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Morphological characterization of grain-scale sphericity using 2D x-ray microtomography images

Caractérisation morphologique de la sphéricité à l'échelle des grains à l'aide d'images de microtomographie à rayons x 2D

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ABSTRACT: Geotechnical engineering has traditionally used laboratory or in situ testing to determine soil properties. With the advancement of computational techniques and data processing performances, new possibilities have been investigated. In the context of morphological and geometric characterization on a grain scale, X-ray computed tomography (μCT) has served as an input for determining these parameters. The challenge still lies in standardizing the analysis methodologies into an appropriate and applicable approach for larger groups of granular materials. In this context, this article aims to propose a new algorithm implemented in Python to determine the overall sphericity classification of soil samples through a computational tool that analyses high-resolution particle-scale images from microtomography tests. The focus of this research is on performing the morphological analysis of the sphericity of particles using 2D images. The code was implemented in an open-source programming language and its applicability has been shown for an uncontaminated sand sample, based on experimental results. This method allows for more accurate determination of soil parameters and has the potential to reduces operational costs related to some laboratory tests.

RÉSUMÉ: L'ingénierie géotechnique utilise traditionnellement des essais en laboratoire ou in situ pour déterminer les propriétés du sol. Avec les progrès des techniques informatiques et des performances de traitement des données, de nouvelles possibilités ont été étudiées. Dans le contexte de la caractérisation morphologique et géométrique à l'échelle du grain, la tomographie à rayons X (μCT) a servi d'intrant pour la détermination de ces paramètres. Le défi consiste toujours à normaliser les méthodologies d'analyse en une approche appropriée et applicable à des groupes plus importants de matériaux granulaires. Dans ce contexte, cet article vise à proposer un nouvel algorithme implémenté en Python pour déterminer la classification globale de la sphéricité des échantillons de sol par le biais d'un outil informatique qui analyse les images haute résolution à l'échelle des particules provenant des tests de microtomographie. Cette recherche se concentre sur l'analyse morphologique de la sphéricité des particules à l'aide d'images 2D. Le code a été mis en œuvre dans un langage de programmation libre et son applicabilité a été démontrée pour un échantillon de sable non contaminé, sur la base de résultats expérimentaux. Cette méthode permet une détermination plus précise des paramètres du sol et a le potentiel de réduire les coûts opérationnels liés à certains tests de laboratoire.

Keywords: Microtomography; sphericity; grain-scale; image processing; python.

1 INTRODUCTION

In pursuit of solving problems and improving results, engineering has evolved and benefited from technology to enhance and optimize processes and outcomes. In this context, geotechnical engineering may encounter situations of uncertainty and variability in laboratory investigations, which need to be addressed in order to minimize or eliminate errors in soil property measurements. These errors, as indicated by Vanmarcke (1977), constitute one of the three sources of uncertainties in soil structure characterization, in addition to knowledge gaps, as outlined by Lacasse and Nadim (1996), and parameter uncertainty due to human errors or deficiencies in the equipment used to determine soil properties, as stated by Morgenstern (1995).

One of the alternatives for mitigating the impact of these sources of uncertainty is the use of equipments with pore-scale accuracy for geometric particle characterization, which can reveal the soil structure through computational procedures such as the processing and analysis of X-ray microtomography images. The interest of geotechnical engineering in obtaining these characterizations is particularly significant in the study and prediction of soil infiltration capacity, a crucial factor in engineering solutions such as stormwater management in urban centers, peak flow reduction, and contamination plume studies (Durand et al., 2012), as well as the study of micro-scale mechanical behavior, such as particle crushing and rearrangement (Cheng et al., 2019). Specifically regarding geometric sphericity characterization, it plays a significant role in influencing anisotropy levels (Oboudi et al., 2016), experimental effects on mechanical strength (Casagrande, 2005), and drag coefficient in particle-fluid systems (Mendes and Melo, 2011).

Therefore, this paper aims to propose an alternative approach involving the use of microtomography images combined with open-source image processing codes, aiming for reduced human interference and consequently minimizing errors and rework, saving time and effort in obtaining sphericity measurements.

