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Exploring the contact types within mixtures of different shapes at the steady state by DEM

Y. Yang [a,b,*], Y.M. Cheng [c], J.A. Wang [d]

[a] Department of Civil Engineering, Chu Hai College of Higher Education, Hong Kong, China
[b] State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xu Zhou, China
[c] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China
[d] School of Civil and Environmental Engineering, University of Science and Technology Beijing, Beijing, China

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ABSTRACT

A series of numerical tests on the quasi-static deformation of dense granular media by the discrete element method (DEM) are performed to investigate the behaviour of mixtures of shapes that are composed of round and non-convex (elongate) particles. Four representative contact types, which are classified into circle-circle contacts (CC), circle-elongate contacts (CE), simple elongate-elongate contacts (EE1) and multiple elongate-elongate contacts (EEm), are studied with respect to the macroscopic granular mechanical responses. It is found that the contact force ratio (K) of these four contacts can be considered to explain the variation of the steady friction angle. Another interesting finding is that the probability density function (PDF) of friction mobilisation (I_m) for the CE contacts is insensitive at the mixture of 30%–60% elongated particles. However, the PDF curves of the normalised contact forces of EE1 and EEm show a nearly linear increasing relationship with the increased percentage of Elongated particles. It should be point out that the variation of the contact normal anisotropic coefficient is insensitive with the contact portions of EE1 and EEm in this study.

1. Introduction

Granular materials, such as gravel, sand, rock and asphalt are quite common media in civil engineering. Due to their inherent discontinuous and heterogeneous feature, the mechanical responses of these materials are rather complicated. Moreover, they can also be influenced by many factors such as particle size distribution, grain mineralogy, grain surface texture, particle shape and others. Comparing with other affected factors, the role of particle shape within the sand deformation process is much more difficult to describe [1]. Previous studies have shown that particle shape can mainly control both the macro- and microscales behaviour of a granular assembly. From a macroperspective, many researchers have found that the strength properties of granular materials are highly related to the particle shape. This point has been verified from both experimental tests and numerical simulations [2–7]. Moreover, granular packing density can be influenced by particle shapes. Abbireddy and Clayton [8] performed a series numerical tests to explore the relationship of initial void ratios and particle shape, which can influence the maximum and minimum void ratios of a granular packing. Other investigations have also been carried out to explore the relationship between particle shape and packing density [2,4,8–10]. Furthermore, both the static and dynamic liquefaction can be influenced by the particle shape [11,12]. From a micro perspective, particle shape can influence the contact force distribution [4,13]. Meanwhile, the global average value and the probability density distribution of the friction mobilisation can also be influenced by particle shape effect [14]. In addition, the statistics of micro-anisotropic coefficient are highly depend on the particle shape [4,14–16].

The natural sand is made of different particle shapes and sizes. Particle size distribution and particle shape can both influence the mechanical behaviour of granular materials. Many of previous studies seldom solely studied on the influence of particle shape, where the coefficient of uniformity (C_u) is not fixed. This would induce some certain level confusion that we cannot obtain a precise relationship between particle shape and macromechanical parameters [1]. Since particle grading may also influence the macroresponses. Normally, the mechanical behaviour of these binary shape mixtures is very complicated and highly nonlinear. Some laboratory tests are also proposed for identifying the characteristic response of these binary shape mixtures. Shin and Santamarina [3] performed useful laboratory tests to study the mechanical response of sand mixtures made of round and irregular sands under lower confining stress, where the crushing effect can be ignored. Although the mean size (D_{50}) of all tested sands keeps the same, there still exists a small variation of C_u value from 1.2 to 1.9. Recently Yang and Luo [1] propose a

* Corresponding author at: Department of Civil Engineering, Chu Hai College of Higher Education, Hong Kong, China.
E-mail addresses: cseyangy@chuhai.edu.hk, yi.yang.cse@connect.polyu.hk (Y. Yang).

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much more reasonable laboratory scheme to study the binary mixtures of the Fujian sand and glass beads with the same grading Cu by both undrained and drained triaxial tests. And the relationship between particle shape and granular strength properties is reasonably constructed. However, these traditional experimental devices cannot provide a full view from both microscale and macroscale. Even for some advanced and expensive imaged devices such as X-ray CT cannot capture the accurate contact force distribution within the irregular grains [17,18] . The DEM proposed by Cundall and Strack [19], which is adopted in this paper, is an alternative and economic approach to investigate the mechanical responses of binary shape mixtures under both microscale and macroscale.

