Wettability of natural surface soils of Hong Kong

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ABSTRACT: Changes in soil wettability impact the hydraulic and mechanical behavior of soils. The occurrence and consequences of soil water repellency have been reported in many parts of the world and mostly within an agricultural and hydrologic context, but little is known on its existence in regions with a subtropical climate (such as Hong Kong) and within a geotechnical context. The aim of this paper is to conduct a preliminary investigation on the wettability of natural soils from Hong Kong. At 120 locations across the territory, samples of soil overlying different geological materials were collected from the surface layer (0-5cm). The persistence of soil water repellency was determined by using the Water Drop Penetration Time (WDPT) test on field-moist samples. The degree of soil water repellency was determined via contact angle measurements (CA) using the Sessile Drop Method (SDM). Based on the results, the prevailing underlying geological materials dictate the persistence and degree of the soil water repellency. The soils from the sedimentary geology locations were found to be the most water repellent, followed by the quaternary deposits samples and the samples from the granite locations. However, over 78% of the soil samples with volcanics as parent rock were wettable.

1 INTRODUCTION

The interfacial tensions between the solid, liquid and air of a water drop on a layer of soil particles, generate a relationship with the contact angle (CA) which is a direct expression of the wettability of the soil (Shaw, 1992). The CA θ_y, is determined by the mechanical equilibrium under the action of three interfacial tensions, namely the solid – air (γ_{sa}), solid – liquid (γ_{sl}), and liquid – air (γ_{la}). The relationship describing the balance of interfacial forces is the Young's equation.

In soils, wettability is variable, with CAs ranging from 0° to ~120°. In its extreme form, soil water repellency (CA>90°) develops in some forest, natural, contaminated and wildfire-affected soils due to naturally occurring waxes, fungi and organic matter and occurs in the top 5 cm of the soil profile (surface soil) which is mostly composed of organic matter, roots, bacteria and fungi. The CAs magnitude is intrinsically linked to the organics characteristics and content and, the soil water content (Figure 1). A critical soil water content has been identified whereby soils are water repellent for a water content lower than it and wettable for a water content higher than the critical soil water content (Dekker et al., 2001; DeJonge et al., 1999). This also translates into a lower wettability (or higher water repellency) near the surface, and a higher wettability (or lower water repellency) with depth, as illustrated in Figure 1.

Soil wettability has practical implications to ground engineering. (1) At the field scale, water repellency generates a sealing effect from rainfall ranging from total (no infiltration) to partial (preferential flow) (Ritsema et al., 1998) leading to erosion and debris flows (reference). (2) Since it develops at very shallow depths, soil-atmosphere-vegetation interactions will be affected, experimental evidence revealed a reduced soil water retention (Lourenço et al., 2015a) and lower evaporation rate (Shokri et al., 2009) for soils with CAs<90°. (3) Suction in unsaturated soils depends not only on the soil water content and volumetric changes but also on the CAs and the surface tension of the air-water interfaces (reference). Therefore, it emerges that the soil water content and soil organic content are critical factors in dictating changes of soil wettability, not only for water repellent soils (CAs>90°), where most studies from soil science have focused, but also for CAs<90°.

This paper aims to assess the wettability of Hong Kong soils, covering the whole CA range. The specific objectives of the paper are (1) to determine the soil wettability in surface samples (0-5cm) taken from natural slopes across the territory by using the parent bedrock material as a proxy; (2) to use this diverse sample pool to identify the parameters thought to control wettability (i.e. soil water content, organic matter content); and (3) discuss the implications of the results to soil physical processes such as debris flows or erosion, and the hydraulic and mechanical behaviour. It should be noted the assessment represents a snapshot of natural soil wettability in time and space because soil wettability is time-dependent and seldom with a patchy distribution in the field (e.g. Doerr et al., 2000).

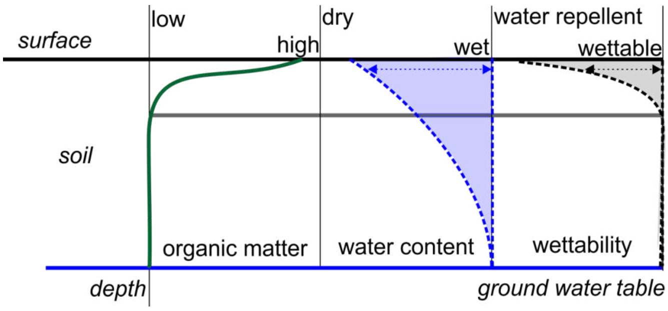

Figure 1. Schematic for the natural soil wettability variation with depth as a function of the soil water content and organic matter.

