Infrastructure Facility, Newcastle University, Newcastle upon Tyne, United Kingdom.

Research associate, School of Engineering, Newcastle University, Newcastle upon Tyne, United Kingdom.

Formerly: *Guest researcher, WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland.*

Formerly: *Postdoctoral researcher, Institute for Geotechnical Engineering, ETH Zurich, Zurich, Switzerland.*

Orcid: 0000-0002-2257-7025

2. Frank Graf, Dr. Sc. Nat.

Scientific staff member, WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland.

3. Sarah M. Springman, CBE, FEng, MA, MPhil, PhD, DSc (h.c.) mult., DPhil (h.c.), DEng (h.c.), FICE, FWES, MInstRE, SIA

Professor, Institute for Geotechnical Engineering, ETH Zurich, Zurich, Switzerland.

Corresponding author:

anil.yildiz@newcastle.ac.uk

National Green Infrastructure Facility

Urban Sciences Building, NE4 5TG, Newcastle upon Tyne, United Kingdom

Number of words: 2012

Number of figures and tables: 6

Keywords: Vegetation, partial saturation, laboratory tests

Abstract

Mechanical contribution of roots to the shear strength of saturated soils is not the only function of vegetation in favour of slope stability. Plants also cause an increase in the strength due to plant-induced suction, resulting from partial saturation. Although understanding, quantifying and modelling the shearing behaviour of soils is directly related to the volume change characteristics of soil, dilative behaviour of rooted soils has not been of much interest. Large-scale suction-monitored direct shear tests were performed on specimens planted with a mixture of species from different plant functional groups. Increase in matric suction, which was linked to root biomass and root:shoot ratio, resulted in higher maximum dilatancy angles. It was also found that maximum dilatancy is controlled by net normal stress, but not effective stress.

List of notations

dy/dx	Rate of dilation
σ'	Effective stress
$(\sigma - u_a)$	Net normal stress
$(u_a - u_w)$	Matric suction

1. Introduction

Volume change characteristics of soil, either under saturated or partially saturated conditions, are key components in understanding and modelling soil behaviour. Dilatancy in saturated soils has been investigated extensively for decades (Bolton, 1986). Validity of the stress–dilatancy theories have been demonstrated for unsaturated sands (Fern et al., 2016), and various attempts have been made in quantifying and modelling the dilatant behaviour of unsaturated soil (Hossain and Yin, 2010; Chiu and Ng, 2003).

Observations in the literature on the volume change behaviour of soils under partially saturated conditions can be summarised as:

- A higher tendency to dilate with an increase in suction under constant confining pressure, and a corresponding increase in peak shear stress (Cattoni et al., 2007; Ng and Zhou, 2005)
- A decrease in dilatancy angle with an increase in normal stress under constant suction (Schnellmann et al., 2013)

Removal of water via plant roots and interception of precipitation by the canopy cause partial saturation in the soil, resulting in plant-induced suction. Various biotic parameters, such as root biomass, root:shoot ratio, leaf area index, root length density, have been linked to plant-induced suction (Boldrin et al., 2017; Ni et al., 2017). Recent investigations were conducted to quantify the shear strength of root-permeated soils under partially saturated conditions with laboratory experiments (Gonzalez-Ollauri and Mickovski, 2017; Yildiz et al., 2019).

In case of saturated rooted soils, a new modelling framework, considering the effects of dilatancy for root-permeated soils, has been introduced by Muir Wood et al. (2016). Dilatancy angle–peak friction angle relationship for root-permeated soils tested in direct shear at low normal stresses, i.e. less than 20 kPa, has been established (Yildiz et al., 2018). Recently,

Mahannopkul and Jotisankasa (2019) presented measurements of dilatancy angle for root-permeated soils with suctions less than 50 kPa.

