Particuology 25 (2016) 23–35

Contents lists available at ScienceDirect

Particuology

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

Quantified evaluation of particle shape effects from micro-to-macro scales for non-convex grains

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ARTICLE INFO

Article history:
Received 28 July 2014
Received in revised form
20 November 2014
Accepted 30 January 2015
Available online 22 June 2015

Keywords:
Quantitative analysis
Shape factor
Statistical analysis
Micro–macro indexes

ABSTRACT

Particle shape plays an important role in both the micro and macro scales responses of a granular assembly. This paper presents a systematic way to interpret the shape effects of granular material during quasi-static shearing. A more suitable shape descriptor is suggested for the quantitative analysis of the macroscale strength indexes and contact parameters for non-convex grains, with special consideration given to the peak state and critical state. Through a series of numerical simulations and related post-processing analysis, particle shape is found to directly influence the strain localisation patterns, microscale fabric distributions, microscale mobilisation indexes, and probability distribution of the normalised contact normal force. Additionally, the accuracy of the stress–force–fabric relationship can be influenced by the average normal force and the distribution of contact vectors. Moreover, particle shape plays a more important role than do the confining pressures in determining the friction angle. Strong force chains and the dilation effect are also found to be strongly influenced by the high confining pressure.

Introduction

Particle shape can directly influence the structural features of granular assemblies, which ultimately control the mechanical properties of the granular material. Generally speaking, the peak friction angle and the peak dilation angle of circular disks (2D) or spheres (3D) are significantly lower than those of natural sand, which has an irregular particle shape. Many previous studies have aimed to determine the shape effect of granular materials. Two main approaches exist for investigating the shape effect. The first approach is to establish the rolling resistance model (Iwashita & Oda, 1998; Jiang, Leroueil, Zhu, Yu, & Konrad, 2009; Jiang, Yu, & Harris, 2005). However, the real rotation mechanism (instead of an artificial mechanism) is constrained by the particle's geometry, which may induce an asymmetric stress tensor for an individual particle. The second approach generates an appropriate model of the grain shape, in which the modelling geometry of the irregular particles can be divided into two main groups by contact: (1) a smooth-convex shape and (2) a non-convex shape. Smooth-convex particles can be generated using arbitrary functions or superquadric formulations based on previous work. The simplest smooth-convex shape is an ellipse. An ellipse shape has been used in many studies (Ng, 1994; Rothenburg & Bathurst, 1992). The non-convex particles can be formed by polygonal (Mirghasemi, Rothenburg, & Matyas, 2002; Seyedi Hosseininia, 2012) or by combining clusters (Abedi & Mirghasemi, 2011; Lu & McDowell, 2007; Jensen, Bosscher, Plesha, & Edil, 1999). Some advanced engineering techniques (Digitial, SEM, and X-ray) and robust algorithms have also been applied to establish realistic microscale particle geometry for the three-dimensional (3D) condition (Fu et al., 2006, 2012; Wang, Park, & Fu, 2007a; Alonso-Marroquín & Wang, 2009; Ferellec & McDowell, 2010; Liu et al., 2013; Williams, Chen, Weeger, & Donohue, 2014). There is no doubt that real physical grains are 3D in geometry; however, more artificial assumptions are required in the realistic geometry algorithms. Additionally, 3D simulations require significantly higher-performance devices, or even parallel analysis. Many previous studies have demonstrated that a 2D discrete element model can adequately capture various complex mechanical features of granular materials (Rothenburg & Bathurst, 1989, 1992; Ng, 1994; Luding, 2005; Jiang, Yu, & Harris, 2006; Wang, Dove, & Gutierrez, 2007b; Abedi & Mirghasemi, 2011; Seyedi Hosseininia, 2012, 2013; Zhou, Huang, Wang, & Wang, 2013; Jiang, Chen, Tapias, Arroyo, & Fang, 2014). Moreover, the visual deformation patterns and force chains are easily captured by 2D analysis; therefore, this study uses 2D numerical simulations, which are sufficient for the fundamental study of the physical and mechanical properties of

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http://dx.doi.org/10.1016/j.partic.2015.01.008

the granular assemblages. The authors here choose combining clusters to generate non-convex particles for the shape effect analysis, which can lead to a better understanding of the problem.

Although non-convex particles are well recognised in the real granular world, they are still not fully understood either on a laboratory experimental scale or through simulated numerical methods, particularly for quantitative analysis. A quantitative analysis study is thus important to understand the more detailed behaviour of granular materials. Many different quantitative shape descriptors have been proposed for this purpose in previous studies (Cho, Dodds, & Santamarina, 2006; Sukumaran & Ashmawy, 2001; Ehrlich & Weinberg, 1970; Powers, 1953; Krumbein, 1941; Wadell, 1932), but very few comparisons of mechanical properties are performed on these common particle shape definitions, particularly for non-convex shapes. In the present study, eight different particle shapes are evaluated using four quantitative shape descriptors to address this insufficiency. This methodology provides an additional approach for a suitable and adequate shape index. Next, quantitative relationships between particle shape and strength indexes are investigated. In addition, the patterns of strain localisation for different shapes are captured. The relationships between particle shape and microscale fabric parameters are also evaluated at the peak state (peak stress ratio $\left(\frac{\tau_f}{\sigma_n}\right)_{\max}$ and critical state (stress ratio $\left(\frac{\tau_f}{\sigma_n}\right) = \text{constant}$). Moreover, the accuracy of stress–force–fabric (SFF) (Christoffersen, Mehrabadi, & Nemat-Nasser, 1981; Rothenburg & Bathurst, 1989; Guo & Zhao, 2013; Li & Yu, 2013; Seyedi Hosseininia, 2013) is investigated, with special consideration of the accuracy of average contact normal forces and the distribution of contact vectors. In this paper, an evaluation of particle interlocking effects from peak state to critical state is also presented to address the particle shape effect using a probabilistic approach (Zhou et al., 2013). The distributions of force chains for different shapes are also compared quantitatively by the shape descriptor. The inter-particle force network is a striking feature that determines the mechanical properties of granular mass (Radjai, Jean, Moreau, & Roux, 1996; Sun, Jin, Liu, & Zhang, 2010). It can be used to describe the strength variation at critical state in a microscale model. Additionally, the authors find that the relationship between the strong force network and the confining pressures can explain the decrease in the strength indexes with the increased confining intensities.