2 METHODS

2.1 *Soil collection*

To select the locations for the sample collection the parent bedrock material distribution was used. The bedrock geology controls the particle size distribution (thus relevant to soil water repellency as it frequently develops in coarser soils) and debris flow location (of engineering geology significance). Most of the Hong Kong territory (~85%) comprises of granitic (granite and andesite) and volcanic bedrock (tuff and rhyolite) with the remaining of sedimentary origin (sandstones to mudstones and marble) (Fyfe et al., 2000). For representativeness, an average of 15 samples was collected from soils derived from each parent rock.

Samples were collected from seven locations: Lantau Island (tuff and rhyolite from the Lantau Volcanic Group), Tai Tam in south Hong Kong Island (granite from the Mount Butler Granite Formation), Lamma Island (granite from the South Lamma Granite Formation), Sheung Shui in the NW New Territories (quaternary alluvium from an aborted meander of the Ng Tung River), Pat Sin Leng and Plover Cove in the NE New Territories (conglomerates to siltstones from the Pat Sin Leng Formation and Bluff Head Formation, respectively) and Tai Po Kau in the New Territories (tuff from the Yim Tin Tsai Formation) (Figure 2). Samples were collected along hiking trails at regular intervals of approximately 500m. Geographical coordinates are provided in Table 1. The survey was conducted in the dry season (October to February) over a period of two years i.e. two consecutive dry seasons.

Table 1. Sample collection and location.

Location	Samples	Coordinates
Lantau Island	16	N22°14'54.6" E113°56'35.6"
Tai Tam	10	N22°15'30" E114°11'43"
Sheung Shui	30	N22°30'45" E114°8'2"
Pat Sin Leng	19	N22°30'8" E114°14'7"
Tai Po Kau	20	NA
Plover Cove	10	N22°27.654' E114°15.644'
Lamma Island	15	N22°12.185' E114°07.863'

Samples were retrieved from the surface of the ground (down to 5 cm depth where the soil was still vegetated with fine roots and organic matter) with a metal spoon and stored in transparent plastic bags (~50g). The bags were labelled and sealed to preserve the water content. Field information such as the date, weather conditions (average air temperature, Relative Humidity and antecedent rainfall), geographical coordinates, parent rock, land use, and slope angle were noted. The presence of colluvium (transported slope deposits) was equally recorded to confirm the continuity of the bedrock upslope. A total of 120 samples were collected from the seven locations and transported to the laboratory. In the laboratory all samples were sieved to a 2mm aperture, sealed back into the bags and stored until further use.

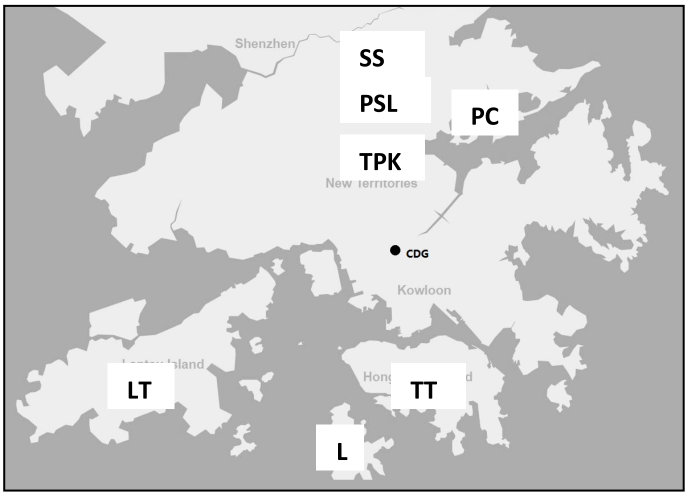

Figure 2. Samples location and parent rock material; TT – Tai Tam (granite); L – Lamma Island (granite); LT – Lantau Island (volcanics); TPK – Tai Po Kau (volcanics); PC – Plover Cove (sedimentary); PSL – Pat Sin Leng (sedimentary); SS – Sheung Shui (quaternary)

2.2 *Wettability assessment*

To assess the soil wettability, samples were collected from the field at shallow depths (< 5cm) and tested in the lab at the field moisture. The organics content was also determined. Wettability measurements included the Water Drop Penetration Time test

(WDPT), frequently employed in soil science as an estimate of the persistency of soil water repellency (how long does it last) and CA measurements which quantify its magnitude via a sessile drop placed on the surface of a layer of particles.