The aim of this study is to characterise the volume change behaviour of vegetated specimens in direct shear under partially saturated conditions. The objectives are:

- to investigate the links between dilatancy angle and biotic, as well as abiotic, parameters
- to define a dilatancy angle – matric suction relationship

2. Materials & methods

2.1. Soil

Soil used in this study was procured near St. Antoenien, Praetigau in the Grisons, Switzerland. A heavy rainfall event in August 2005 resulted in numerous landslides all around Switzerland. Fifty landslides took place around Praetigau and were documented (Rickli and Graf, 2009). Characterisation tests were performed after discarding particles greater than 20 mm. The soil was classified as a clayey sand (SC), based on the Unified Soil Classification System (USCS), and its index properties are given in Table 1.

2.2. Plant species

The variance in biodiversity on a slope in a subalpine grassland or a pasture was mimicked by using *Poa pratensis* (L.), *Anthyllis vulneraria* (L.), *Trifolium pratense* (L.), *Achillea millefolium* (L.), *Alnus incana* (L.) Moench. and *Salix appendiculata* Vill. Species were chosen to be representative of different plant functional types, found commonly in grasslands and pastures in Switzerland (Pohl et al., 2009), or used in soil bioengineering (Bischetti et al., 2014).

2.3. Experimental programme

Three factors, each with two levels, were defined, and combinations of these factors were chosen to form treatments in this study. Details of each treatment are given in Table 2. Effects

of biodiversity were tested with the plant diversity factor. “Low plant diversity” consists of *Poa pratensis* (L.), *Trifolium pratense* (L.), and *Alnus incana* (L.) Moench., while all the species given in Section 2.2 form “High plant diversity”. Plant age effects were investigated with two plant growth durations, as 6 and 12 months. The treatments inoculated with mycorrhizal fungi were used to compare with the non-inoculated treatments.

Direct shear tests were performed at the end of the growth period with an Inclina Large-scale Direct Shear Apparatus (ILDSA), at a constant rate of horizontal displacement of 1 mm/min up to 190 mm. Three levels of normal loads, 1.5 kN, 2.75 kN and 4.0 kN, were applied. The dilatancy angle was calculated by taking the inverse tangent of rate of dilation (dy/dx), which is the ratio of change in normal displacement (dy) and shear displacement at 2-mm steps ($dx=2$ mm). Maximum dilatancy angle was taken as the highest value observed.

Samples were prepared in shear boxes with dimensions of 500x500x400 mm, and plants were grown in the boxes for the duration according to the treatments. Matric suction was monitored with tensiometers (UMS T5x) around the shear zone during shearing, and the matric suction at peak shear stress was obtained by taking the average value of the tensiometer readings. Details of the treatments and testing can be found in Yildiz et al. (2019).

3. Results

Twenty one experiments were performed on partially saturated root-permeated soil samples in this study. Matric suction at peak ranged between 11 kPa to 97 kPa, and all samples showed dilatant behaviour during shearing, with maximum dilation angles ranging between 1.55° and 18.1°.

Fig. 1a illustrates how the variation in degree of saturation affected the maximum dilatancy angle. An increase in degree of saturation resulted in lower values of maximum dilatancy angle. A stress-dilatancy relationship has been presented in Fig. 1b, showing a linear

increase in normalised shear stress with increasing dilatancy. Lastly, root:shoot ratio was chosen as the biotic parameter to correlate with dilatancy in this study, and a significant positive correlation was found between these two parameters (See Fig. 1c).

Fig. 2 shows normal load at peak shear stress and the maximum dilatancy angle. Mean values of maximum dilatancy angle measured at each level of increasing normal load were 11.3°, 6.02° and 5.32°. A linear regression was fitted to the data, and a significant negative correlation ($R^2=0.38$, $p<0.01$) was found.

Three samples were chosen with comparable low matric suction values, i.e. 11 – 12 kPa, and similar root:shoot ratios, namely 0.126, 0.138 and 0.174, each performed at a different normal load to investigate the dilatant behaviour under varying net normal stress. Fig. 3 shows the dilatancy angle – shear displacement graphs from these three experiments. Maximum dilatancy angles calculated for the tests at 1.5 kN, 2.75 kN and 4.0 kN were 10.0°, 5.95°, 1.56°, respectively.

