

Bioavailable water in coarse soils: A fractal approach

Vance Almquist^{a,1,2}, Christopher Brueck^{b,1,2}, Stephen Clarke^{a,1,2}, Thomas Wanzek^{a,1,2},
Maria Ines Dragila^{a,*}

^a Department of Crop and Soil Science, Oregon State University, Corvallis, OR 97333, USA

^b Department of Chemical, Biological and Environmental Engineering, Oregon State University, Corvallis, OR 97333, USA

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ABSTRACT

This paper addresses the contribution of *thick water films* to the total water pool retained in sandy loam soils. A thick film ($> 1 \mu\text{m}$ thick) is one of the configurations that water can adopt within unsaturated soil, along with filled capillary pores and adsorbed thin films ($\sim 10^2 \text{ nm}$ thick). It is important to quantify their respective contributions to moisture content, because each of these liquid configurations exhibits different physical properties and is governed by different mechanisms, and therefore serve a different function in soil ecosystem processes. To quantify the amount of water held in thick films, we first represent the pore structure by a fractal model developed using a fractal Koch curve. The analytical fractal model was then used to develop a series of unit pore moisture retention functions, which were then integrated across a natural particle size distribution to yield the retention function for thick films. The design of the fractal unit pore was based on X-ray microtomography and microscopy images of a sandy agricultural soil. Using the model, thick films were calculated to range from $3 \mu\text{m}$ to $140 \mu\text{m}$ thick and to contribute up to 40% of pore water saturation under capillary tensions between 2–10 kPa (20–100 cm). Using a HYDRUS-1D drainage model, it was determined that a sandy loam starting at saturation will drain to a tension of 10 kPa (100 cm) over a period of 9 days. Thick films, therefore, may contribute a substantial proportion of moisture in sandy loam soil over agronomically relevant matric potentials and timescales. Because of its physical properties, including connectivity throughout air-filled pore spaces and simultaneous contact with solid and gas phases, it is further suggested that the thick film water pool plays an important role in hydrologic, microbial, biochemical and rhizosphere processes.

1. Introduction

1.1. Objectives

The moisture content of a draining soil can be divided into three liquid pools, filled capillary pores, thick films, and adsorbed thin films. *Thick films* comprises water that clings to the walls of air-filled pores, is $> 1 \mu\text{m}$ in thickness and is likely to flow between roughness elements. Their contribution to many soil processes, especially microbial processes has been discussed in the literature. This manuscript investigates *thick films* and their contributions to soil moisture. Thick films may provide a unique and valuable service to many soil ecosystem functions because of their high interfacial area (Brusseau et al., 2006), and because of their simultaneous connectivity with solid and gas phases that facilitate moist biochemical processes via a relatively thin water layer with ready access to the gas phase. Relative to capillary

water, thick films may bolster microbial communities by increasing gas exchange rates, and nutrient and moisture availability (Ebrahimi and Or, 2015; Wang and Or, 2013). Liquid films may also accelerate biogeochemical processes relevant to ecosystem and global climate function, including heterotrophic carbon mineralization (Moyano et al., 2013), denitrification (ButterbachBahl et al., 2013) and in general, the overall fate of soil organic carbon (Six et al., 2004). In turn, the hydrated status of organic matter will impact many of the physical properties of films (Carminati et al., 2017), including water retention (Schaumann et al., 2000), water repellency (Epstein et al., 2011; Moradi et al., 2012; Morales et al., 2010), and hydraulic conductivity (Kroener et al., 2014). This manuscript quantifies the contribution of thick films to the soil's moisture content and defines its relevant matric potential range.

* Corresponding author.

E-mail address: maria.dragila@oregonstate.edu (M.I. Dragila).

¹ All authors contributed equally.

² Authors in alphabetical order.

1.2. Background

The distribution of water among the three water pools – capillary, thick film and adsorbed thin films – is determined by pore-scale morphology and interfacial physics. Water within *filled capillary pores* is held in pores by interfacial tension and capillary pressure is traditionally described by the Young-Laplace equation. *Thick films* ($> 1 \mu\text{m}$) cling to the walls of air-filled pores trapped between roughness elements (e.g., Paradiš et al., 2017; Kibbey, 2013) and in pore corners (Tuller and Or, 2001). Their matric potential is also controlled by interfacial curvature. *Adsorbed thin films* ($\sim 10^2 \text{ nm}$) are controlled by van der Waals and London forces from the solid surfaces and become the prominent water pool as the soil approaches residual saturation (Tokunaga, 2009; Tuller et al., 1999). Thick and thin films are differentiated by the physics that controls each. Adsorptive forces that control thin films do not extend the distances necessary to significantly impact thick films, leaving interfacial capillarity as the dominant force controlling the morphology of thick films.

