Computers and Geotechnics 69 (2015) 279–290

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

A new method to identify void constrictions in micro-CT images of sand

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ARTICLE INFO

Article history:
Received 16 October 2014
Received in revised form 16 February 2015
Accepted 30 May 2015

Keywords:
Constriction
Void geometry
Image analysis
Micro-Computed Tomography
Granular filter

ABSTRACT

Micro-Computed Tomography (micro-CT) provides 3D images of the internal structure of sands, allowing quantitative measurements of internal features, including void topology. Methods have already been proposed to measure constriction sizes from idealised particle arrangements or from micro-CT data, however the 3D geometry of constrictions in sands is extremely complex and can be difficult to interpret using existing methods. This paper outlines a new method to measure and visualise void constrictions in sands using micro-CT data, with a view to assessing performance of granular filters. The method is based on watershed segmentation of the void space. Synthetic data obtained from DEM simulations are used to validate the new algorithm and its performance against existing image-based methods is assessed by considering micro-CT data for a representative filter material.

1. Introduction

This paper outlines a new method to identify void constrictions in micro-Computed Tomography (micro-CT) images of sands. As well as providing computationally efficient and accurate measurements of the number and size of constrictions, the proposed method also produces useful visual outputs to aid interpretation of the void structure. To validate the new method, results are compared against a range of existing methods, using both micro-CT images of real sand and synthetic images of idealised materials generated by the Discrete Element Method (DEM). The proposed algorithm will be of use in advancing the understanding of mechanisms associated with the performance of granular filters, as used in geotechnical engineering structures such as embankment dams and flood embankments.

2. Background

2.1. Micro-CT

Modern 3D imaging techniques allow non-destructive observation and measurement of the internal structure of soils. Micro-CT has been used to investigate a number of properties in rocks and soils (Hall et al. [1]; Hasan and Alshibli [2]; Fonseca et al. [3]; and the review article by Cnudde and Boone [4]). The detailed procedure for obtaining micro-CT images is not discussed here, however it is useful to understand the steps involved in processing a micro-CT image, prior to any quantitative analysis. Micro-Computed Tomography (micro-CT) uses a series of X-ray images (radiographs), obtained at controlled orientations of the sample, to reconstruct a full 3D image of the internal structure, resolving features which are a few μm in size. Following reconstruction, a CT scan generates a 3D image consisting of voxels, where the voxel colour (or intensity) quantifies the attenuation of the X-rays at the corresponding point in the sample, as shown in Fig. 1(a), which is an example image of Leighton Buzzard Sand with a resolution of approximately $10 \times 10 \times 10\,\mu m$ per voxel. The void space and solid particles have different densities and different atomic numbers, therefore they have different levels of X-ray attenuation and hence different colours in the final image. An intensity threshold can be selected to distinguish the void and particle phases and so a binary image is created that divides the sample into solid particles and void space. The example binary image shown in Fig. 1(b) was produced from the data in Fig. 1(a) using the open source software ImageJ [5], with median filtering and binary thresholding based on Otsu's method [6]. This type of binary image is used as the input for image analyses discussed later in this paper.

2.2. Void geometry in sands

Before discussing methods to measure void constrictions, it is important to understand some key conceptual issues regarding the void space. Fig. 2(a) shows a schematic 3D structure of particles (grey) and voids (white). It is relatively easy to visualise a single particle in this schematic image, however it is very difficult to

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http://dx.doi.org/10.1016/j.compgeo.2015.05.012
0266-352X/

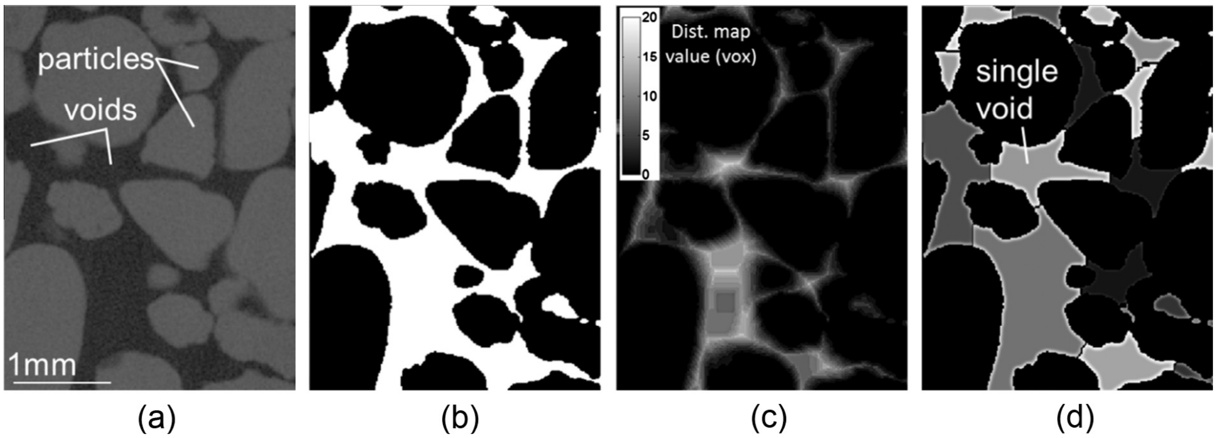

Fig. 1. Image processing and segmentation: (a) 2D slice from micro-CT image; (b) binary image; (c) distance map of void space (lighter shade = larger distance); and (d) individual voids (by watershed), each grey shade represents a separate void.