4. Discussion

It was demonstrated on completely decomposed granite (CDG) soil (Hossain and Yin, 2010) and well graded sand (Schnellmann et al., 2013) with direct shear tests, on reconstituted samples of silty sand (Cattoni et al., 2007) and an aeolian silt (Cui and Delage, 1996) with triaxial compression tests, and on a moraine slope with in-situ direct shear tests (Springman et al., 2003) that an increase in confining pressure or normal stress can result in a lower dilatancy angle. Large-scale direct shear tests in this study were performed with suction monitoring at three levels of applied normal loads. It is not trivial to isolate the effects of net normal stress and matric suction on dilatancy angle completely, but general trends show how the behaviour changes.

Small variations at each discrete level of applied normal load (See Fig. 2) shows that the ILDSA was capable of minimising the change of normal load during shearing, so that the normal load was applied very precisely. Mean values of normal load at peak were 1.50, 2.73, 3.99 kN, with standard deviations 16 N, 32 N, 33 N. Similar to unsaturated fallow soils, root-permeated soils tested in this study under partially saturated conditions exhibited a decrease in dilatancy when sheared under higher normal loads. Although a linear curve-fitting was performed over this range of normal load, the data can also be interpreted with an asymptotic relationship at higher levels of normal stress. The distinct tests, presented in Fig. 3, clearly show the effect of confining pressure on the maximum dilatancy angles in unsaturated root-permeated soils. Furthermore, shapes of the curves do not suggest any clearly identifiable peak shear stress for these tests.

Fig. 4 illustrates the relationship between matric suction and maximum dilatancy angle in this study, as well as other comparable works from the literature. Even though three different normal loads were applied and it was shown that the maximum dilatancy angle decreased with increasing level of normal load, a rise in maximum dilatancy angle was observed with an increase in matric suction regardless of the applied normal load (See black solid line in Fig. 4, $R^2=0.65$, $p<0.001$), similar to the empirical relationships established for partially saturated soils.

Although a highly non-linear relationship of dilatancy and matric suction was suggested for CDG soil based on suction-controlled direct shear tests (Hossain and Yin, 2010; Ng and Zhou, 2005), this non-linear curve can also be considered as a bilinear curve, i.e. two linear segments with different slopes. Compacted specimens were tested with matric suctions up to 300 kPa under various net normal stresses between 50 to 300 kPa (Hossain and Yin, 2010), and with suction values up to 400 kPa under a net normal stress of 50 kPa (Ng and Zhou, 2005),

1 whereas the highest values of matric suction and net normal stress in this study were less than
2 100 kPa and 20 kPa, respectively.

3 The linear relationship between maximum dilatancy angle and matric suction established
4 herein is in agreement with the first segment of the bilinear curve defined by (Ng and Zhou,
5 2005), dashed line in Fig. 4. It can be speculated that the non-linearity of the dilatancy-suction
6 relationship takes place at higher suction values, e.g. 100 kPa. When the measurements from
7 Hossain and Yin (2010) and Ng and Zhou (2005) are compared at the same net normal stress,
8 i.e. 50 kPa, dilatancy angles for suction values higher than 200 kPa do not change significantly,
9 whereas at higher net normal stresses dilation became more significant even at higher suction
10 values.

11 Mean values of dilatancy angles at matric suction values of 10 and 20 kPa for root-
12 permeated soils obtained by Mahannopkul and Jotisankasa (2019) were similar to those
13 measured in this study. Dilatancy angles differ significantly for suction values around 50 kPa.
14 However, an increase in dilatancy angle with increasing matric suction can be seen in both
15 studies on root-permeated soils under partially saturated conditions. It should also be noted that
16 the sample sizes tested in both studies are different, which can affect the volume change
17 behaviour measured in a direct shear box (Wu et al., 2008).

18 The underlying mechanism and physical process of why and how matric suction
19 increases dilatancy is still unclear. Suction causes an increase in the effective stress, which
20 should decrease the dilatancy. Dilatancy in saturated soils is known to decrease with increasing
21 effective stress. Many studies, including this one, showed that dilatancy angle rises with
22 increasing suction. There was a negative correlation between maximum dilatancy angle and
23 the net normal stress in this study ($R^2=0.47$, $p<0.001$), suggesting that higher net normal stress
24 causes a reduction in dilatancy. However, linear regression analysis did not yield any

1 statistically significant relationship for effective stress, if it is calculated with Eq. 1 (Bishop,
2 1959) and assuming that the coefficient χ is equal to degree of saturation.

