Powder Technology 291 (2016) 262–275

Contents lists available at ScienceDirect

Powder Technology

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

3D quantitative shape analysis on form, roundness, and compactness with μCT

Budi Zhao, Jianfeng Wang *

Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China

ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form 18 December 2015
Accepted 19 December 2015
Available online 29 December 2015

Keywords:
Compactness
Form
Reconstructed surface mesh
Roundness
Voxel assembly
X-ray tomography

ABSTRACT

Particle shape plays an important role in determining the engineering behaviour of granular materials. In this regard, characterisation and quantification of particle shape are essential for understanding the behaviour of granular materials. X-ray micro-computed tomography (μCT) enables observation of particle morphology at ever-greater resolutions. The challenge has thus become extracting quantified shape parameters from these rich three-dimensional (3D) images. In this paper, we implement X-ray μCT to obtain 3D particle morphology and utilize image processing and analysis techniques to quantify it at different scales. A novel framework is proposed to measure 3D shape parameters of form, roundness, and compactness. New 3D roundness indexes were formulated from the local curvature on reconstructed triangular surface mesh. Subsequently, this method is utilized to study the change of particle shape by single particle crushing tests on Leighton Buzzard sand (LBS) particles. It is found that compactness value (i.e., sphericity) could be influenced by both form and roundness. Then, the distributions of shape parameters are characterised by Weibull statistics. It shows that single particle crushing tests generate more irregular fragments which have smaller shape parameters with larger variance for the measured shape parameters.

1. Introduction

The analysis of particle shape and its influence on the mechanical behaviour of granular materials has been the subject in geology and engineering science for a long time. Particle shape influences attainable density, stiffness, compressibility and critical state parameters, such as critical state friction angle (e.g., [1–3]). The end resistance of cone penetration test (CPT) at a given relative density and stress level is affected significantly by particle shape [4]. On the other hand, particle damage under elevated stress levels changes particle shape, e.g. smaller particles which are less spherical, less convex and with lower aspect ratio are generated when particles suffer catastrophic splitting [5]. Numerical modelling, e.g. discrete element method and molecular dynamics method, has been shown to constitute an important way to understand the influences of particle shape on the behaviour of granular materials (e.g., [6–10]). Although comprehensive laboratory and numerical tests have been conducted, there are few techniques to predict the mechanical behaviour of irregularly shaped particles. The lack of models and correlations can be attributed to the difficulty of defining and measuring shape descriptors for a wide variety of complex particle shapes.

Most of widely implemented rules to quantify particle shape have been developed by sedimentary geologists, which are qualitative shape determinations made by two-dimensional (2D) visual classification. These methods are time-consuming and too subjective to generate parameters that could be utilized for simulating and modelling for geotechnical engineering purposes. Acknowledging these drawbacks, many researchers adopted advanced devices (e.g., optical microscopy, laser beam systems, interferometer, and X-ray μCT) and robust numerical methods to obtain more comprehensive quantitative particle shape indexes. These shape quantification methods can be divided into two groups, i.e. two-dimensional (2D) methods and three-dimensional (3D) methods.

Two-dimensional methods collect 2D projections from scanning electron microscope (SEM), optical microscopy or laser beam systems and implement digital image processing techniques to quantify particle shape. Various approaches have been proposed for characterising particle shape from the collected 2D projections. Generally, common 2D shape factors indicate the aspect ratio of two dimensions (e.g., Feret dimensions and principal dimensions) or describe the deviations of the shape of a particle from the circular shapes (e.g., the area-equivalent circle and the inscribed circle). This kind of evaluation technique has been combined with high-speed camera in many commercial 2D particle size and particle shape analysis systems, e.g., DiaInspect.OSM (Vollstädt-Diamant GmbH), CAMSIZER (Retsch Technology) and QICPIC (Sympatec GmbH). Examples of these systems' application include obtaining the database of sand particles [11] and quality control of abrasive materials [12]. Theoretical model is also shown to have significance in examining the relationship between these shape factors [13].

* Corresponding author.
E-mail address: jefwang@cityu.edu.hk (J. Wang).

http://dx.doi.org/10.1016/j.powtec.2015.12.029
0032-5910/

Recently, a novel method has been proposed to quantify roundness, a scale dependent variable, by fitting circles to the identified corners of a particle outline [14]. A more complex and theoretical method, Fourier mathematical method, has also been developed. It was found that Fourier descriptors, which are determined by taking the Fourier transformation of the outline of sand particles, were closely related to shape factors [15,16]. Although 2D methods can characterise and quantify shape characteristics, noticeable difference between 2D and 3D shape indexes have been found [17,18]. Indexes based on 2D projects may highly depend on the choice of observing directions, which will result in non-unique shape descriptors for a given individual particle.

