Examining the hydromechanical behaviour of water repellent sand

C.T.S. Beckett
School of Engineering, Institute for Infrastructure and Environment, The University of Edinburgh, Edinburgh, Scotland, U.K.

D.G. Toll
Department of Engineering, Durham University, U.K.

A.B. Fourie
School of Civil, Environmental and Mining Engineering, The University of Western Australia, Perth, WA

P.R. Ward
School of Plant Biology, The University of Western Australia, Australia CSIRO Sustainable Agriculture Flagship, CSIRO Plant Industry, Australia

ABSTRACT: Climate change will expose geotechnical structures to increasingly extreme weather conditions, for example flooding, severe rainfall and droughts. Such changes demand novel, sustainable solutions to ensure lasting design confidence: water repellent sandy soils may offer such a solution. Water repellency is a natural phenomenon associated with soils in arid regions, caused by the build-up of long-chained organic compounds on or between soil particles or by severe heating events, for example bushfires. Some studies have independently examined retention and hydromechanical properties of water repellent sandy soils, however the link between the two remains poorly understood. Such understanding is needed to permit the material's use in geotechnical design. This paper discusses a pilot study examining the retention properties and hydromechanical response of a water repellent and natural (hydrophilic) sand representative of Western Australian soils. Results indicated that current testing methods may be inappropriate for water repellent soils, generating unrealistic hydromechanical behaviour. Work identifying appropriate testing methodologies is ongoing.

1 INTRODUCTION

Climate change will expose geotechnical structures to increasingly extreme weather conditions, threatening their future resilience (Jenkins et al. 2009). In particular, flooding, severe rainfall, heatwaves and droughts may all compromise current low-permeability hydraulic or capillary barriers through excessive inundation or cracking. Water repellent granular soils may offer a novel solution to this issue: their granular nature makes them resistant to volumetric change whilst repellency can be controlled by the degree of chemical treatment (Ng and Lourenço, 2016, Lourenço et al., 2017). Water repellent soils may also retard root growth (Roper et al., 2015), making them a promising candidate for use as impermeable or semi- impermeable liners for waste storage.

A water repellent surface is defined as one where the water-solid contact angle is ≥90°. Soil water repellency naturally arises due to deposition of organic (waxy or humic) matter and, in a temporary form, from excessive drying (e.g. bushfires) (DeBano, 2000). Repellent surfaces can also be created artificially through exposure to wastewater (Travis et al. 2008) or through mechanical processes, for example the creation of clean mineral surfaces during rock crushing or abrasion (Lourenço et al., 2015). Soil scientists have acknowledged water repellency as a critical soil constraint for over a century; in Western Australia alone, it is responsible for an estimated annual revenue loss of over $330m (GRDC, 2014). However, water repellency has only recently come to the attention of geotechnical engineers. As such, understanding of its effects on granular soil properties when unsaturated is in its infancy, precluding the material's use in geotechnical design.

This paper discusses a pilot study examining the hydromechanical behaviour of a sandy soil in a natural and artificially-hydrophobised state. Results highlighted several inconsistencies between experimental results and literature data as well as between theoretical and imposed hydraulic properties, identify critical topics for further research.

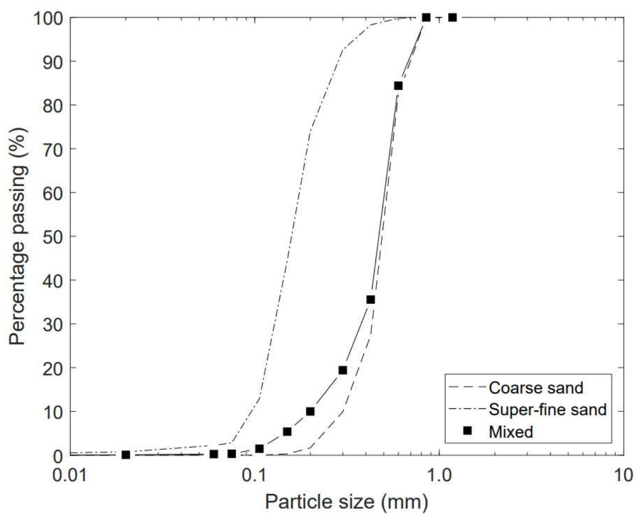

Figure 1. Particle grading curves for coarse and fine sand and the final mix.

