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Processes in model slopes made of mixtures of wettable and water repellent sand: Implications for the initiation of debris flows in dry slopes

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ABSTRACT

Debris flows in slopes initially dry, such as post-wildfire debris flows, are initiated by surface runoff and sediment bulking due to reduced infiltration. Soil water repellency, extreme dry soils, and loose, cohesionless materials influence their initiation. The exact link between these features, the resulting infiltration processes and the initiation mechanism of a debris flow remains unclear. Here, we examine the relation between soil particle wettability and slope processes in physical models. Flume experiments were conducted in 10% increments of mass ratios of wettable to water repellent sand, subjected to artificial rainfall with monitoring of soil water content, pore water pressure, sediment and water discharge and failure mode. To date, wettability was considered only for the water repellent end, because it reduces infiltration, enhancing surface runoff. This study demonstrates that slight wettability changes, in the full wettable to water repellent range, impact a variety of slope processes. The two extremes, fully wettable and water repellent gave opposite responses, retrogressive slides for infiltration-initiated in wettable sand and erosion by surface runoff in water repellent sand. The transition was dominated by surface runoff and preferential flow, yielding a combination of erosion and slides. From the tests, a continuous capping effect generated by water repellency was a necessary condition for erosion and sand bulking i.e., the generation of runoff-initiated debris flows. The sensitivity of the model slope response to artificial rainfall was particularly acute at high ratios of wettable to water repellent sand. For mixtures above a critical ratio of wettable to water repellent sand, the measurements with an index test revealed a fully wettable material despite differences in the infiltration, saturation and pore water pressure built-up trends. Implications for post-wildfire debris flows and debris flows in slopes initially dry in general are discussed.

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1. Introduction

Debris flows are often mobilized by a shallow slide in response to infiltration, saturation and rising pore water pressures (Ellen and Fleming, 1987). However, this mechanism does not hold for slopes affected by wildfires, where debris flows are triggered by surface runoff and sediment bulking in response to short duration, high intensity rainfall events (Wondzell and King, 2003; Cannon and Gartner, 2005). In such cases, the key factor controlling infiltration is soil water repellency, the others being extreme dry soils (Moody and Ebel, 2012) and sealing of pores by ash (Mallik et al., 1984; Gabet and Sternberg, 2008; Woods and Balfour, 2010). Soil water repellency (Fig. 1) develops with the presence of organic water repellent substances (generated by the wildfires but also naturally occurring) and when the soil becomes dry (Doerr et al., 2000), and is quantified via the contact angles of water drops in contact with the soil, wettable soils have contact angles <90° and water repellent soils >90°. The general term 'soil particle wettability' includes wettable and water repellent soils.

The ninety-degree contact angle represents a threshold at which the mechanical and hydraulic behaviour of the soil, and therefore the slope response, is expected to change. The significance of the threshold can be demonstrated with Young–Laplace equation, which states that soil particle wettability (θ) relates to matric suction (s), and the radius (r) and surface tension (T) of the water menisci via $s = 2T\cos\theta / r$ (Fisher, 1926). Matric suction, which controls unsaturated soil behaviour (Fredlund and Rahardjo, 1993), will be the highest for low contact angles (wettable soils) and the lowest for high contact angles (water repellent soils). This suggests that soils with high contact angles are likely to be mechanically weaker, therefore more prone to landslides. Byun et al. (2011) showed decreasing friction angles for synthetic water repellent soils. For the capillary rise in unsaturated soils, the same equation can be rewritten as, $h = \cos\theta 2T / r\rho g$, where h is the capillary rise, ρ is the density of water, and g is the gravitational constant. Water will only rise (or infiltrate) for contact angles <90°. For contact angles >90°, water will only infiltrate when the water-entry pressure is exceeded (the height of water above the water repellent surface).

Soil wettability however is a dynamic property, sensitive to soil–atmosphere interactions. Soil wettability depends on a critical water content: soils are water repellent for a water content lower than the

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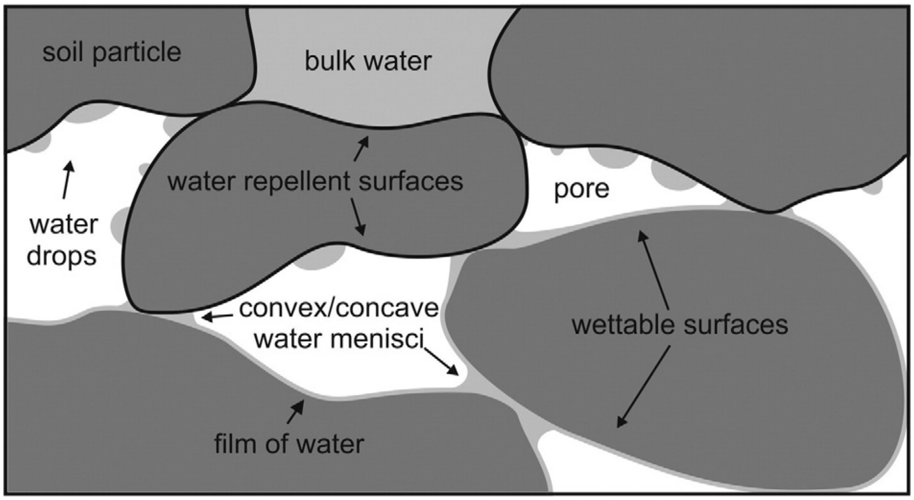