2 MATERIALS AND METHODS

In this article, the study material consisted of microtomography images from Zubeldia (2013). These images were obtained from common construction sand in the Federal District, supplied by the Geotechnical Laboratory of the University of Brasília, and were described by the author as pure and poorly graded sand according to the Unified Soil Classification System (USCS). Specimens were molded in Polymerase Chain Reaction (PCR) tubes and microtomographed using the Sky Scan 1172, producing 610 2D images (slices) with a resolution of 5.94 µm per pixel.

From the 2D images generated on the Sky Scan 1172 microtomography machine, the code available at https://github.com/thaiskogui/ECSMGE24 was created and executed, which uses open-source computer vision Python libraries such as OpenCV, Pillow, Scikit-Image as well as other libraries such as NumPy, Matplotlib and Pandas, to identify the sphericity of particles. In short, the algorithm-covers the following steps: pre-processing of 2D images; particle segmentation; and calculation of the sphericity parameter in 2D images according to Rittenhouse (1943).

During the preprocessing of 2D images, GaussianBlur filter was applied to minimize noise and maintain the main structures of the images, yielding better results for global image thresholding using the Otsu method. The Otsu method determines an ideal automatic threshold value from histogram analysis, separating the foreground elements (particles identified as white) from the background (black).

Following the thresholded image obtained during preprocessing, particle segmentation was performed using the Watershed segmentation technique. This technique is particularly useful for cases of overlapping or closely adjacent objects, which are often observed in the 2D microtomography images in this study due to the proximity of sand particles. After segmentation, each particle was individually identified and assigned a unique identifier. All these previous steps are exemplified in one of the 2D images as shown in Figure 1.

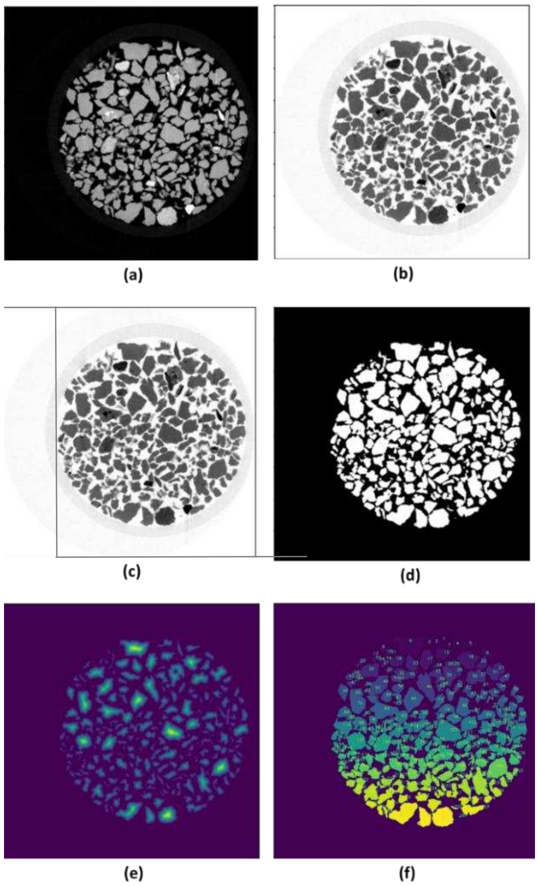

Figure 1. Image processing flowchart (a) original 2D image; (b) inverted image matrix; (c) GaussianBlur filter implementation; (d) binarization by Otsu method; (e) watershed implementation; and (f) numbered distinction of each grain.

The last step of calculating the sphericity parameter in 2D images was based on the definition presented by Rittenhouse (1943), who defined sphericity as the relationship between the diameter of the circle with an area equal to the projection of the particle and the diameter of the smallest circumscribed circle to the particle. This relationship can also be represented by the ratio between the area of the grain and the area of the smallest circle circumscribed by the grain, as demonstrated in:

$$S_i = \frac{d_{pp,i}}{d_{sc,i}} 100\% = \frac{\left(\frac{\pi d_{pp,i}^2}{4}\right)}{\left(\frac{\pi d_{sc,i}^2}{4}\right)} 100\% = \frac{A_{g,i}}{A_{sc,i}} \qquad (1)$$

where Si (dimensionless) is the sphericity of the grain; dpp,i (L) is the diameter of the circle with an area equal to the projection of a particle; dsc,i (L) is the diameter of the smallest circle circumscribed in a particle; Ag,i (L^2) is the area of grain i; and Asc,i (L^2) is the area of the smallest circle circumscribed by a grain i.