2 EXPERIMENTAL PROGRAMME

2.1 *Materials*

It is well known that water repellency is affected by soil impurities (e.g. organic material or mineralogical differences). Hence, this study used an 'artificial' soil, formed from the mix of clean commercial products of constant mineralogy, to examine repellency's effects on hydromechanical behaviour. Coarse and fine sand (both 99.8% silica) were mixed in the proportions 88.5-11.5% respectively to match compositions typical of sandy soils worst affected by water repellency in Western Australia (USCS poorly-graded sand, SP, d_{50}=0.48 mm) (Harper & Gilkes, 1994). Particle grading curves for the initial and combined materials are shown in Figure 1. Maximum and minimum void ratios (e_{max} and e_{min}) for the mixed sand were 0.614 and 0.394 by ASTM D4254-16 and D4253-16 respectively.

2.2 *Hydrophobisation*

Sand was hydrophobised by mixing with dimethyldichlorosilane (DMDCS), following procedures described in Ng and Lourenço (2016) and in discussion with those authors.

Treating soils with DMDCS is a hazardous procedure. It must be stored in a refrigerator (below 8˚C) and used in a nitrogen-rich environment in a fume cupboard. The operator must also wear protective gloves, clothes, eye/face shield and a respirator is recommended. However, once treated, the sand is inert and can be handled without gloves.

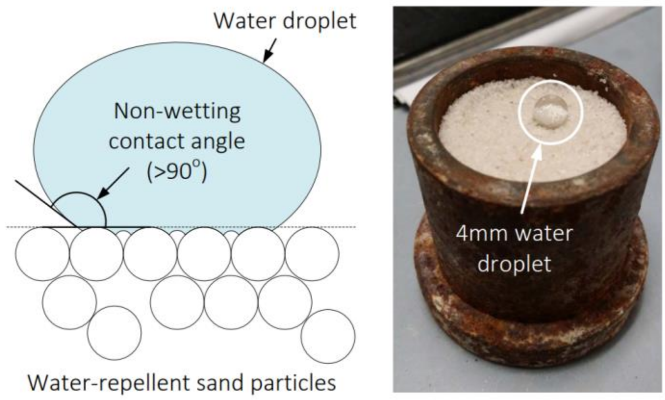

Figure 2. Water droplet sitting on top of DMDCS-treated sandy soil: left) conceptual; right) laboratory testing, 60 minutes after deposition.

1 mL of DMDCS, measured and administered using a graded syringe, was added to 1 kg of sand (in 500 g increments) and mixed for one minute. Repellency was assessed using the Water Drop Penetration Time (WDPT) test described in Beckett et al. (2016); a random 50 g of treated material was removed per batch, tamped into a container and 4 mm water droplets deposited on its surface in random locations using a calibrated pipette, as shown in Figure 2. The treatment was deemed successful if the droplets had not infiltrated the sand after 60 minutes (a WDPT rating of "extreme" water repellence), indicating contact angles 120°. Sub-samples of the treated material were tested prior to, during and after the main testing programme to ensure repellence consistency.

2.3 *Retention property testing*

Lourenço et al. (2012) and later Lourenço et al. (2017) demonstrated that water menisci adopt convex forms when suspended between water repellent particles. Such menisci would be expected to develop overall-positive water pressures, rather than the negative pressures commonly associated with liquid bridge formation (Rabinovich et al. 2005). Retention properties of water repellent and hydrophilic soils may there- fore differ significantly, consequently affecting material hydromechanical behaviour.