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad (1)$$

4 It can be suggested that the dilatancy for unsaturated soils is controlled by the net normal stress
5 rather than the effective stress. Other researchers claimed that the dilatancy enhancement may
6 be due to the aggregation of grains tied together by menisci and modified soil fabric (Fern et
7 al., 2016) or closer particle packing under high suction (Ng and Zhou, 2005).

8 Lastly, plant-induced suction was shown to increase with root biomass and root:shoot
9 ratio, which was linked to normalised shear stress and penetration resistance (Boldrin et al.,
10 2018). As dilatancy for soils under partially saturated conditions is controlled by matric suction
11 and net normal stress, the increase in root:shoot ratio was also correlated with the maximum
12 dilatancy angle (See Fig. 1c).

13 **5. Conclusions**

14 This research presents dilatancy angle and suction measurements from large-scale direct shear
15 tests on root-permeated soils under partially saturated conditions. Results indicate that the
16 stress-dilatancy relationship, which was validated for unsaturated soils, is also applicable to
17 rooted soils. Increase in root biomass and root:shoot ratio resulted in higher plant-induced
18 suction, which in turn, enhanced the dilatancy. Future work should focus on differentiating the
19 effects of roots and matric suction on the dilatant behaviour of the unsaturated soils.

20 **Acknowledgements**

21 This study was funded by the Swiss National Science Foundation within the framework of the
22 National Research Programme 68 “Sustainable Use of Soil as a Resource” (NRP 68, Project
23 no. 143122).

References

- Bischetti GB, Di Fi Dio M, and Florineth F (2014) On the origin of soil bioengineering. *Landscape Research* **39(5)**: 583–595, <http://dx.doi.org/10.1080/01426397.2012.730139>.
- Bishop AW (1959) The principle of effective stress. *Tecknisk Ukeblad* **106(39)**: 859–863.
- Boldrin D, Leung AK, and Bengough AG (2017) Correlating hydrologic reinforcement of vegetated soil with plant traits during establishment of woody perennials. *Plant and Soil* **416**: 437–451, <http://dx.doi.org/10.1007/s11104-017-3211-3>.
- Boldrin D, Leung AK, and Bengough AG (2018) Hydrologic reinforcement induced by contrasting woody species during summer and winter. *Plant and Soil* **427**: 369–390, <http://dx.doi.org/10.1007/s11104-018-3640-7>.
- Bolton MD (1986) The strength and dilatancy of sands. *Géotechnique* **36(1)**: 65–78, <http://dx.doi.org/10.1680/geot.1986.36.1.65>.
- Cattoni E, Cecconi M, and Pane V (2007) Geotechnical properties of an unsaturated pyroclastic soil from Roma. *Bulletin of Engineering Geology and the Environment* **66**: 403–414, <http://dx.doi.org/10.1007/s10064-007-0096-z>.
- Chiu CF and Ng CWW (2003) A state-dependent elasto-plastic model for saturated and unsaturated soils. *Géotechnique* **53(9)**: 809–829.
- Cui YJ and Delage P (1996) Yielding and plastic behaviour of an unsaturated compacted silt. *Géotechnique* **46(2)**: 291–311, <http://dx.doi.org/10.1680/geot.1996.46.2.291>.
- Fern EJ, Robert DJ, and Soga K (2016) Modeling the Stress-Dilatancy Relationship of Unsaturated Silica Sand in Triaxial Compression Tests. *Journal of Geotechnical and Geoenvironmental Engineering* **142(11)**: 04016055, [http://dx.doi.org/10.1061/\(ASCE\)GT.1943-5606.0001546](http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0001546).
- Gonzalez-Ollauri A and Mickovski SB (2017) Plant-soil reinforcement response under different soil hydrological regimes. *Geoderma* **285**: 141–150,

1 <http://dx.doi.org/10.1016/j.geoderma.2016.10.002>.

