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Quantifying representative elementary volume of connectivity for translucent granular materials by light transmission micro-tomography

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ABSTRACT

Aquifers composed of granular materials are major repositories of groundwater resource in which water can flow freely and be stored abundantly. Undoubtedly, exploring connectivity of granular materials is essential to understand the mechanism of water and contaminant migration in subsurface environment, while characterizing the connectivity remains a difficult task currently. This study proposes a new light transmission micro-tomography (LTM) with high resolution to address this problem. The new approach relies on scanning micro-structure by light transmission through translucent granular materials in given thickness. An experiment of light transmission through a two dimensional (2D) sandbox packed by heterogeneous translucent silica is conducted to examine the efficiency of LTM in capturing all the features of connectivity including porosity (n), density (ρ), solid phase-pores interface area (A_{sp}), and tortuosity (τ). Considering the importance of representative elementary volume (REV) in characterizing the representativeness and reliability of connectivity, associated REV scales of characteristic variables are also estimated using a criterion of relative gradient error (ε_g^i). Results suggest that the frequencies of minimum REV sizes of connectivity are close to Gaussian distribution in 0.0–12.0 mm and the REV size of approximately 10.0 mm is available to represent connectivity of translucent silica. Then the quantification of connectivity and the corresponding REV estimates are significant for accurate simulation of fluid migration and for associated optimal design of contaminant remediation in subsurface environment. More important, this study provides the possibility of rapid, handy and economical on-site measurements of connectivity for translucent materials.

1. Introduction

More than 90% of all available freshwater is groundwater on our planet (Boswinkel, 2000; Asuquo and Etim, 2012; Valipour, 2012, 2015; Yannopoulos et al., 2015; Valipour and Singh, 2016). Water below the surface of the earth is arguably one of the most precious natural resources for human life, in more detail, groundwater is important water supply for domestic, agricultural, industrial and ecosystem water consumption (Bakshevskaia and Pozdniakov, 2016; Cui et al., 2016; Liu et al., 2016). Particularly, groundwater resource is quite rich in aquifers composed of granular material with larger pore space and porosity around the world such as coastal and river bank sandy aquifer. Due to their rich storage space, relative high porosity and good connectivity, the sandy aquifers are available to store abundant groundwater resource. Groundwater tends to move along relatively short flow paths freely in local subsurface flow systems due to the high hydraulic conductivity of sandy aquifer. For these reasons, aquifers composed of granular material become major repositories of groundwater resource which is important to satisfy the intensive water consumption arising from rapid economic development in large parts of the world. With the increasing of pressures from water consumption and demand, abundant and precious groundwater resource around the world has been exploited seriously owning to urbanization, population growth, agricultural and industrial development, and natural groundwater incidentally, is threatened by pollution from human activities (Malov, 2016; Rezaei et al., 2016; Shoushtari et al., 2016; Zakari et al., 2016). Depletion of groundwater resources due to unsustainable exploitation in aquifers now has become a global environmental problem (van Dijk et al., 2016). Worse still, granular material aquifers are rather susceptible to contamination from human activities, which provides a conduit for the transport of contaminants in aquifer systems (Tye and Lapworth, 2016). Especially, it has been recognized that contamination can trigger or facilitate water-mineral interactions in aquifer systems, leading to the change of aquifer connectivity such as porosity (Pacheco and Szocs, 2006; Pacheco, 2013; Pacheco

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et al., 2013, 2015). As a consequence, it is important to investigate the micro-structure and connectivity of the granular material to further understand the mechanism of water and contaminant migration in aquifers.

To deepen the understanding of water and contaminant migration behavior in the subsurface environment, translucent silica is widely used in high quality laboratory experiments what is effective to study micro-structure and connectivity of sandy aquifers (Niemet and Selker, 2001; Bob et al., 2008; Costanza-Robinson et al., 2011). On the other hand, translucent silica is also used for numerous industry applications such as refractory materials in high-temperature industries (Bouvry et al., 2016), while quantifying connectivity of this type of material is complex indeed. Technological advances and increased availability of facilities for non-destructive and non-invasive high resolution laboratory techniques, such as utilizations of X-ray, gamma ray micro-tomography in the measurement of material micro-structure properties are becoming more and more widespread (Brown and Hsieh, 2000; Niemet and Selker, 2001; Al-Raoush and Willson, 2005; Bob et al., 2008; Al-Raoush and Papadopoulos, 2010; Costanza-Robinson et al., 2011; Al-Raoush, 2012; Borges and Pires, 2012; Fernandes et al., 2012; Rozenbaum and du Roscoat, 2014). By means of gamma ray computerized tomography, Brown and Hsieh (2000) found both density and macropore index of collected dolomite cores to converge to single values with increasing measured volumes which fits to the definition and prediction of representative elementary volume (REV). Using gamma ray computed tomography, the minimum volume of soil to be collected for bulk density measurements was evaluated to achieve representative bulk density, indicating that the representative volumes should be 50–100 cm^3 (Borges and Pires, 2012). In the similar application of gamma-ray computed tomography, representative elementary sizes of porosity for Brazilian tropical soil were assessed in micro scanning measurements (Borges et al., 2012). Meanwhile, 3D images of natural sand, sandstone and siltstone were obtained through X-ray computed tomography to estimate the REV of system parameters such as porosity (Al-Raoush and Papadopoulos, 2010). Boever et al. (2016) proposed on-site measurements of micro-structure and permeability for sandstones and granular limestone was measured based on X-ray computed tomography techniques. Much more interesting, thermal radiative properties of translucent material was retrieved utilizing X-ray computed tomography and emittance models (Bouvry et al., 2016). Nonetheless, in order to facilitate X-ray or gamma ray penetrate through the materials to achieve tomography with high spatial resolution, the samples used in experiments for micro-tomography are typically quite small (Costanza-Robinson et al., 2011). Another disadvantageous aspect associated with the use of X-ray and gamma ray radiation is their limitations in practical micro measurements such as requirement of high energy sources, hazard working environment, high cost, complex measurement procedures with long time (Niemet and Selker, 2001; Bob et al., 2008). Fortunately, the newest light transmission visualization (LTV) technique can provide effective approach for convenient measurement of fluid in translucent porous media. Currently, only fluid saturation can be achieved by previous light transmission technique and the features of connectivity are still hard to derive (Niemet and Selker, 2001; Bob et al., 2008).

