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Evaluation of granular particle roundness using digital image processing and computational geometry

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HIGHLIGHTS

- The computation of Wadell roundness is automated using the proposed innovative algorithms.
- The B-spline curve is introduced to reconstruct particle outline from discrete image pixels.
- The particle corners are effectively identified and filled with best-fitted circles.

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ABSTRACT

The engineering behaviors of granular materials has been proven to be influenced by particle roundness. Based on several computational geometry algorithms and a well-acknowledged roundness definition, an innovative roundness evaluation method is developed. Algorithm verifications are performed to verify the reliability and the capacity of this proposed method. Relative to the traditional chart method, the proposed method is more effective and more objective. The motivation of this study is to facilitate future studies on the relationship between microscopic particle shape and the microscopic mechanical behavior of granular materials.

1. Introduction

Many studies have established that particle shape significantly influences the engineering properties of granular materials, such as the maximum or minimum void ratio [1–3], shear strength [4], stiffness [5], and dilation behavior [6]. To quantitatively investigate this influence, several shape descriptors have been proposed [7]. As shown in Fig. 1, these descriptors have been generally classified into three independent scales, namely, form (large scale), roundness (intermediate scale) and roughness (small scale) [8,9].

Currently, the descriptors of the form and roughness scales can be accurately calculated using existing algorithms (e.g., a bounding box [10] or locally weighted regression smoothing [11]). Some of these algorithms are available in several commercial morphological systems (e.g., the aggregate image measurement system, AIMS [12]). However, due to the complexity of real particle outlines, evaluating particle roundness remains a challenging task.

Particle roundness (Rd) was originally defined by Wadell [13]:

$$Rd = \sum_{m=1}^{n_{corner}} r_m / (n_{corner} \cdot R_{max}) \quad (1)$$

where n_{corner} is the number of corners, r_m is the radius of curvature of the mth corner, and R_{max} is the radius of the maximum inscribed circle.

After the definition of roundness was proposed, several manual methods for determining particle roundness were developed. The first method, suggested by Wadell [14], has been widely used in multiple research and industrial fields, including geotechnical engineering and powder engineering [15–17]. The procedure requires the following three steps: (1) identification of the corners of the particle outline by visual observation; (2) determination of a series of circles that fits inside all the identified corners by manual comparison of each corner outline with the transparent circle template; and (3) determination of the maximum circle size, known as the maximum inscribed circle (MIC), among the circles that fit inside the overall outline of the particle. The original roundness determination procedure strictly follows the initial roundness definition. However, this procedure requires a considerable amount of time and manual work. To address this limitation, several chart methods, such as the methods proposed by Krumbein & Sloss

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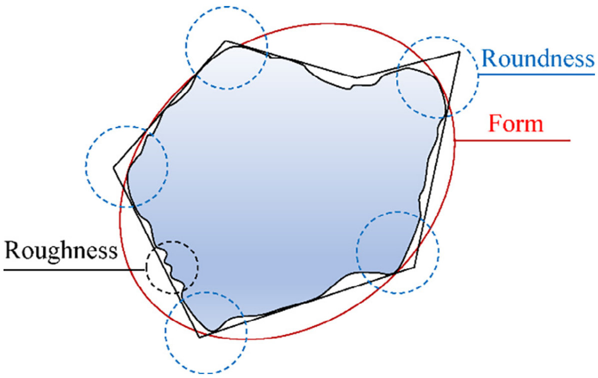

Fig. 1. Classification of particle shape features on three different scales (from Barret [8] and ISO [9]).

[18,19] and Powers [20], have been proposed in accordance with Wadell's concept. A chart method evaluates the particle roundness by comparing a particle sample with particle images in a predetermined chart. These methods are less time-consuming but more subjective than Wadell's original procedure, mainly because these methods rely on a visual comparison to match the particle of interest with projections in a chart.

In recent years, digital image processing techniques have enabled researchers to rapidly and automatically acquire the outline of a granular particle from 2D projection images. Several alternative roundness indexes have been proposed based on the 2D projection images of particles. Sukumaran & Ashmawy proposed the angularity index to characterize the roundness of sand particles based on image analysis [21]. Al-Rousan & Masad employed several angularity indexes to describe the shape of ballast aggregate; for example, they used surface erosion-dilation, fractal dimensions, the gradient angularity index and Fourier analyses [22]. Li et al. implemented a Fourier shape coefficient to quantify the sharpness of sediment particles [23]. Arasan et al. applied the fractal geometry technique to characterize particle shape by investigating the correlations between the fractal dimension and particle shape features [24]. Su & Yan included a gradient-based angularity index for general shape particles using Fourier series analysis [25]. However, their definitions are not identical to Wadell's original definition of roundness.

