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Hydrologic behavior of model slopes with synthetic water repellent soils

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ABSTRACT

In the natural environment, soil water repellency decreases infiltration, increases runoff, and increases erosion in slopes. In the built environment, soil water repellency offers the opportunity to develop granular materials with controllable wettability for slope stabilization. In this paper, the influence of soil water repellency on the hydrological response of slopes is investigated. Twenty-four flume tests were carried out in model slopes under artificial rainfall; soils with various wettability levels were tested, including wettable (Contact Angle, CA < 90°), subcritical water repellent (CA ~ 90°) and water repellent (CA > 90°). Various rainfall intensities (30 mm/h and 70 mm/h), slope angles (20° and 40°) and relative compactions (70% and 90%) were applied to model the response of natural and man-made slopes to rainfall. To quantitatively assess the hydrological response, a number of measurements were made: runoff rate, effective rainfall rate, time to ponding, time to steady state, runoff acceleration, total water storage and wetting front rate. Overall, an increase in soil water repellency reduces infiltration and shortens the time for runoff generation, with the effects amplified for high rainfall intensity. Comparatively, the slope angle and relative compaction had only a minor contribution to the slope hydrology. The subcritical water repellent soils sustained infiltration for longer than both the wettable and water repellent soils, which presents an added advantage if they are to be used in the built environment as barriers. This study revealed substantial impacts of man-made or synthetically induced soil water repellency on the hydrological behavior of model slopes in controlled conditions. The results shed light on our understanding of hydrological processes in environments where the occurrence of natural soil water repellency is likely, such as slopes subjected to wildfires and in agricultural and forested slopes.

1. Introduction

Wildfire-induced water repellent soil (soil that exhibit low affinity for water) is widely known for altering the hydrological responses and vadose zone processes of hillslopes, such as formation of unstable wetting front and fingered flow (preferential flow), restricted soil water movement and redistribution, decreased infiltration rate and promoted surface runoff (Doerr et al., 2006; Ritsema and Dekker, 2000; DeBano, 2000). By impeding infiltration into soil matrix, enhancing the overland flow and increasing the erodibility of soils, the likelihood of post-wildfire debris flows and consequent flash floods is increased (Fox et al., 2007; Cannon et al., 2008; Kean et al., 2012; Robichaud et al., 2016).

Soil wettability, a measure of the affinity of soils for water, is closely related to the stability of slopes. The strong correlation between post-wildfire debris flows and the formation or enhancement of soil water repellency has been extensively reported. Soil water repellency reduces the infiltration rate and increases the erodibility thereby resulting in increased overland flow and erosion. On the other hand, for wettable natural soils (soils that exhibit high affinity for water) the infiltration rate is relatively high and rainwater is able to infiltrate through the slope and form a saturated zone above any impermeable layer, leading to a rapid rise in the pore water pressure and a decrease of the effective stress and soil strength eventually triggering failure (Wang and Sassa, 2001; Tohari et al., 2007) whilst other factors known to influence slope stability of wettable soils such as rainfall intensity (RI), slope angle and relative compaction (for man-made slopes) have been widely reported and known for decades, little is known about their effects with regard to water repellent soils in slopes.

The soil-hydraulic properties of burned and unburned soils have been measured and compared). Ebel and Moody (2017) reported that the mean value of sorptivity (a measure of the liquid

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movement in a porous material by capillarity) for unburned soils was seven times greater than that of burned soils, whereas the field saturated hydraulic conductivity was not significantly decreased in burned soils compared with unaffected soils. However, Fox et al. (2007) and Robichaud (2000) conducted laboratory and field experiments and observed reduced saturated hydraulic conductivity on water repellent soils. The effects of water repellency on other soil properties have also been investigated, such as water retention (Czachor et al., 2010; Lourenço et al., 2015a), splash erodibility (Ahn et al., 2013), water drop impact (Hamlett et al., 2013), and permeability and compressibility for saturated wax-coated soils (Bardet et al., 2014), water entry pressure and friction angle (Lee et al., 2015) and small-strain shear modulus (Choi et al., 2016). However, although the association between wildfire-induced water repellency and enhanced hydrological response in the form of runoff and erosion is generally accepted, it is challenging to separate the influence of water repellency from other impacts such as a reduction in the vegetation cover and surface sealing with pore clogging.

Although soil water repellency is generally linked to limited or no infiltration, debris flows and erosion, its ability to impede water infiltration into soil has drawn the interest of engineers due to its waterproof capabilities. Synthetic water repellent soils have been used for water harvesting in arid areas (Meyers and Frasier, 1969). DeBano (1981) proposed the installation of a water repellent layer in the pavement base to prevent water permeation and protect the pavement from freezing and thawing. The potential use of synthetic water repellent soils as alternative landfill cover has also been proposed by Dell'Avanzi et al. (2010). Lourenço et al. (2015c) conducted a series of flume tests to model the response of slopes under rainfall, by manipulating the level of wettability from wettable to water repellent to explore the application of water repellent soils in slope engineering. Bardet et al. (2014) applied wax-coated sands on horseracing tracks and sports fields to avoid the degradation of the soil properties under rainfall.

