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Prediction of permeability of monodisperse granular materials with a micromechanics approach

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ABSTRACT

Prediction of the permeability of porous media is of vital importance to such fields as petroleum engineering, agricultural engineering and civil engineering. The liquid water within unsaturated granular materials is distinguished as the intergranular layer, the wetting layer and the water film. By means of the micromechanics approach, a physical conceptual model is developed to predict the permeability (intrinsic and relative permeabilities) of the monodisperse granular materials. The proposed model has been validated by comparing the available experimental data and the empirical models, and has been used to re-interpret the Kozeny–Carman's relation in particular. The results obtained with this model show that the intergranular water will dominate the flow transport when the saturation degree is higher than the residual saturation degree; when the saturation degree is below the residual saturation degree, the wetting layer will govern the flow transport and the relative permeability will decrease by 3 to 8 orders of magnitude depending on the connectivity of the wetting layer.

1. Introduction

Advective transport of liquid water in porous media is a common phenomenon in several engineering fields, such as civil engineering, agricultural engineering and petroleum engineering. The accurate estimate of permeability is essential to the realistic prediction of the fluid movement within porous media.

Numerous models, e.g., Kozeny–Carman's relation and Van Genuchten's model, were developed to estimate the permeability of saturated and unsaturated porous media (Carman, 1937; Brooks and Corey, 1964; Van Genuchten, 1980). Although most of these models for permeability have been proven to be effective and robust in the engineering domain, the fitting parameters in these models lack a clear physical meaning and these models are phenomenological in nature (Peters and Durner, 2008; Lebeau and Konrad, 2010). It should also be noted that these models for unsaturated porous media are proposed on the premise of the effective saturation degree, which means that these models are invalid below a residual saturation degree. This is because the wetting layer flow (and/or water film flow), proven to be significant in the low saturation regime (Blunt et al., 2002; Tuller and Or, 2002; Peters and Durner, 2008; Lebeau and Konrad, 2010), is not accounted for in these models.

The micromechanics approach was firstly employed by Ene and Sanchez-Palencia (1975) to predict flow permeability. In their work, Darcy's law was derived via the homogenization of the local fluid flow which is characterized by the Navier–Stokes equation. This approach has been implemented for granular material and consolidated material by many researchers (Oron and Berkowitz, 1998; Gruescu et al., 2007; Lemarchand et al., 2009; Dormieux et al., 2011; Nguyen, 2014). However, the micromechanics model for predicting the permeability of the unsaturated granular material has not been proposed to date.

A random packing of monodisperse spheres is a simple yet realistic model for monodisperse granular materials, e.g. well-sorted unconsolidated sand or well-sorted consolidated sandstone (Bryant and Blunt, 1992). The aim of this paper is to investigate the evolution of the permeability of monodisperse granular materials with saturation degree by means of the micromechanics methodology. A micromechanics model for intrinsic and relative permeability will be developed based on the physical characterization of the water distribution at the local scale, where not only the intergranular water but also the wetting layers and water films will be accounted for. The homogenization approach will then be applied to derive the permeability. This approach provides a bridge to link the local water morphology to macroscopic permeability.

Note that the permeability in this text is closely related to the water distribution (i.e., water morphology). The effect of the viscosity of liquid is not considered in this work. Moreover, in this work, we focus on the liquid permeability instead of the gas permeability, as other complex

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mechanisms, such as the Klinkenberg effect and Knudsen effect, would have to be accounted for in the latter.

2. Physical characterization of the liquid within unsaturated granular materials

2.1. Evolution of water distribution during desaturation

The transport property of unsaturated granular material is essentially a question of water distribution morphology and a local physical property for saturation regimes ranging from full saturation to intermediate saturation and to low saturation.

2.1.1. Full saturation regime

In the full saturation regime, the theoretical and experimental findings (Blunt et al., 2002; Han et al., 2009) have demonstrated that the transport in fully saturated sandstone is mostly realized via the intergranular water. The monodisperse granular material can be simplified as Hashin's composites, i.e., as a sphere assemblage, in which a composite consists of a solid sphere surrounded by a concentric spherical shell filled with fluid (Hashin and Shtrikman, 1963; Auriault et al., 2009). The composite of spheres inherently exhibit the connectivity of the fluid, pore size and porosity (Auriault et al., 2009). Owing to this specific morphology, the intergranular water is denoted as the intergranular layer in this work.

2.1.2. Intermediate saturation regime

In the intermediate saturation regime, there may primarily be two components of liquid water: the intergranular layer aforementioned and the wetting layer. The latter consists of the interconnected capillary water trapped in the surface roughness of the solid grains and the pendular rings at grain contacts; see Fig. 1. The wetting layer is significantly influenced by the surface characteristic of the solid grain and the capillary pressure. Generally, the characteristic thickness of the wetting layer is of the order of submicrons (Blunt et al., 2002; Han et al., 2009; Kibbey, 2013).