Recently, several researchers have attempted to develop roundness computation algorithms to compute roundness descriptors that follow the Wadell definition. Mollon & Zhao [10] employed the overlapping discrete element cluster (ODEC) technique to compute roundness globally. This method fits circles to both corner and non-corner portions of the particle outline. The degree of consistency between this algorithm and the roundness definition is not well documented. Zheng & Hryciw [26] employed computational geometry algorithms to incorporate outline segmentation into a roundness calculation. Their study verified the accuracy of the Krumbein & Sloss chart. However, in this method, the corner is not precisely identified.

On the basis of these previous achievements, the present study focuses on the development of a robust particle roundness evaluation method. The proposed method is expected to assist researchers in studying the particle shapes of granular materials and the correlation between such shapes and the engineering properties of the aggregate system. During this evaluation, boundary pixels of a particle are first extracted from the particle image by implementing the well-known Canny algorithm [27]. The continuous particle outline can be generated from these discrete boundary pixels using a B-spline curve. Then, the MIC is found using a modified ODEC method, and the best-fitted circle for each corner is identified based on the least square approach. Finally, the roundness is computed based on Wadell's definition.

2. Generation of a particle outline

2.1. Acquiring discrete points of the particle outline

The roundness evaluation process starts with particle projection, which can be accurately represented by a binarized particle image (Fig. 2a). The image can be easily acquired by various types of imaging devices and easily converted into a binarized image using one of several digital image processing tools (e.g., ImageJ, the image processing toolboxes in MATLAB, or Photoshop). In these images, pixels along the particle outline can be easily detected and extracted by implementing the Canny algorithm [27] (Fig. 2b). After extraction, the discrete points on the particle outline can be acquired, and their coordinates can also be calculated (for example, point A in Fig. 3). These discrete points are used to generate a continuous particle outline, as described in the following section.

2.2. Closed B-spline curve generation

To precisely compute the particle roundness, the continuous particle outline is first reconstructed from discrete outline points using the closed B-spline curve function. The closed B-spline curve is widely used in the field of computer-aided geometric design (CAGD) [28]. As shown in Fig. 4, a closed B-spline curve $Sp(t)$ of degree k can be generated from $n+1$ discrete outline points $p_0^o, p_1^o \ldots, p_n^o$. The parameterized function of this curve can be presented as follows [29]:

$$Sp(t) = \sum_{i=0}^{n+k} p_i N_i^k(t), \quad t \in [0, 1] \tag{2}$$

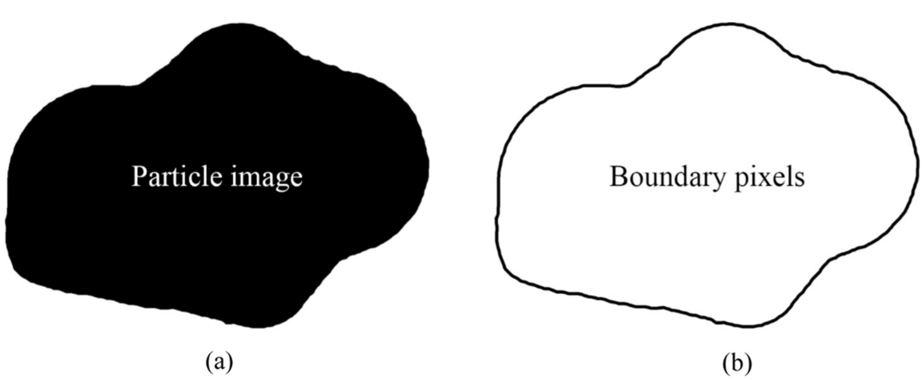

Fig. 2. (a) Binarized particle image and (b) extracted boundary pixels (the example image was randomly selected from the Krumbein & Sloss chart [32], and the outline is detected and extracted using the Canny algorithm [27]).