To date, the use of synthetic water repellent soils has only considered a fully water repellent condition where no infiltration occurs (impermeable to water). However, wettability is controllable with the possibility of adjusting its condition so that some water infiltrates (i.e. semi-permeable to water). This could represent an added advantage for applications where vegetation is required to grow or where erosion is expected. Therefore, since extreme wettability conditions can cause slope instability in the form of landslides or erosion, the optimal conditions that reduce or inhibit slope instability need to be established so that synthetic water repellent soils could be deployed on sloping ground. This paper explores the influence of four factors assumed to alter the hydrologic response of the slope, namely: level of water repellency, slope angle, soil relative density and rainfall intensity.

The aim of the paper is to investigate the effect of synthetically induced soil water repellency on the hydrological response of slopes with a view to establish the conditions that minimize slope instability, either through excessive runoff, erosion or slope failure. In particular, soils with three wettability levels (wettable, subcritical water repellent and water repellent) were tested through a series of flume tests in model slopes at defined relative compactions, slope angles and rainfall intensities. The wettability levels are based on the contact angle (CA). When a drop of water is placed on a water repellent soil, the three phase contact line, formed between the particles, water, and air will move in response to the forces arising from the three interfacial tensions generating a relationship expressed by the contact angle (CA) which is a direct expression of the wettability of the soil. The CA of a wettable soil and water repellent soil is <90° and >90° respectively, and a subcritical water repellent soil has a CA ~90°. A subcritical water-repellent condition reduces infiltration and is generally regarded as a wettability boundary between wettable and water repellent soil (Czachor et al., 2010). The specific objectives of the study are: 1) to identify the infiltration modes and estimate the infiltration rates for the different wettability levels; 2) to assess the longevity of the wettability levels (for the sub-critical and water repellent soils); 3) to assess the effects of rainfall intensity, slope angle and relative compaction on the hydrological responses within each wettability level; and 4) to determine the optimal conditions under which the runoff, erosion or slope failure is diminished or inhibited.

2. Materials and methods

2.1. Soil description

The soil selected in this study is completely decomposed granite (CDG), collected from Happy Valley, Hong Kong, which is widespread locally and commonly used as an engineering soil and fill material (Lumb, 1965). The mineralogy of CDG was analyzed using X-ray diffraction (XRD) (Philips, PW1710 Automated Powder Diffractometer, Almelo, The Netherlands), and the major mineral compositions are quartz and kaolinite. Particle size distribution, compaction behavior and organic matter content were obtained for the natural CDG (Table 1). The percentage of sand and fines was 49.47% and 34.47% respectively. The high proportion of fines agrees with the large proportion of kaolinite from the XRD results. The CDG is classified as a well-graded silty sand based on the particle size distribution (Fig. 1). The maximum dry density and optimum water content with the light Proctor test were 1.57 Mg/m^3 and 23%, respectively. Loss on ignition (LOI) analysis was conducted to determine the organic matter content (BS 1377–3, 1990). Sub-samples were heated at 450 °C for 1 h. The organic content was 1.95%. The soil was air-dried and sieved (6.30 mm mesh with the coarser material discarded) for further use.

2.2. Soil water repellency assessment

Two measuring techniques were adopted in this study to assess the level of water repellency of different soil samples: the sessile drop method (SDM) and water drop penetration time (WDPT).

2.2.1. Sessile drop method

The SDM is a direct method to measure the CA of water drop on a soil sample surface. This method was improved by Bachmann et al. (2000) and the procedure is as follows: the soil is sprinkled on a double-sided adhesive tape fixed on a glass slide, the excess particles are removed to ensure a monolayer of particles is fixed and any motion of the particles is prevented. Placing the slide on a goniometer's stage and dispensing a droplet of deionized water (10 μL) on the sample. CA measurements are then performed with a goniometer (DSA 25, KRÜSS GmbH, Germany), by analyzing the shape of the droplet on the soil surface. The analyzing technique proposed by Saulick et al. (2017) was adopted. By applying this

Table 1
Physical properties of Completely Decomposed Granite.

Parameters (unit)	Values
Specific gravity, G_s	2.65
Optimum water content	23%
Maximum dry density (g/cm^3)	1.57
Coefficient of uniformity, Cu	690
Coefficient of curvature, Cc	2.32
Maximum void ratio, e_{max}	1.37
Organic matter content	1.95%