Computers and Geotechnics 73 (2016) 142–152

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Segmentation of contacting soil particles in images by modified watershed analysis

Junxing Zheng [a,1], Roman D. Hryciw [b,*]

[a] Department of Civil and Environmental Engineering, University of Michigan, 2340 GG Brown, Ann Arbor, MI 48109-2125, USA
[b] Department of Civil and Environmental Engineering, University of Michigan, 2366 GG Brown, Ann Arbor, MI 48109-2125, USA

ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form 12 October 2015
Accepted 7 November 2015
Available online 24 December 2015

Keywords:
Geotechnical engineering
Computer methods
Particle size
Particle shape
Image processing
Image analysis

ABSTRACT

Image-based soil particle size and shape characterization relies on computer methods to process and analyze the images. For contacting particles spread on a flat surface this requires delineation of particle boundaries through shape-based image segmentation. The traditional method using watershed analysis fails for particles that have constrictions (are peanut-shaped). The oversegmentation interprets such particles as being two, thereby underestimating the long particle dimension by about 50% and overestimating particle sphericity by about a factor of two. This paper presents a solution to the problem of oversegmentation through morphologic reconstruction. The key to this improvement is distinguishing the necks in peanut shaped particles from actual contacts between particles. A parameter α is defined to quantify the necks and contacts. Approximately 220,000 particles in a range of 2.0–35.0 mm having various shapes and angularities were studied to find typical α values for necks and contacts. An algorithm is proposed to correct the oversegmentation based on α. The results show that this improved watershed analysis accurately segments sand particles at contacts while preserving the continuity of peanut shaped particles. Example lab tests demonstrate the significance of the problem and its solution.

1. Introduction

As in many sciences and other engineering disciplines, the use of digital image processing and analysis in geotechnics is increasing at a rapid pace. The resolutions of digital cameras have increased logarithmically with time since their introduction in the early 2000s. Concomitantly, computer image processing algorithms have proliferated. Not surprisingly, image-based soil particle size and shape characterization methods, also known as optical or computational granulometry, have witnessed major advances over this period. However, when having to analyze images of contacting soil particles, difficulties in delineating their boundaries still exist. The most straightforward remedy is to physically spread the particles on a flat surface and separate them prior to image capture. This requires a major manual effort if a statistically valid number of soil particles are to be analyzed. Nevertheless, due to their simplicity, such physical separation approaches have been used by Kuo et al. [1], Raschke and Hryciw [2], Mora et al. [3], Banta et al. [4], Fletcher [5], Mahmoud et al. [6], Arasan et al. [7], Kumara et al. [8], Tafesse et al. [9] and others summarized in Hryciw et al. [10]. Alternatively, to reduce this physical work, various devices have been developed which physically separate the soil particles from each other. For example, a conveyor belt has been used to release particles so that they fall individually in front of a high-speed camera. A commercial device, the VideoGrader VDG40, developed by the French Public Works Laboratory, uses this approach to rapidly compute size and shape distributions of soil particles from 1 mm to 50 mm [11]. A similar system, called QICPIC, was used by Altuhafi et al. [12] to study the particle size and shape distributions of 36 sands. Such systems allow a large number of soil particles to be photographed and rapidly analyzed.

However, such systems have their own limitations. It is difficult to maintain camera focus because the distance between the falling soil particles and camera lens varies. The maximum particle sizes are limited by the conveyor size and the expense of high speed cameras and the motors needed to drive the belts impede wider usage of such systems in traditional soil testing laboratories. In view of these limitations, Ghalib and Hryciw [13], Ohm and Hryciw [14], and Zheng et al. [15] opted to spread soil particles on a flat surface, but instead of manually separating them prior to image capture, used image analysis to *segment* (i.e. digitally separate) the contacting particles. Such systems are easily constructed and

* Corresponding author. Tel.: +1 (734)763 5491.
E-mail addresses: junxing@umich.edu (J. Zheng), romanh@umich.edu (R.D. Hryciw).
[1] Tel.: +1 (734)764 8495.

http://dx.doi.org/10.1016/j.compgeo.2015.11.025
0266-352X/

use off-the-shelf cameras. The camera focus is not an issue in this method. There is no practical limit to the size of the particles that can be photographed; the camera simply needs to be moved upward to capture larger numbers of coarser gravels and cobbles. Only one image is needed unless stereo pairs are desired to obtain a vertical particle dimensions [15]. The only challenge lay in development of a reliable image segmentation computer algorithm.

Image segmentation is an active research area in computer vision and various approaches to segmentation have been developed. They may be divided into two broad categories: *color-based methods* and *shape-based methods*. The color-based methods identify particles by segmenting images based on the similarity of the colors in regions of the image. These methods are not always successful because particles often contain internal textures (color variations) while adjoining particles often have identical coloration. Shape-based methods, such as watershed analysis [13–15], segment images based on the shapes of regions in the photos. Watershed analysis has been shown to successfully separate most regularly-shaped particles in a typical soil specimen. However, peanut-shaped particles are always *oversegmented*. Meaning, they are misidentified as two and occasionally even three particles. This occurs because of the inherent assumption that the objects being segmented contain no "necks". Many soil particles are slightly peanut-shaped and thus contain such constricted sections. This paper demonstrates the significance of the problem in geotechnics and presents a numerical improvement to watershed analysis, based on image morphology reconstruction, to overcome it.