Three-dimensional particle morphology is usually measured by X-ray μCT or 3D laser scanner, and then processed to retrieve particle surface information. Image analysing methods are implemented to quantify particle shape from the surface information. In general, these methods could be classified into three groups. The first one has been performed on voxel assembly to obtain particle orientation, principal dimensions, volume and surface area [17–19]. This method usually leads to a large variance in estimated surface area due to the fact that different types of boundary voxels are not well distinguished and classified. This problem has been solved by identifying the local configuration of each boundary voxel using Marching Cubes algorithm, and assigning a surface area weight to each configuration [20]. The second method is based on reconstructed surface, which is composed of triangular surface meshes. It can be obtained by a three-dimensional laser scanner [21] or performing Marching Cube algorithm on voxel assembly [19]. The triangular mesh surface provides a more accurate representation of particle surface than the voxel assembly, which resulted in a more precise surface area estimation. A more complex and theoretical method performs 3D spherical harmonic analysis to mathematically characterise the morphology of particles, and then calculates shape factors [22–27]. However, it does not seem to provide an efficient way to obtain shape descriptors after applying complex algorithms to approximate the morphology of particles.

The aim of this work is to perform comprehensive 3D particle shape quantification at different shape scales. We first introduced a framework to quantify 3D particle shape with X-ray μCT images. A series of image processing techniques were used to generate voxel assembly and reconstructed surface mesh to characterise particle morphology. Then image analysis techniques were implemented on reconstructed surface to quantify particle shape, specifically on form, roundness and compactness. Secondly, this framework was applied to analyse the morphology change made by single particle crushing tests on Leighton Buzzard sand (LBS) particles. The shape parameters of LBS particles and LBS fragments were characterised statistically.

2. Methodology

X-ray μCT and 3D laser scanner are two common instruments that can be used to acquire 3D surface information for particle shape analysis. Due to the limited resolution, 3D laser scanner is not suitable for small sand particles, e.g. 1 mm–2 mm LBS particles measured in this study. Therefore, we implemented X-ray μCT scanning to obtain 3D grey-level CT images. These images were put through a series of image processing and analysis methods to obtain different 3D particle morphology data and shape factors, respectively. This procedure is

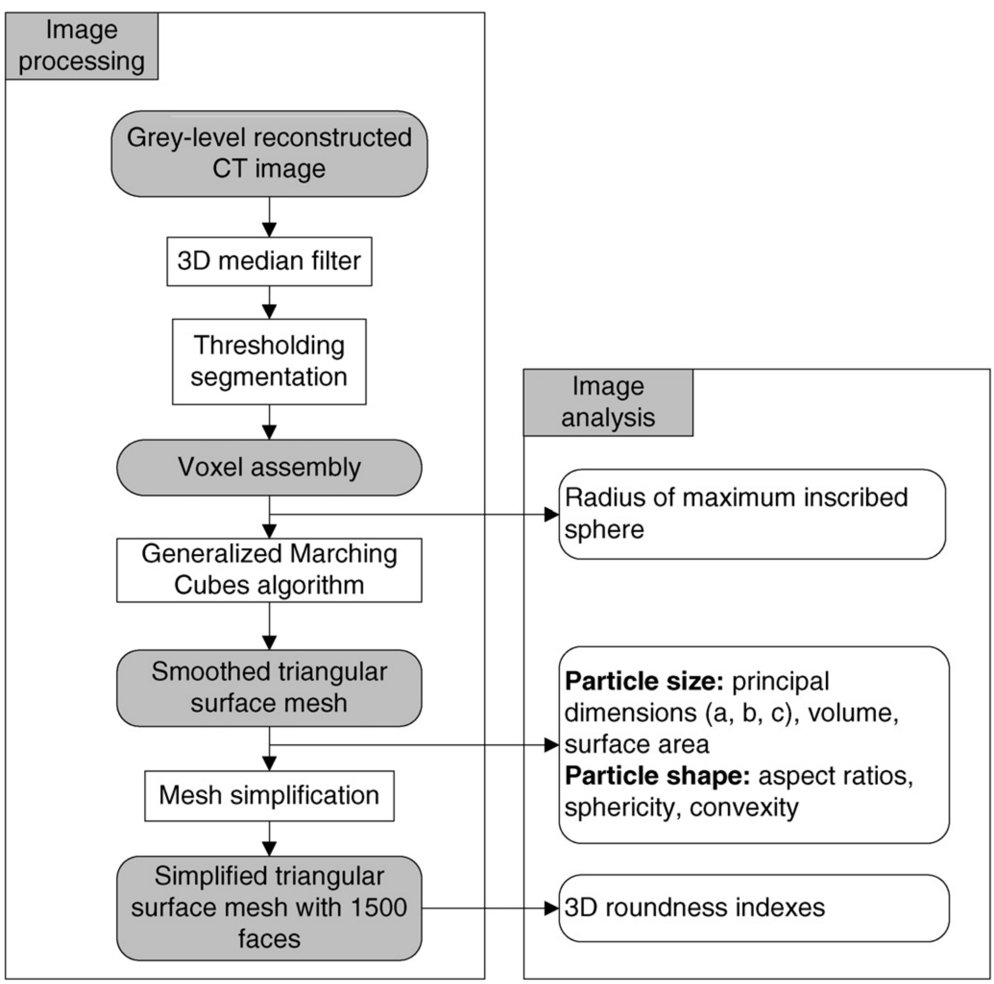

Fig. 1. Flowchart illustrating image processing and analysing with X-ray μCT images.