This study presents a comprehensive analysis of particle shape effects using the discrete element method (DEM), which captures the micro mechanical behaviour of the granular assembly. Section 2 of this paper describes the definitions for the particle shape indexes, which are analysed and compared in a later section. The general formulation of the SFF relationship is also briefly introduced in this section. Next, the DEM simulations and results for the biaxial drained tests are given in Section 3. Quantified macroscopic and microscopic responses are also interpreted by the shape index in this section. The main conclusions of this study are presented in the final section.

Particle shape description and SFF relationship

Using the DEM method, rigid particles with soft contacts can be used to reflect the contact geometry and evaluate the fundamental features of a cohesionless material. Seven non-convex particles are employed in the present DEM analysis, where each irregular particle is expanded using a standard element to prevent incorrect moments of inertia. Hence, the combined clump density is modified and reassigned $\left(\rho_{\text{clump}} = \frac{V_{\text{clump}}\rho_{\text{disk}}}{V_{\text{overlap}}+V_{\text{clump}}}\right)$. Next, the numerical results are compared. The particle shape categories are shown in Fig. 1(a) and Table 1. Four simple quantitative shape indexes

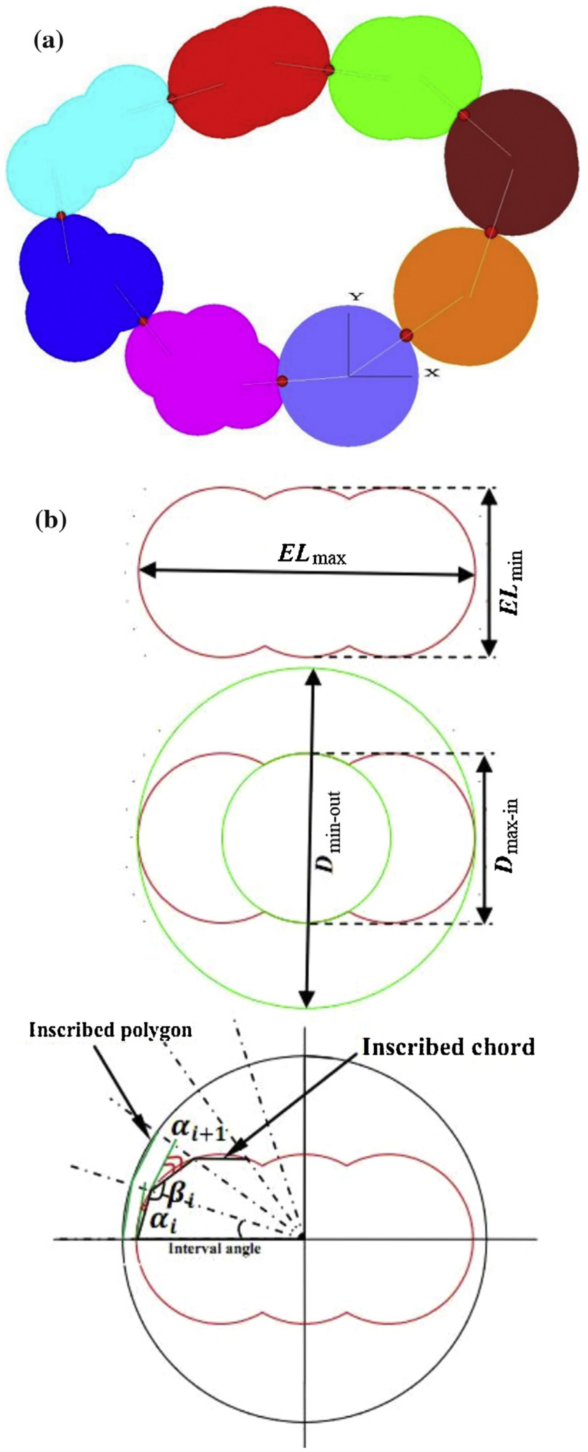

Fig. 1. (a) Schematic of the particle shapes; (b) illustration of different particle shape indexes.

Table 1
Quantitative value of the shape indexes.

Category	Aspect ratio	Circularity	SF (%)	AF (%)
Circular	1.0	1.0	0	0
Elongated1	0.952	0.952	4	0.1
Elongated2	0.909	0.909	8	0.4
Elongated3	0.80	0.80	19.8	1.9
Elongated4	0.667	0.667	33.3	3.88
Elongated5	0.50	0.5	45.8	13.2
Triangular	0.957	0.722	34.5	10.4
Rhombus	0.804	0.710	35.1 (N=40) 33.6 (N=80)	12.9 12.96