2.1.3. Low saturation regime

In the low saturation regime, all of the intergranular layers are drained out; thus, the water phase is mainly localized in the pendular rings and surface roughness of the grain surface; see Fig. 1. Nevertheless, the trapped wetting layer remains continuous when the saturation degree decreases down to 1% (Dullien et al., 1989; Blunt et al., 2002). Hereafter, the wetting layers become progressively discontinuous, and the water films adsorbed on the grain surface interconnect the isolated wetting layer. At this stage, the water film plays a dominant role in the transport. The thickness of the water films is of the order of nanometers; moreover, the thickness and stability of the water film is governed by the so-called disjoining pressure (Deryagin and Churaev, 1987).

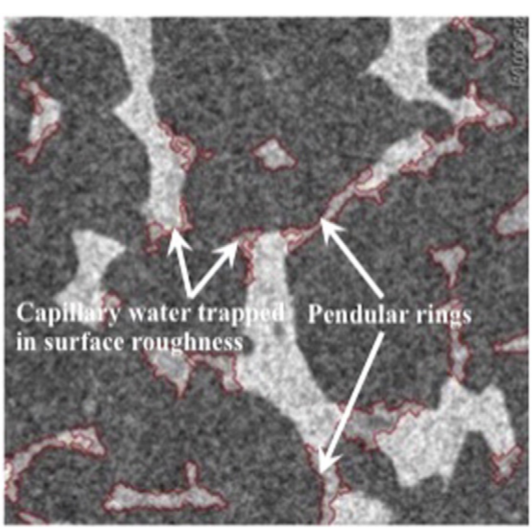

Fig. 1. Schematic illustration of water distribution in sandstone at saturation degree $Sr = 0.3$; the domains surrounded by the red curves represent the capillary water trapped in pendular rings and the surface roughness, the gray domains represent the gaseous phase and the black domains are sandstone grains, modified from Han et al. (2009).

In this work, the subscripts/superscripts s, g, l, il, wl and wf represent the solid phase, gaseous phase, liquid phase, intergranular layer, wetting layer and water film, respectively.

2.2. Local permeability

To characterize the local fluid flow in granular materials, several assumptions should be made to simplify the problem (Blunt et al., 2002): (1) the liquid flow is laminar (Poiseuille flow) in granular materials since the Reynolds number of the in-pore fluid is small enough so that the inertial effect is negligible in the momentum balance equation of the fluid; (2) all the fluids in granular materials are at steady state which means the variation of the density of liquid flow with time can be neglected in the mass balance equation; (3) all of the fluids are immiscible, and the liquid fluid is incompressible and considered to be a Newtonian fluid.

The intergranular layer flow, wetting layer flow, and water film flow are treated as Poiseuille flows and their filtration velocity profile of the intergranular flow on the flat plane is schematically depicted in Fig. 2. As illustrated in Fig. 2, the intergranular layer is assumed to be a Newtonian fluid with constant density and viscosity and to have only one non-zero velocity component along the Z-axis parallel to the surface of the plane (Or et al., 2000; Tuller and Or, 2002; Lebeau and Konrad, 2010; Dormieux et al., 2011). The Poiseuille flows can thus be characterized by the simplified Navier–Stokes equation (Spurk, 1997):

$$-\frac{\mathrm{dP}}{\mathrm{dz}} = \mu_0 \frac{d^2 v(y)}{dy^2} \tag{1}$$

where $v(y)$ is the velocity along y direction and y is the distance normal to the flat plane , P is the applied pressure on the Poiseuille flow, μ_0 is the viscosity of bulk liquid.

Carrying out double integration of Eq. (1) yields (Or et al., 2000):

$$v(y) = \frac{y^2 - 2\delta y}{2\mu_0}\left(-\frac{dP}{dz}\right). \tag{2}$$

The average velocity of the Poiseuille flow $\bar{v}$ can be achieved by the integration of Eq. (2) and being divided by its thickness h (Or et al., 2000):

$$\bar{v} = \frac{\delta^2}{3\mu_0}\left(-\frac{dP}{dz}\right) \tag{3}$$

Eq. (3) is derived from the simplified Navier–Stokes equation and can be taken as Darcy's law for Poiseuille flow. Therefore, the intergranular layer flow can be expressed as vector form:

$$\underline{z} \in \Omega^{il}: \qquad \underline{v}_{il}(\underline{z}) = -\frac{K^{il}}{\mu_0}\underline{\mathrm{grad}}_{il}P(\underline{z}) = -\frac{e^2}{3\mu_0}\underline{\mathrm{grad}}_{il}P(\underline{z}) \tag{4}$$

where $\underline{\mathrm{grad}}_{il}P(\underline{z})$ is the pressure gradient in the intergranular layer and e is the thickness of the intergranular layer. Herein, the physical meaning of e is that e ideally stands for the radius of the pore throat within granular materials (Dormieux et al., 2011).