2 Hossain MA and Yin J-H (2010) Shear strength and dilative characteristics of an unsaturated
3 compacted completely decomposed granite soil. *Canadian Geotechnical Journal* **47**: 1112–
4 1126, <http://dx.doi.org/10.1139/T10-015>.

5 Mahannopkul K and Jotisankasa A (2019) Influences of root concentration and suction on
6 *Chrysopogon zizanioides* reinforcement of soil. *Soils and Foundations* **59(2)**: 500–516,
7 <http://dx.doi.org/10.1016/j.sandf.2018.12.014>.

8 Muir Wood D, Diambra A, and Ibraim E (2016) Fibres and soils: A route towards modelling
9 of root-soil systems. *Soils and Foundations* **56(5)**: 765–778,
10 <http://dx.doi.org/10.1016/j.sandf.2016.08.003>.

11 Ng W and Zhou B (2005) Effects of soil suction on dilatancy of an unsaturated soil. In
12 *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical*
13 *Engineering*, pp. 559–562.

14 Ni JJ, Leung AK, Ng CWW, and So PS (2017) Investigation of plant growth and transpiration-
15 induced matric suction under mixed grass–tree conditions. *Canadian Geotechnical Journal* **54**:
16 561–573, <http://dx.doi.org/10.1139/cgj-2016-0226>.

17 Pohl M, Alig D, Körner C, and Rixen C (2009) Higher plant diversity enhances soil stability
18 in disturbed alpine ecosystems. *Plant and Soil* **324**: 91–102, [http://dx.doi.org/10.1007/s11104-](http://dx.doi.org/10.1007/s11104-009-9906-3)
19 009-9906-3.

20 Rickli C and Graf F (2009) Effects of forests on shallow landslides – case studies in
21 Switzerland. *Forest Snow Landscape Research* **82(1)**: 33–44.

22 Schnellmann R, Rahardjo H, and Schneider HR (2013) Unsaturated shear strength of a silty
23 sand. *Engineering Geology* **162**: 88–96, <http://dx.doi.org/10.1016/j.enggeo.2013.05.011>.

24 Springman SM, Jommi C, and Teyssie P (2003) Instabilities on moraine slopes induced by
25 loss of suction: a case history. *Géotechnique* **53(1)**: 3–10,

1 <http://dx.doi.org/10.1680/geot.2003.53.1.3>.

2 Yildiz A, Graf F, Rickli C, and Springman SM (2018) Determination of the shearing behaviour
3 of root-permeated soils with a large-scale direct shear apparatus. *Catena* **166**: 98–113,
4 <http://dx.doi.org/10.1016/j.catena.2018.03.022>.

5 Yildiz A, Graf F, Rickli C, and Springman SM (2019) Assessment of plant-induced suction
6 and its effects on the shear strength of rooted soils. *Proceedings of the Institution of Civil
7 Engineers - Geotechnical Engineering* **172(6)**: 507–519,
8 <http://dx.doi.org/10.1680/jgeen.18.00209>.

Figure 1: Relationships of maximum dilatancy angle with (a) degree of saturation, (b) normalised shear stress, and (c) root:shoot ratio. Legend, e.g. T1 to T4, shows the treatments.

Figure 2: Variation of normal load at peak and maximum dilatancy angle. Error bars show $\pm$ one standard deviation. Intersection point of the bars is the mean value at each level of normal load.

Figure 3: Dilatancy angle – shear displacement graphs of three experiments at low matrix suction, i.e. 10 – 12 kPa. Positive values indicate expansion.

Figure 4: Maximum dilatancy angle – matric suction graphs of tests presented in this study, as well as values from Ng and Zhou (2005), Hossain and Yin (2010), and Mahannopkul and Jotisankasa (2019).

Table 1. Index properties of soil used in this study.

Gravel-Sand-Fines	[%]	14.0-45.9-40.1
Liquid limit	[%]	23.5
Plastic limit	[%]	13.7
Plasticity index	[-]	9.8
Specific gravity	[-]	2.69

Table 2: Details of treatments tested in this study

Treatment	Plant diversity	Plant age [months]	Inoculation	No. of samples
T1	Low	6	-	5
T2	Low	12	-	6
T3	Low	6	+	4
T4	High	6	-	6