To minimize the computational cost, the relationship between areas in Equation 1 was used as an equivalent to the definition of Rittenhouse (1943), which indicated that the degree of sphericity varies from 0 to 1, taking values of 0.45 as a practical reference for more elongated particles and 0.97 for very spherical particles.

It is worth noticing that recent studies indicated that 2D measure can reasonably approximate the real 3D sphericity, using as projection direction called "plane of greatest stability" (Rorato et al., 2019). Other measures, such as perimeter sphericity, could be also considered, but are not considered in the present paper for simplicity and since the main goal is to provide a open-source implementation of the general procedure, not of a particular assessment method.

However, it was possible to find, in each of the 2D microtomographic sections, the sphericity of each identified grain, generating data for analysis of the sphericity frequency distribution of the specimen and its representative average sphericity.

3 RESULTS AND DISCUSSION

After completing the three steps (pre-processing, particle segmentation and calculation of the sphericity parameter), 152,028 sand grain particles were identified, each with their respective particle area data, smallest circle circumscribed to the particle and calculation of sphericity according to Equation 1.

From the data on the sphericities of each grain and a previous treatment of the data with the identification and removal of outliers, the following descriptive statistics in Table 1 were obtained.

Table 1. Descriptive statistics of sphericity.

Parameter	Value
Mean	0.535516
Standard deviation	0.102641
Minimum	0.299322
Quartile 1	0.461724
Quartile 2 (Median)	0.540525
Quartile 3	0.612649
Maximum	0.758905

Hence, it was possible to evaluate the frequency distribution of the sample's sphericities, as well as its cumulative distribution, respectively represented in Figure 2 and Figure 3.

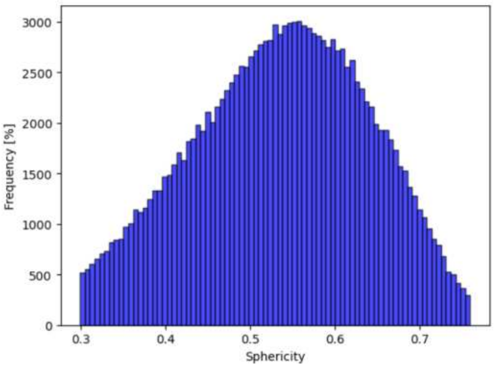

Figure 2. Distribution of sphericity frequency.

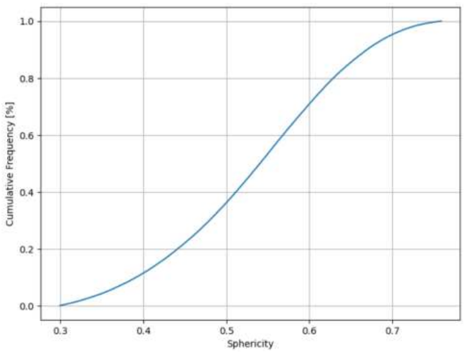

Figure 3. Cumulative distribution of sphericity.

To classify the sphericity of the sample, the sphericity index intervals mentioned by Nunes et al. (2021) as shown in Table 2.

Table 2. Classification by sphericity interval.

Classification	Sphericity interval
Lamellar/elongated	≤ 0.5
Low sphericity	0.5 – 0.6
Medium sphericity	0.6 – 0.8
High sphericity	> 0.8

Thus, considering Table 2 and the sample in general, the average sphericity obtained of approximately 53% indicates a low sphericity classification.

4 CONCLUSIONS

As shown in the present work, it is possible to infer the sphericity parameter based on 2D images, reducing procedural efforts in laboratory tests, simply by scanning the sample using x-ray microtomography and executing the suggested algorithm.

It is important to highlight that prior treatment of sphericity data is recommended, such as the identification and removal of outliers, to obtain less distortion in the results of descriptive statistics, since in image processing, the singular non-identification of a particle may occur due to joining it with another very close one, or also the creation of particles from noise in the image.

Furthermore, it is important to highlight that 2D analysis has inherent limitations and is a simplification of the real 3D nature of the soil, however, there are correlations between 2D and 3D analysis algorithms, achieving the objective of this article of presenting a simple procedure based one theoretical and computational approaches. Future works may address the generalization of the procedures hereby presented, incorporating other 2D sphericity assessment algorithms as well as 3D analyses.

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