Water repellent and hydrophilic samples were initially prepared via tamping to a dry density of 1836 kg/m^3, or 75% of the maximum density of the hydrophilic sand (e=0.45). However, an error during testing increased the void ratio of both materials to 0.94. Samples were saturated (B-value >0.99) under back pressure (100-250kPa) and exposed to incremental suction increases via the axis translation technique, equilibrating samples between each stage to produce the drying curve. Reversing this process produced the wetting curve. A single drying and wetting cycle was completed per material for the pilot study.

2.4 *Direct shear testing*

Water repellent and hydrophilic direct shear test samples were prepared as per retention samples, excepting that void ratio remained at e = 0.45 until the beginning of the test. Samples were tested at three suction and normal stress levels, as listed in Table 1. Nonzero suctions were selected to be between the air entry value and the maximum retention curve gradient and near the residual suction value (all in drying). The minimum normal stress of 15 kPa was dictated by the accuracy of the equipment.

Table 1: Direct shear testing normal stresses and suction levels.

Material	Normal stress (kPa)	Suction (kPa)
Hydrophilic	15	0
	20	10
	25	25
Water repellent	15	0
	25	10
	35	40

3 RESULTS AND DISCUSSION

3.1 *Retention properties*

Soil water retention curves for the hydrophilic and water repellent sands are shown in Figure 3. Volumetric changes during testing were not recorded; hence, results are presented in terms of overall gravimetric water content.

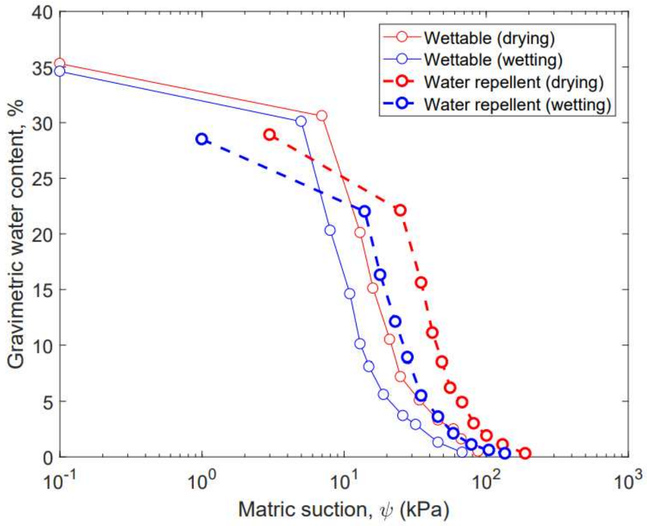

Figure 3. Hydrophilic and water repellent sand soil water retention curves (both at e = 0.94).

Two features of the retention curves in Figure 3 are particularly striking: first, that water repellent curves were similar in shape to their hydrophilic counterparts but were displaced to higher suctions (i.e. for a given suction, water contents were higher in the water repellent sand than in the hydrophilic sand); and second, that both materials displayed hysteresis between wetting and drying. That both materials should display similar behaviour was unexpected, given the anticipated differences in meniscus geometry. A possible interpretation is that the use of axis translation forced menisci to adopt concave forms in both materials to maintain pressure equilibrium, contrary to shapes that may be adopted under atmospheric conditions. Retention hysteresis may then have arisen following the conventional assumption of changes between wetting and drying contact angles. This interpretation is examined schematically in Figure 4. For the simplistic capillary tube analogy, matric suction (ψ_m) generated under a concave meniscus is given by

$$\psi_m = \frac{2\gamma \cos(\theta_{slv})}{R} \tag{1}$$

where γ is the air-water surface tension: increasing the contact angle between drying and wetting reduces the suction that can be maintained in a pore of a given radius R. Eq. (1) requires, however, that contact angles remain ≤ 90° for suction to remain positive; capillary tube surfaces are always assumed to be parallel. This restriction can be overcome by assuming curved, rather than planar, contact surfaces, e.g. for those disc particles shown in Figure 4. Increasing the contact angle for menisci in Figure 4 also reduces the water content that can be retained at a given suction (demonstrated by the constant meniscus radius r), as expected via Eq. (1) and found experimentally in Figure 3. Further work is required to substantiate this interpretation: for example, any contribution to hysteresis from film adsorption and meniscus rupture and coalescence mechanisms (Beckett & Augarde, 2013), not considered in Figure 4, will also be affected by surface wettability.

