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Sub-particle-scale investigation of seepage in sands

Howard F. Taylor [a,*], Catherine O'Sullivan [a], Way Way Sim [b,1], Simon J. Carr [c]

[a] *Dept. of Civil & Environmental Eng., Imperial College London, UK*
[b] *Atkins, Bristol, UK*
[c] *Centre for Micromorphology, School of Geography, Queen Mary University of London, UK*

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Abstract

While seepage poses significant challenges to many geotechnical projects and hydraulic conductivity is a key soil property, the fundamental pore-scale understanding of the water flow in soil is poor. The seepage velocities considered in geotechnical engineering are area-averaged flow rates and their relation to the actual fluid velocity is unclear. Some of the predictive formulae for sand currently used in engineering practice were developed using simplified particle-scale analytical models whose validity is not well-established. Recent advances in modelling and imaging enable these uncertainties associated with seepage to be addressed and this paper proposes a first principles simulation approach in which the flow in the void space is modelled by applying Computational Fluid Dynamics (CFD) to void geometries obtained using X-ray micro-Computed Tomography (microCT). The model was verified by comparing it to hydraulic conductivity data from laboratory permeameter tests on the same materials. The generated data provide significant sub-particle-scale insight into fluid velocities and head loss. The results are used to show that the existing models for predicting hydraulic conductivity struggle to account for the full range of particle variables and fail to explain the true governing variables, which relate to the micro-scale properties of the void space.

Keywords: Seepage; Sands; Permeability; Numerical modelling; Laboratory tests (**IGC**: D04/E13)

1. Introduction

In seepage analyses, geotechnical engineers typically consider soil as a porous continuum and apply Darcy's law, assigning a hydraulic conductivity or permeability (k) to the soil continuum. The importance of understanding the fundamental seepage process is emphasized in textbooks including those by Harr (1990) and Mitchell and Soga (2005). The present contribution improves upon the schematic diagrams and analytical models proposed in these texts by using high resolution 3D images and computational fluid dynamics (CFD), with a discretization resolution that is smaller than the particle size, to quantify the fluid flow within the void space of sands. The insight that can be obtained from this approach can advance the understanding of internal instability and filtration (Dallo and Wang, 2016; Kenney et al., 1985; Kézdi, 1979); ground improvement (Kim and Whittle, 2009); the mechanical dispersion of contaminants (discussed in Fetter (1994) and Fitts (2012)); and well development in in-situ permeability testing (Cashman and Preene, 2001), etc.

Previous studies have combined microCT imaging and network models to study porous sandstone (Mostaghimi et al., 2013; Pereira Nunes et al., 2015; Piller et al., 2014), and network models have been proposed for granular materials (e.g., Chareyre et al., 2012). However, the more

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* Corresponding author at: Dept. of Civil & Environmental Eng., Imperial College London, SW7 2AZ, UK.
E-mail address: howardftaylor@hotmail.co.uk (H.F. Taylor).
[1] Formerly Imperial College London, UK.

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open void geometry in sands makes these models difficult to apply (Taylor et al., 2016). Numerical models (Yazdchi and Luding, 2013) and empirical studies (Indraratna et al., 2012) support the hypothesis that the seepage behaviour in granular materials is governed by the narrowest points in the void space, referred to as 'constrictions'.

This paper describes the experimental procedure to acquire microCT images; pore-scale CFD simulations; and model verification by a comparison with laboratory permeameter tests. The generated data enable an analysis of the local velocities and the fundamental mechanisms of head loss in sand. The technique is applied to reassess the basis for the Kozeny-Carmen equation and other equations used to predict hydraulic conductivity in geotechnical analyses.

2. Acquisition of void topography

2.1. Specimen preparation

Referring to Table 1 and Fig. 1, four materials were chosen to enable consideration of the influence of particle size distribution (PSD) and particle shape. Each material sample was prepared in a triaxial cell using the dry deposition method (Ishihara, 1993) and densified to a relative density of approximately 50–70% (based on the maximum and minimum void ratios achievable by this deposition method) by tapping the base of the cell. Air suction of approximately 30 kPa was applied to the top cap temporarily, to maintain sample integrity until the cell was assembled, and then cell air pressure of 30 kPa was applied. To preserve the void structure and to produce samples small enough to allow high resolution imaging (Cnudde and Boone, 2013), triaxial samples were impregnated with resin and sub-sampled, as described in Fonseca et al. (2013). Referring to Fig. 2 (a), the resin was drawn up from the base by elevating the resin container and applying a small amount of air suction (≈1 kPa) at the top cap. The resin was allowed to cure for at least 24 h before coring 9 mm central sub-samples. For test repeatability, two separate triaxial samples were prepared for material Sand-Cu3, identified as [1] and [2], making a total of five samples.

2.2. MicroCT imaging

The 9-mm cores were scanned using a Nikon XT–H–225 microCT scanner at Queen Mary University of London, using the scanning parameters given in Table 2. Image processing involved median filtering and threshold segmentation, using the method proposed by Otsu (1979), to produce the 3D binary images shown in Fig. 3 where each voxel is designated to be solid (grey in Fig. 3) or void (transparent) depending on the level of X-ray attenuation.

The samples were inhomogeneous, and thus, the PSDs (as presented in Fig. 1) were determined for each core using the microCT data, following the approach detailed in Fonseca et al. (2012). Watershed segmentation of the particle phase was used to identify individual particles; employing a principle component analysis, the particle orientations were determined and used to define an orthogonal bounding box around each particle. The intermediate length of the bounding box was taken as the particle size for use in the PSD. For comparison, the points in Fig. 1, denoted as "*LAB* D_{10} & D_{60}", indicate the particle sizes for 10% passing and 60% passing by mass, respectively, measured in the laboratory by dry sieving. These points show a good agreement between the image-based particle sizes and conventional laboratory methods. The materials were characterised by their coefficient of uniformity, $C_u = D_{60}/D_{10}$ (with values of either 1.5 or 3), and their material type ('Sand' denotes Leighton Buzzard Sand, while 'Beads' denoted aluminium borosilicate glass beads).

Any approach to partitioning the continuous void space will be subjective. In the current study, the constrictions were geometrically identified following the approach described in Taylor et al. (2015). Referring to Fig. 4, the void space was segmented into discrete void regions using watershed segmentation. This process defines the void boundaries; constriction diameters were then calculated as the local maxima of the distance map on the boundary surface, as this defines the largest spheres which can fit across the boundary. A post-processing step is required to remove the extraneous local maxima so that only meaningful constrictions are identified (full details are given in Taylor et al. (2015)). Taylor et al. (2015) demonstrated that this approach gives results that are comparable with other geometric partitioning algorithms (notably the Delaunay triangulation method used in DEM studies (Reboul

Table 1
Material properties.

Name	Material	Target D_{10} (mm)	Target D_{60} (mm)	Median sphericity[a]	Median aspect ratio[a]	Median convexity[a]
Sand-Cu3[1]	Leighton Buzzard Sand	0.4	1.2	0.9	0.75	0.95
Sand-Cu3[2]		0.4	1.2			
Sand-Cu1.5		0.5	0.75			
Beads-Cu3	Borosilicate Glass Beads	0.4	1.2	0.95	0.97	0.97
Beads-Cu1.5		0.5	0.75			

[a] Measured by laser scanning as described in Cavarretta et al. (2012) and Altuhafi et al. (2013).