The WDPT is the time for a water drop of 80µl to infiltrate into a granular soil. Water repellency is classified according to a rating class system that ranges from wettable (class 0 with the water drop infiltration in < 5s) to extreme (class 10 with the water drop infiltration > 5h) (Doerr et al., 2006). The sample preparation procedure consisted in filling a Petri dish (4 cm diameter) with the soil in a very loose condition and adding a volume of 80µl of water to the soil. A stop-watch was used to time the penetration. A minimum of three drops were recorded and their average taken.

The Drop Shape Analyser 25(DSA) (KRÜSS, Hamburg, Germany) was used for CA measurements. The sample preparation procedure for the SDM first consisted of gluing a double-sided tape on one side of a microscope slide. The soil was gently sprinkled on the surface of the tape and gently shaken to remove the excess material. This was then followed by applying a 1N force on the slide. The procedure was repeated twice. The glass slide was then placed on the stage of the DSA and a volume of 10µl added to the surface by means of an automated syringe. The evolution of the air–water interface of the drop was recorded by means of a charge coupled device camera with a resolution of 82 frames per second and the CA determined by using a curve-fitting algorithm based on Young–Laplace equation applied to the first recorded images, typically within the first 50 ms to minimize gravity and roughness effects (Bachmann et al., 2003; Saulick et al., 2017). To limit the large standard deviations associated with CA measurements, a minimum of ten readings were recorded for each sample. The ambient temperature and Relative Humidity were recorded during the measurements.

The samples were then oven-dried to compute the field water content. Measurements were conducted on the same original soil sample (from the same bag) which was split in three portions, one for the WDPT, one for the CA and the remaining for the loss on ignition.

To determine the organic matter content for each sample, the loss on ignition test was conducted. The soil sample was oven-dried at 105°C for 24 hours followed by 500°C for 2 hours to remove the organic matter.

3 RESULTS AND DISCUSSION

3.1 *Soil water content*

The results revealed a significant variability in the soil wettability, both from the WDPT and CA measurements. At field moisture, and for a wide range of soil water contents (0.7% to 47.7%) the WDPT revealed extreme soil water repellency (class 9 or 10) for 30% of the samples from Tai Tam and 20% of the samples from Plover Cove and a wettable condition (class 0) for all samples from Tai Po Kau and 93% of the samples from Lamma. The remaining locations had variable persistency of the soil water repellency (Figure 3). The soil water contents, at which the water repellency persistence was the highest, were found to be in the range 7% to 30%.

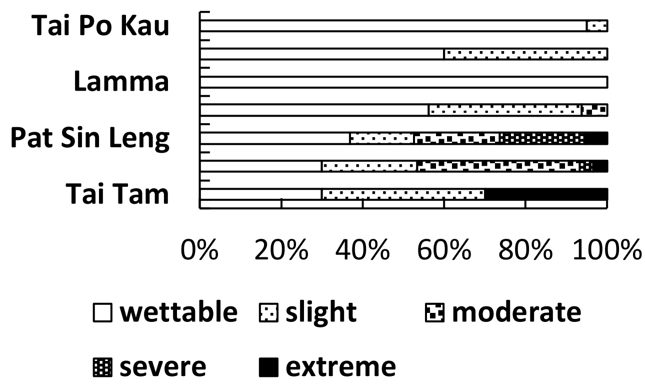

Figure 3. Soil wettability results showing the Water Drop Penetration Time versus water content for samples from all locations at field moisture.

Soil wettability (via the CAs) reduced with an increase in the soil water content. The CAs were higher for the Tai Tam samples (23° to 106°) followed by the Plover Cove samples (58° to 87°) and the lowest for the Lamma samples (6° to 31°) (Figure 4).

The WDPT data broadly correlated with the CA data. Soils from Tai Tam and Plover Cove had the highest number of extreme water repellent samples and higher CAs while Lamma and Tai Po Kau had the highest number of wettable samples and the lowest CAs. Leelamanie et al. (2008) demonstrated that there was a correlation between log (WDPT) and CA measured by SDM and the Capillary Rise Method (method based on the rise of water in a capillary with soil with the CAs computed via the Washburn equation) for fine sand coated with stearic acid. However, from the soil science literature they are not expected to correlate, as WDPT measures the persistency of soil water repellency and the CAs its magnitude.