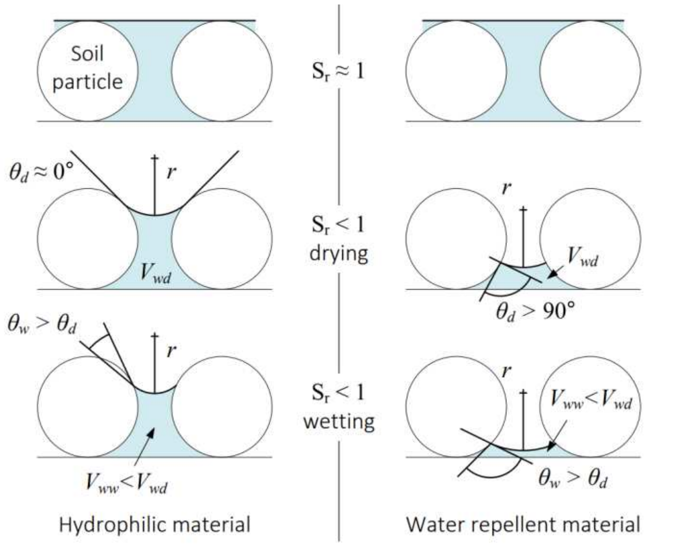

Figure 4. Mechanism demonstrating hysteresis in hydrophilic and water repellent granular soils due to changes in contact angles under axis translation. V_{wd}, V_{wd}: volume of water in drying and wetting respectively; θ_d, θ_w, contact angles in drying and wetting respectively.

Literature results describing water repellency's effect on water retention are sparse. In agreement with Figure 3, Bauters et al. (1998) found a transition to higher suction values in drying. However, they found a transition to lower suction values for wetting; notably, positive heads were needed to achieve full saturation for mixes containing > 5% water repellent material. Retention curves in that work were determined through the hanging column method. Such a mechanism may have been more representative of natural hydraulic behaviour of water repellent soils than that arising from axis translation. However, material in that work was a mixture of a water repellent sand (also rated "extreme" by the WDPT) and the same sand untreated, not exceeding a respective 1:15 mix: although bulk contact angles by the WDPT exceeded 90° , preferential drainage channels may have existed in the sample tank. Furthermore, void ratios were not recorded, precluding direct comparisons between derived retention curves.

Contrary to (Bauters et al. 1998), Davis et al. (2009), Czachor et al. (2010) and Liu et al. (2012)

found a transition to lower suctions after hydrophobisation. Davis et al. (2009) examined wetting and drying retention under vapour equilibrium, reporting positive suctions in both wetting and drying. They found that drying suctions reduced on DMDCS treatment but that wetting suctions were unaffected, so that the hydrophilic materials displayed the greatest hysteresis. Unlike in axis translation, water menisci are not forced to adopt concave forms under vapour equilibrium, as demonstrated by Lourenço et al. (2017) using environmental scanning electron microscopy. However, equivalent suctions for vapour equilibrium humidities are calculated using the well-known Kelvin equation, which implicitly assumes that particle surfaces are wettable (i.e. $\theta_{slv} = 0$, Fisher & Israelachvili, 1979): reported results may not therefore reflect actual in situ pore water pressures.

Czachor et al. (2010) and Liu et al. (2012) determined retention properties using pressure plates. They also found positive suctions in wetting and drying, however possibly as a result of the use of axis translation. Both wetting and drying suctions reduced in Czachor et al. (2010), using octadecylamine:propanol solution treatment. However, void ratio reduced with increasing water repellency from 0.81 to 0.59: reducing void ratio would increase drying suctions, which may have countered any effects on retention caused by DMDCS treatment. Void ratio was controlled in Liu et al. (2012) for soils treated with DMDCS. Drying suctions reduced in fine soils, however little change occurred for a sandy soil (e = 0.65 throughout). Lourenço et al. (2015) also found that wetting and drying suctions reduced on DMDCS treatment, measuring suctions using tensiometers. However, material water repellency was sub-critical (i.e. $\theta_{slv} < 90^{\circ}$) to permit tensiometer use and void ratio increased between the water repellent and hydrophilic samples (0.59 c.f. 0.55), which may account for the effect.