2. Watershed analysis and oversegmentation

Watershed analysis actually involves two steps: *distance transformation* and *watershed transformation*. In distance transformation, at each point within a particle interior such as point (x, y) in Fig. 1(a), the minimum distance to any point on the particle boundary (i.e. the shortest distance to a white pixel in Fig. 1(a)) is found. For point (x, y), this distance is $D(x, y)$. The $D(x, y)$ values are found for every pixel in the black areas of Fig. 1(a). The matrix of $D(x, y)$ values are then contoured to create a *Euclidean distance map*, or simply *distance map as* shown in Fig. 1(b).

Conceptually, the distance map in Fig. 1(b) can be regarded as an inverted topographic surface. The distances $D(x, y)$ could be thought of as topographic depths at locations (x, y) as shown in Fig. 2(a). Each soil particle is thus represented by a *basin* or *watershed*. The deepest point in a watershed is called a *local minima*. Since the Euclidean distances are relatively small along the line of contact between soil particles, *contact ridges* form there. These ridges are akin to watershed divides.

The watershed transformation is then performed on the distance map. The process may be thought of as the progressive filling of the basins from below by a uniformly rising water table. Eventually, the waters from two basins will meet along the ridges separating them. These ridges between basins identify the boundaries of contacting soil particles as shown in Fig. 2(b). This "basin filling algorithm" was originally proposed by Meyer and Beucher [16].

A problem arises when soil particles are peanut shaped, such as the ones labeled 1, 2, and 3 in Fig. 1(b). Such particles will contain two, and possibly more, local minima. The shallower points between two local minima create *neck ridges* as shown in Fig. 2(a). As shown in Fig. 2(b), along with the segmentations at contact ridges, segmentation also occurs at the neck ridges of peanut-shaped particles. Such *oversegmentation* divides such particles into two parts. It will later be shown that this creates errors in the computed particle size and shape distributions. To effectively avoid such oversegmentation, neck ridges (false contacts) will need to be distinguished from contact ridges (real contacts between particles).

3. Discrimination of necks and contacts

The discrimination of necks from contacts is difficult due to the highly irregular shape of soil particles. By contrast, it is generally easy to distinguish necks from contacts by eye as evidenced by Fig. 3(a). Recognizing this, Ohm [17] developed an operator-assisted algorithm to join the parts of oversegmented particles. After watershed analysis produced the segmentation shown in Fig. 3(a), an operator would judge which particles were oversegmented and needed to have their parts joined. Since contacts are typically shorter than necks, the decisions are typically based on the widths of the "narrow regions" shown by the arrows in Fig. 3 (a). The angle at which two particle outlines meet at their contact is also typically more acute compared to the angle made in the neck region of peanut-shaped particles. In Ohm's procedure, the computer operator manually clicks on the two parts of an oversegmented particle, in the vicinity of the open circles shown in Fig. 3 (a). The program then automatically stitches the two parts into one particle resulting in Fig. 3(b). This operator-assisted method achieved almost 100% accuracy. However, considerable time and effort had to be expended to find and manually stitch the hundreds of oversegmented soil particles in an image that may contain

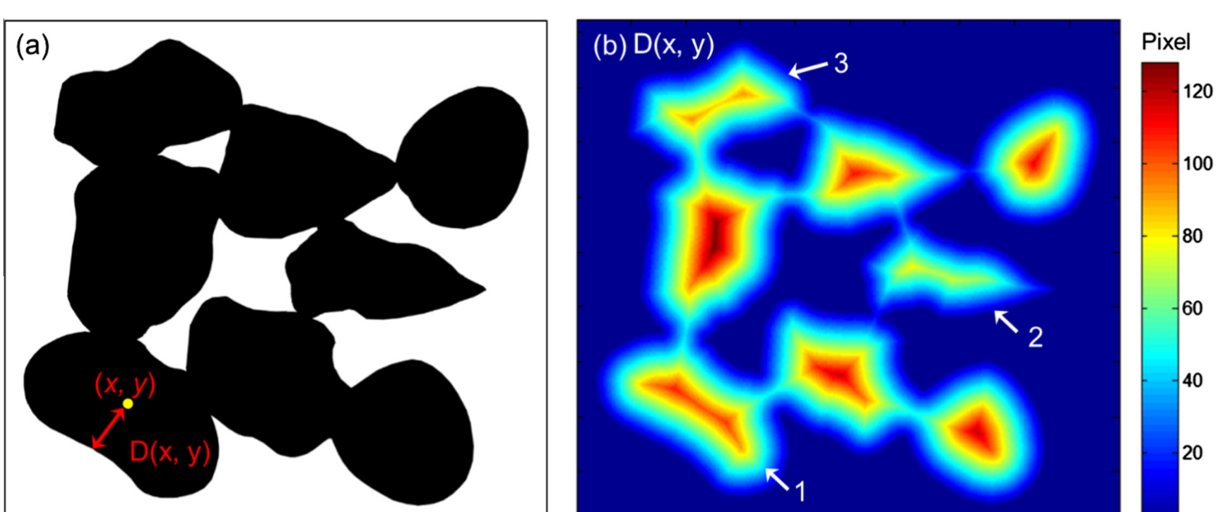

Fig. 1. Distance transformation.