There is no correlation between the soil organic content and soil wettability for the WDPT and CAs except for a linear correlation for the Sheung Shui samples (R^2=0.61). The organics content ranged between 1.3% and 17.4% for all samples with Pat Sin Leng achieving the highest average organic matter content at 9.9% and Tai Tam the lowest at 6.1% (Table 2).

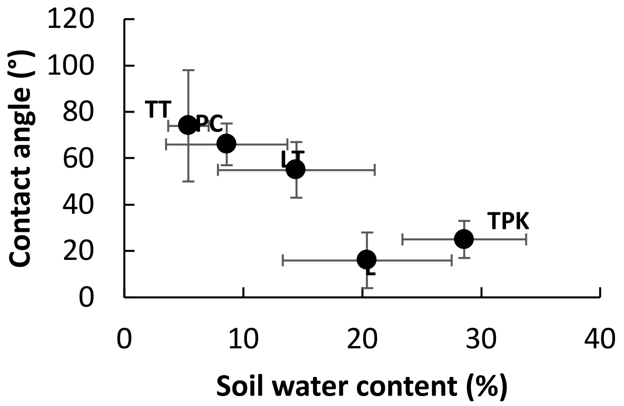

Figure 4. Soil wettability results showing the Contact Angle versus water content for samples from available locations at field moisture; TT – Tai Tam (granite); L – Lamma Island (granite); LT – Lantau Island (volcanics); TPK – Tai Po Kau (volcanics)

Table 2. Organic matter content.

Location	Organics (%)
Lantau Island	9.6±3.5
Tai Tam	6.1±1.6
Sheung Shui	9.3±4.2
Pat Sin Leng	9.9±4.5
Tai Po Kau	9.4±2.8
Plover Cove	9.8±5.9
Lamma Island	7.9±2.8

3.2 *Implications*

With only 7% of the samples revealing extreme soil water repellency and 2% of the samples with CAs higher than 90°, its occurrence in Hong Kong is not significant. However, soil water repellency is a soil condition rather soil type, changing with time and environmental conditions, therefore its incidence in the territory could be more extensive. For the areas with sedimentary geology, soil water repellency of the surface soils will delay infiltration during a rainfall event and increase runoff while the water repellency persists. Given its known patchy distribution in the field, areas with and without infiltration i.e. preferential flow, may result. Moreover, the wide range of CAs which are all higher than 0° and the fact that a maximum of 38% of the samples have WDPT ratings from slight to severe water repellency, suggests that sub-critical water repellent conditions (CA <90°) could prevail in these soils. This would lead to a reduction in the soil water retention of the soils, i.e. the drying path of the Soil Water Retention Curve for a water repellent soil is positioned below an equivalent wettable soil (Lourenço et al., 2015a), and reduced evaporation rates (Shokri et al., 2009).

3.3 *Experimental considerations*

The measured CAs in Figure 5 were lower than expected. A water repellency rating of extreme usually yields CAs >100°, where a ball-shaped water drop sits on the surface of the soil particles for a period. Reasons for this divergence include (1) inappropriate fitting methods to measure the CA – as demonstrated by Saulick et al. (2017) this generates CA variations ~20°; (2) longer waiting times to measure the CA – usually obtained within milliseconds – for longer waiting times some infiltration may occur reducing the CAs; (3) the generally large particle size of the soils tested may have also contributed to the smaller CAs.

4 CONCLUSIONS

A preliminary assessment of soil water repellency was conducted over a period of two years in the monsoon-influenced subtropical territory of Hong Kong. From a testing programme on soils overlying different geological materials and using both the WDPT (repellency persistence) and SDM (repellency degree) measurements, several key findings arise: (i) the results show a direct relationship with the soil water content; the magnitude of the overall soil water repellency is at its highest for Tai Tam and its lowest for Lamma; (ii) the organic matter content did not show a consistent correlation with the WDPT and CA values. Despite its marginal occurrence in Hong Kong with only 7% of the samples revealing extreme soil water repellency and 2% of the samples with CAs higher than 90°, its occurrence could be greater, due to its time and environmental-dependency (i.e. soils may become more or less water repellent with time).

5 ACKNOWLEDGEMENTS

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