Examining the available literature, it is not surprising that support for results presented in Figure 3 is limited, given the sparsity of results, the range of treatment types used and testing methodologies employed. It is not our intention here to find fault with any of these works. Rather, this brief discussion identified several critical aspects that must be considered during experimental investigations, namely void ratio control and the method used to either apply or cal culate pore water suction. Examinations of meniscus formation and evolution under a range of testing techniques, to relate retention behaviour to real in situ hydraulic properties, are ongoing.

3.2 *Shear strengths*

Peak and residual shear strengths (τ_f) found at each of the suction/normal stress combinations given in Table 1 are shown in Figures 5 and 6 respectively. For each case, shear strengths were interpreted using the independent stress variables (ISVs) approach:

$$\tau_f = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (2)$$

where c' = effective cohesion; ϕ' = effective friction angle associated with net stress ($\sigma - u_a$); and ϕ^b = friction angle associated with a change in suction ($u_a - u_w$) (Fredlund et al., 1978). This method was adopted over the Bishop's effective stress approach (e.g. Khalili & Khabbaz, 1998) as the contributions of suction and net stress to shear strength are readily distinguishable. Although Fredlund et al. (1987) demonstrated that failure envelopes at low matric suctions are non-linear, planar failure envelopes were sufficient to describe shear strength variation. Resulting ISV parameter values for these envelopes (c', ϕ' and ϕ^b) are given in Table 2. It should be noted, however, that the use of a simplified planar failure surface generated some small-but-negative c' values: negative c' values were assumed to be zero in Table 2. Furthermore, residual stresses recorded at $\psi = 0$, $(\sigma - u_a)$ = 15 kPa for the hydrophilic soil were very low. The drop in shear resistance was accompanied by a rapid increase in shear displacement, suggesting a failure of the loading mechanism. This result is shown as an "**x**" in Figure 6 and was discounted when fitting the failure plane.

Table 2: Peak and residual shear strength parameters for hydrophilic and water repellent sand

Material	Parameter	Peak	Residual
Hydrophilic	c'	0	0
	ϕ'	49.0	53.6
	ϕ^b	38.7	31.6
Water repellent	c'	0.95	0
	ϕ'	49.7	49.9
	ϕ^b	27.8	27.8

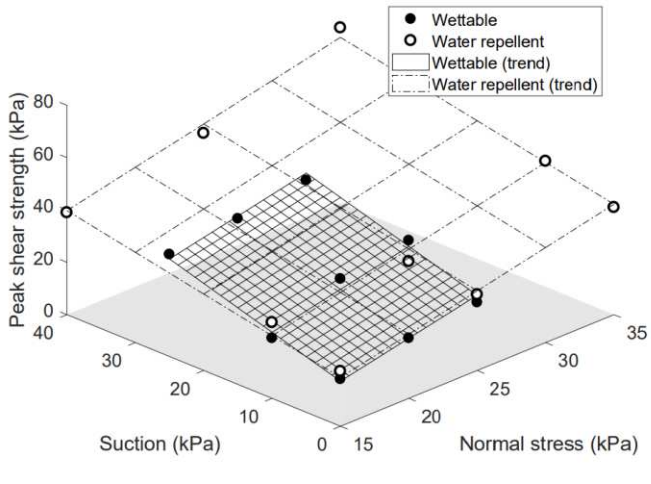

Figure 5. Peak hydrophilic and water repellent sand shear strengths and planar failure envelopes (all at e = 0.45).