Fig. 1. Schematic representation of interacting water with wettable and water repellent particles. After Bachmann et al. (2008).

critical and wettable for a water content higher than the critical (Dekker et al., 2001). Recent work has also shown that the soil water retention is affected by soil wettability. Soils with contact angles <90° have reduced water retention i.e., they are drier than an equivalent wettable soil when dried to the same suction (Arye et al., 2011; Lourenço et al., 2015). Importantly, wettability of natural soils is time-dependent, it may decay or enhance with time and switches from wettable to water repellent, and vice-versa, may also occur with time (Morley et al., 2005) and, it has a patchy distribution in natural soils (Granged et al., 2011; Jackson and Roering, 2009).

Given the variability of soil wettability, both in time and space, and its threshold-dependent behaviour, addressing its role on debris flow initiation is a challenge still to be undertaken. Moreover, debris flow initiation has been documented for the wettable and water repellent ends with little appreciation for the slope response at the transition wettable to water repellent.

Here, through a series of physical experiments we document the role of soil particle wettability in the transition from infiltration to runoff-triggered debris flows by considering the whole wettability spectrum, from wettable (<90°) to water repellent (>90°), by mixing the same material to different ratios of soil with and without water repellent substances. This will reveal whether the transition between runoff and infiltration-initiated debris flows is gradual or threshold-controlled (90°) and will provide an insight into the various processes. To minimize other effects, differences between the experiments will be exclusively due to changes in the affinity of the particle surfaces for water, with all tests starting under the same initial physical conditions (e.g., material, grain-size distribution and density).

This study arises from a context of post-wildfire debris flows, but the results could be applicable to debris flows in some forested areas (where soils are likely to develop water repellency) (Doerr et al., 2006) and to debris flows in dry soils in general, those likely to be initiated by first-time rainfall events at the end of the dry season or after dry weather spells (Coe et al., 2008). Runoff-initiated debris flows linked to fully wettable, saturated soils are not covered here.

2. Materials and methods

2.1. Wettability treatment

To induce and adjust the wettability level, the initial strategy was to use natural oily water repellent substances because they simulate natural water repellent substances more closely, allow switches from wettable to water repellent (and vice-versa) and take into account the time-dependency of soil particle wettability (the contact time with water) (Morley et al., 2005). However, as the laboratory procedures are time-consuming and large amounts of treated material were required, permanent water repellent coatings by silanization (i.e., a synthetic water repellent treatment) were used instead. Despite being artificial, permanent water repellent coatings have also been used in other soil studies (Liu et al., 2012). Note that, in these experiments, we name wettable soils those without water repellent substances and water repellent soils those with water repellent substances.

Water repellency was induced by treatment with dimethyldichlorosilane (DMDCS) and the wettability level adjusted by mixing wettable and water repellent material to different proportions by mass. The fully wettable sample was non-treated and the fully water repellent sample made of 100% treated material. This could constitute an advantage, since water repellency is characterized by spatial variability or patchy distribution both vertically and horizontally (Granged et al., 2011) meaning water would preferably flow through the wettable particles. This co-existence of wettable and water repellent particles has been named fractional wettability (Beatty and Smith, 2010).

As post-wildfires debris flows occur in granular soils, a medium-sized industrial silica sand was used (SS#7). SS#7 is a uniform, fine silica sand with a mean grain size (D_{50}) of 0.13 mm and a uniformity coefficient (U_c) of 2.1. The maximum void ratio (e_{max}) is 1.23. The grain size distribution is shown in Fig. 2 and material properties in Table 1. This

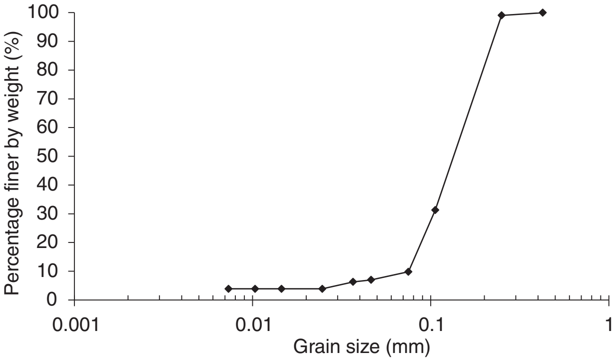

Fig. 2. Grain-size distribution of silica sand #7.

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