To overcome the limitations of X-ray and gamma ray computed tomography in materials properties measurements, a new technique named light transmission micro-tomography (LTM) based on previous light transmission visualization (LTV) technique is proposed to conveniently and effectively quantify connectivity of translucent silica with high spatial resolution (Fig. 1a). Different kinds of translucent silica are packed in a two-dimensional sandbox to let light transmit through and achieve emergent light intensity. Several characteristic variables of heterogeneous translucent silica including porosity (n), density (ρ), solid phase-pores interface area (A_{sp}) and tortuosity (τ) are obtained using LTM to capture the features of connectivity. Meanwhile, associated representative elementary volume (REV) (Fig. 1b) sizes of these multiple variables are estimated by a relative gradient error (ε_g^i) criterion. The limitations of X-ray and gamma ray computed tomography can be overcome by the new LTM method. In addition, unlike the LTV for only quantifying fluid content in translucent materials, LTM is improved to be used for quantifying connectivity of materials and corresponding REVs estimates by leaps and bounds with light transmission technique. In reality, LTM method achieves rapid, handy and economical on-site quantification of connectivity for translucent materials. In particular, LTM and associated REV estimation methods can improve the understanding of water and contaminant migration in natural aquifer, which is significant for protection and utilization of abundant groundwater resource.

2. Micro-structure models of translucent silica

A light transmission visualization was developed for fluid saturation measurements in 2D translucent materials (Niemet and Selker, 2001; Bob et al., 2008). Based on previous LTV method, the new light transmission micro-tomography (LTM) is proposed to achieve high resolution measurements of connectivity for translucent granular materials (Fig. 1a). To quantify the porosity of translucent silica, the pores should be saturated by water. The emergent light intensity after light penetrating through translucent porous media can be calculated by Fresnel's law (Niemet and Selker, 2001; Bob et al., 2008):

$$I_s = CI_o\tau_{s,w}^{2k_0}\exp(-\alpha_s k_s d_s) \tag{1}$$

where I_o and I_s are original light intensity of light source and the emergent light intensity respectively; C is a constant to correct difference in light transmission; $\tau_{s,w}$ is the transmittance at the solid phase-water interface; α_s and d_s are the absorption coefficient and median diameter of the solid particles, respectively; k_o and k_s are the whole numbers of solid particles and pores across the given thickness, respectively.

Consider an infinitesimal element in the 2D translucent porous media and its cross-sectional area (A_o) approaches zero ($A_o \to 0$) as shown in Fig. 1a. The solid particle and pores across light transmitted path of the media thickness L_T can be regarded as lamellar distribution (Fig. 1a). Consequently, the median diameters and total numbers of solid particles and pores (d_o, d_s, k_o, and k_s) satisfy the relationships:

$$nA_oL_T = A_ok_od_o \tag{2}$$

$$k_sd_s + k_od_o = L_T \tag{3}$$

Substituting Eqs. (2) and (3) into Eq. (1) yields:

$$\ln I_s = \beta + n\gamma \tag{4}$$

where $\beta = \ln\left(\frac{CI_o}{e^{\alpha_s d_s L_T}}\right)$ and $\gamma = \ln\left(\tau_{s,w}^{\frac{2L_o}{d_o}}e^{\alpha_s L_T}\right)$. After determining the parameters β and γ values through laboratory experiment, porosity (n) of each pixel of 2D translucent porous media can be obtained through Eq. (4).

In experiment, translucent porous media is fully saturated by water, then the density equals to:

$$\rho = (1.0 - n)\rho_s + n\rho_w \tag{5}$$

where ρ is density of porous media saturated by water; ρ_s is the density of the solid particles of porous media; ρ_w is the density of water.