Peak and residual ϕ' values were nominally equal for the hydrophilic and water repellent soils. However, all samples dilated on shearing, indicating an initially-dense condition. Byun et al. (2012), and later Lourenço et al. (2017), showed that treatment with DMDCS reduced the surface roughness and ϕ' for glass spheres. That changes in ϕ' were not found here suggests that sand particles were sufficiently rough to not be detrimentally affected by DMDCS treatment. Notably, both materials displayed positive ϕ^b values (i.e. suction's effect was beneficial to shear strength in both the water repellent and hydrophilic states). Peak ϕ^b values dropped between the two states but were nominally similar for residual strengths. To the authors' knowledge, this is the first study explicitly reporting ϕ^b values for water repellent granular soils. However, Byun et al. (2012) found a marginal shear strength increase between S_r = 0 and 0.05, suggesting that ϕ^b (had it been calculated) was ≥ 0. It is noted that ϕ^b decreases as suction increases from air entry towards a residual value (Fredlund et al., 1978). A slight reduction may be expected, therefore, by forcing a linear failure envelope through a wider suction range for the water repellent soil than for the hydrophilic. Inspection of results in Figures 5 and 6, however, does *not* suggest that this effect is significant.

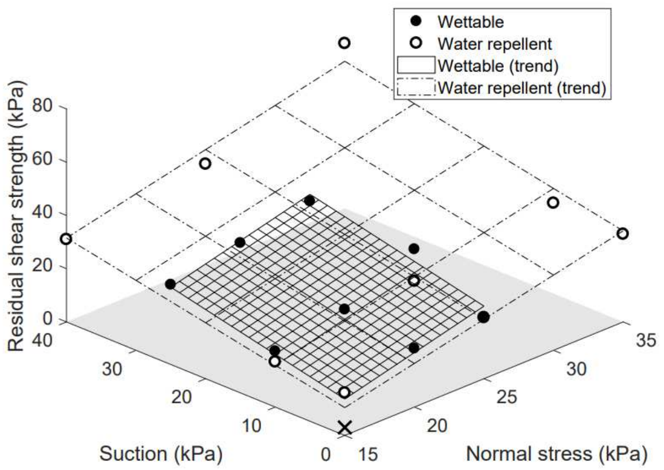

Figure 6. Residual hydrophilic and water repellent sand shear strengths and planar failure envelopes (all at e = 0.45). The datapoint marked as "**x**" showed excessive shear displacement after peak strength and was not included in plane fitting.

4 CONCLUDING REMARKS

Understanding the hydromechanical behaviour of water repellent soils has only recently become of interest to geotechnical research. What information exists paints a muddy picture of these materials' properties, precluding extension to geotechnical design. This paper described a pilot study contrasting the hydromechanical behaviour of a granular material tested under a hydrophilic and water repellent state in order to identify critical issues facing property characterisation.

Retention property testing revealed that wetting and drying suctions increased on DMDCS treatment and that both water repellent and hydrophilic materials exhibited suction hysteresis. A mechanism through which positive suctions and suction hysteresis could be generated between water repellent particles was suggested, based on the popular assumption of increased contact angles between wetting and drying.

Shear strengths for hydrophilic and water repellent material under a range of net stress and suction levels were examined using the independent stress variable method. Results showed that ϕ' was nominally constant between materials for both peak and residual shear stresses, indicating that DMDCS treatment did not significantly affect particle surface properties. Positive ϕ^b values were found for both materials. Peak ϕ^b values reduced between the hydrophilic and water repellent states but were nominally-similar for residual strengths.

Retention and shear strength testing identified a potentially-critical issue surrounding the use of axis translation to test water repellent materials: menisci are likely forced to adopt concave shapes under elevated air pressure. It may therefore be that hydromechanical behaviour identified in this and previous studies may not be representative of water repellent soils under atmospheric conditions. Work to identify the effect of testing method on meniscus concavity, and so induced pore water pressures, is ongoing.

5 ACKNOWLEDGEMENTS

The first author would like to thank Mr Adam Hamilton and Dr Keith Stubbs at The University of Western Australia, Dr Sergio Loureno at The University of Hong Kong and Dr Joao Mendes at Northumbria University for their invaluable help throughout the experimental programme. Retention and shear box testing was performed at E-Precision Laboratories, Perth, WA.

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