While significant advances have been made to quantify the contribution of adsorbed films (Peters, 2013; Rossi and Nimmo, 1994; Rudiyanto et al., 2015; Tuller and Or, 2005), the *thick film* component of soil moisture has received less attention. Because the matric potential range of thick films overlaps that of capillary water, film contribution is not as readily noticeable. However, being able to separate the contribution of each of these two water pools is important, because the physics governing them and the resulting biochemical interactions made possible by these two water pools are different. Using images of particle surface roughness and calculations based on the Young-Laplace equation, Kibbey (2013) demonstrated that fluid films held by grain surface roughness in natural soils may be significantly thicker than predictions based on adsorbed film theory. Tokunaga et al. (2000) explored thick films ($1\text{--}10 \mu\text{m}$) using fractured rocks in which they were able to demonstrate a power-law relationship between film thickness and matric tension. At the single-pore scale, several analytical approaches have been used to quantify retention by films. Tuller and Or (2005) considered corner films, although they modeled these using adsorbed film physics. Peters and Durner (2008) proposed a power-law relationship between hydraulic conductivity and matric tension in the range of thick films. Paradiš et al. (2017) derived a similar relationship from basic principles of lubrication theory showing a power law of the order of 2, and a contribution by films of as much as 30% to the total moisture content, for a sandy soil, based on a single ideal pore. The cumulative result of this research asserts the existence of thick films and their potential to contribute significantly to soil moisture, but quantification to date has been limited to highly simplified pores.

1.3. Approach

In an effort to more faithfully represent the complexity of pore architecture, we have chosen a fractal model approach. Fractals have been used to model soils (Comenga et al., 1998), with work falling into three categories: physical properties, physical processes, and spatial variability (Perfect and Kay, 1995). Tyler and Wheatcraft (1990) employed the Sierpinski carpet to simulate a porous medium and successfully recreated realistic moisture retention values for a wide range of matric tensions. Similarly, Toledo et al. (1994) used the Menger sponge and Mandelbrot's skewed web to create network model simulations of moisture retention that included the effects of pendular rings and thin films. However, while the Sierpinski carpet and the Menger sponge appropriately represent pore volumes, thick films exist on microaggregate surfaces (Paradiš et al., 2017), with surface roughness best depicted by a surface fractal such as the Koch curve (Addison, 1997; Pachepsky et al., 2000; Zhao et al., 2007).

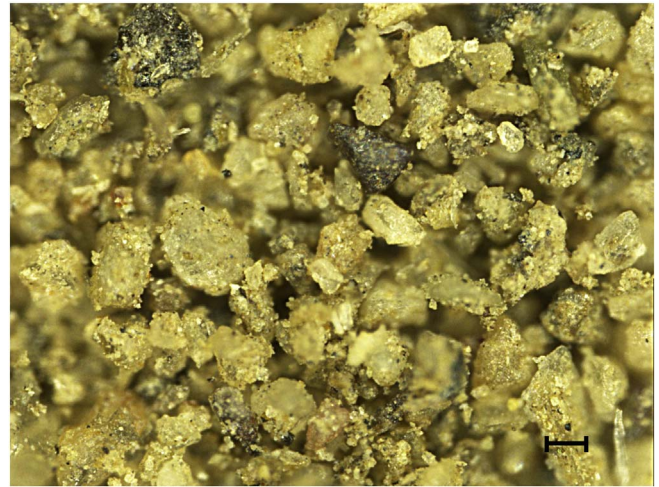


Fig. 1. Bright-field microscopy image of untreated sandy loam soil showing roughness on surface of large sand-sized particles formed by the adhesion of smaller particle size fractions. Soil: Quincy under agricultural use. Scale bar represents $100 \mu\text{m}$.

2. Materials and methods

2.1. Overview

Our investigation employs the Koch curve fractal to construct a 2D analytical pore structure that mimics the pore structure of a sandy loam. Upon completion of the pore geometry, the fractal equation is used to compute a pressure-saturation relationship for thick films during drainage. Quincy agricultural soil (a sandy loam 74% sand, 20% silt and 7% clay) is used as the basis for the pore geometry and subsequent testing of results. The test soil was selected because its pore structure is expected to maximize the contribution of thick films. Coarse sandy soils were shown by Paradiš et al. (2017) to exhibit a simple microstructure comprised of solid sand grains encrusted with fine particles (Fig. 1). These coarse-textured soils drain rapidly because of the predominance of large pores, leaving remnant water mainly in the form of thick films on the rough surfaces of microaggregates. While further drying will reduce water to thin films, we chose to limit our investigation to the intermediate matric potential range dominated by thick films. Our results are expected to have practical applications in improving agricultural soil health and in quantifying soil ecosystem processes, especially for sandy soil textures where micro-aggregates may provide a valuable service in soil moisture retention. Formation and stability of micro-aggregates is tied with the maintenance of organic matter and microbial function which are challenges in sandy soil agriculture. Understanding their role in ecosystem processes may help to focus management approaches.

2.2. Conceptual model

The relationship between the pore surface shape represented by the Koch curve and the water held by that surface is based on the observations of Kibbey (2013). Using a numerical model, Kibbey (2013) demonstrated how the rough surface of a sand grain can pin an air-water interface and yield a thick film under capillary tension. The film's curved interface occupies the space between pinning locations, akin to cables spanning a suspension bridge. During drainage, as film volume decreases and the air-water interface lowers, submerged peaks meet the film surface and establish new pinning locations, subsequently increasing the interfacial curvature (Fig. 2). In this conceptual model, the size, shape, and topography of roughness elements control the saturation-pressure relationship in thick films.

Fig. 3 is an idealization of the pore space observed in Fig. 1. The schematic shows that surface roughness elements are made up of a

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