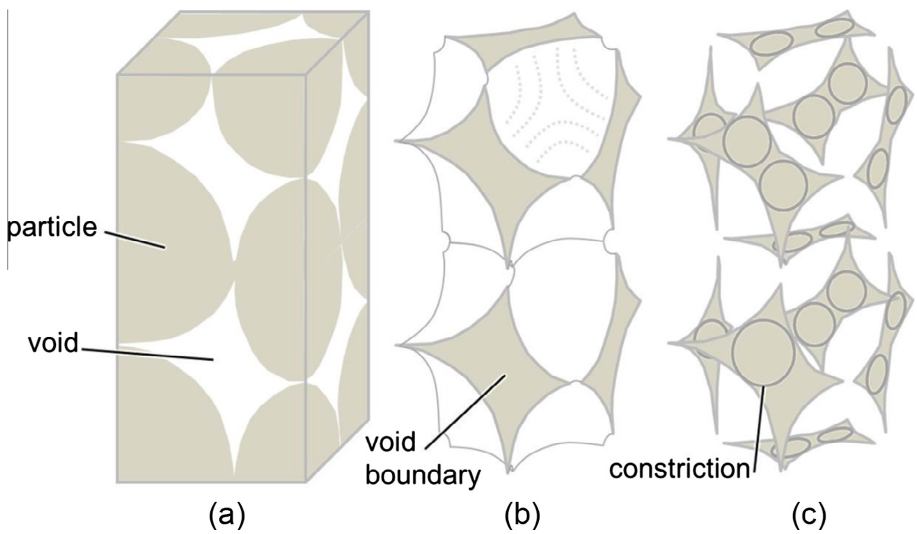

Fig. 2. Schematic soil voids: (a) soil particles (grey) and voids (white); (b) voids (white) and void boundaries (grey); and (c) void constrictions sizes (dark grey circles).

visualise a single void, as the voids are part of a continuous space, rather than being a series of discrete objects with definite physical boundaries. Fig. 2(b) is a visual discretisation of the void space in Fig. 2(a). Here the particles have been removed from the image, leaving what appears to be two voids separated by a 'throat' or 'constriction'. The grey faces represent boundaries between the individual voids and their neighbouring voids. In Fig. 2(c), the dark grey circles represent the largest particles which can fit across the boundaries and the diameters of these circles indicate the 'constriction sizes'. Particles with diameters larger than these circles will not be able to travel through the void space.

2.3. Application of method to design of embankment dams

The need to better understand the movement of fine particles through dam filters provided the main motivation for the current study. This is also a critical issue when assessing internal erosion in gap graded materials used in embankment dam construction [7,8]. As shown in Fig. 3(a) and (b), the size of the fine particles which can fit between the coarse particles depends on the size of the constrictions in the void network; in an effective filter there are sufficient constrictions that are smaller than the finer grains to retain these grains. Current design criteria for filter performance and internal erosion [9,10] are based on laboratory tests, where relationships between the Particle Size Distribution (PSD) and constriction sizes are inferred empirically, but not known. For example, Terzaghi's classic filter criterion was based on the notion that "the *pore size* of a broadly-graded filter comprises at maximum 1/5th of the diameter of the biggest grain of the finest fraction of the filter materials" [11], however this relationship was inferred from laboratory filter tests in which "pore size" (constriction sizes) could not be directly measured. Since the publication of these filter criteria, various methods have been suggested to predict or measure void constriction sizes and these methods are summarised below.

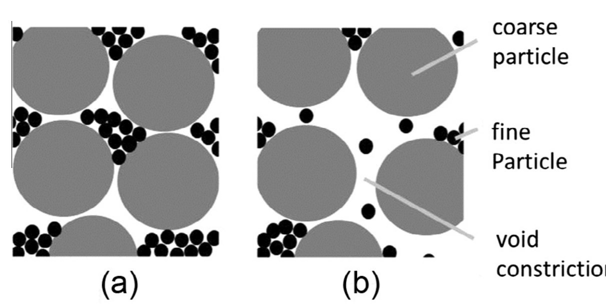

Fig. 3. Schematic of granular filter: (a) effective filter and (b) ineffective filter.