The aim of this paper is to study the relationship between the macroscopic strengthen parameters and the microscopic statistical data for different particle shape mixtures under biaxial loading procedure, where the mass portion of elongated grains (η_m) is varied from 0.0 to 1.0. Moreover, the crushing effect is ignored throughout the loading procedure. The effect of shape will hence be more clearly reflected in this study. The traditional statistical information [20] for the whole domain cannot explain effectively the sudden, unpredictable macroresponse. To achieve better modelling of the macrobehaviour, some descriptors defined under the deeper micro scales are considered. There are two major ways to this approach: using the contact cycles (loop) [21,22] or contact types [4,14,23–25]. These approaches are all mesoscopic structures, and can be considered to explore the mechanism of the load resistance and self-organisation within the granular systems. Compared with the contact loops, the contact types are easier to determine. Therefore, the authors here employ different contact types to explore the micro statistical information. Four respective contact types including circle-circle contacts (CC), circle-elongate contacts (CE), simple elongate-elongate contacts (EE1) and multiple elongate-elongate contacts (EEm) are proposed to describe the overall responses. In a mixture of packed shapes, the development of these contact types with the associated force chains, mobility and fabrics is interesting and can enhance our understanding of the granular media in a deeper scale.

In the following sections, we first give a brief introduction to the basic information about the samples and contact types. Then, some macrosimulation results are presented. Afterwards, the detailed force chains distributions, friction mobilisations and fabrics are explored using the four respective contact types with different η_m. Finally, the main conclusions of this study are presented.

2. Brief description of numerical samples

In the current study, the linear contact model in PFC 2D is adopted to evaluate biaxial shear tests for these binary shape mixtures samples [26]. Fig. 1 is the schematic illustration of the two mixture shapes. There are 11 samples generated with η_m (mass portion of the elongated particles) varied regularly between 0.0 and 1.0. In the present numerical simulation. The numerical sample initially contains 9506 circular particles with dimensions of 100 mm (W) × 200 mm (H). Particle size distribution (PSD) and four proposed contact types are shown in Fig. 2. Additionally, the mean particle diameter D_{50} is 1.5 mm with a uniformity coefficient $C_u = 1.47$. After the target initial porosity (0.16) is obtained through the iterative servo controls, the elongated particles will

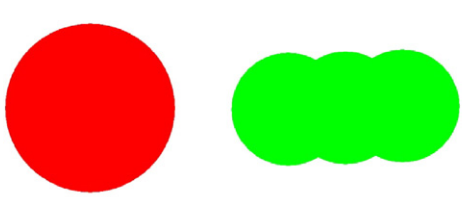

Fig. 1. The two shapes used for the mixture analysis.

subsequently replace the initial disk with an equivalent area and the same centre location to generate the mixture samples. The orientation of the Elongated particles is arbitrarily distributed in the range of 0° and 360°. Each replacement also iterates to the balance state in the analysis. And the aspect ratio and circularity of particle shape indexes are both equivalent as 0.5 for the current elongated particles. The current numerical sample generation procedure has been introduced by the authors [13] for studying the accuracy of stress-force-fabric (SFF) relationship within the highly irregular granular packings, where the contribution of contact vectors or branch vectors cannot be ignored. Due to the large particle number in this study, the subsequent replacement of circle particles with Elongated particles can nearly generate a homogenous distribution. Moreover, the gravity is ignored to avoid force gradients, and the isotropic stress is gradually increased to the target confining pressure (100 kPa). All of the mixture samples are prepared using the same procedure. The isotropic samples of shape mixtures are then subjected to vertical compression under a constant strain rate of 5% per minute. This slow loading rate would ensure the whole deformation procedure is under the quasi-static condition [27]. The confining stress on the lateral walls is constant. All of the simulations in this paper are maintained in a plane-strain condition. The linear contact model with local non-viscous damping is considered throughout this paper. Generally, the selection of contact model also requires careful consideration. For the collision and small strain problems, the difference between the linear contact and non-linear contact model is obvious [28]. However, the numerical specimens in the current study are all in the process of quasi-static behaviour with the emphasis on the mechanical response at the steady state, where the small strain response is ignored in all our simulated tests. And the contact stiffness inside the nonlinear Hertz-Mindlin model varies as the contact force and the relative normal displacement in every numerical step, which would reduce the computing efficiency [29]. Moreover, previous investigation [30] has pointed out that choosing a suitable magnitude of the linear contact stiffness will show a similar macroscopic behaviour as that for Hertzian, especially on the large strain response. Furthermore, recently many researchers still adopt linear contact models to accurately represent the mechanical responses of granular materials [6,8,13,27,29,31–37]. And therefore, for simplicity, the authors would adopt the linear contact model throughout the present numerical tests. Additionally It is well known that only sliding mechanism is unable to control the granular packing within a quasi-static system, therefore, local non-viscos damping is artificially introduced to avoid the non-physical vibrations that develop at the contacts. Detail discussion on the damping model has been investigated by O'Sullivan [28]. The values of the DEM parameters in the current paper and previous publications are provided in Table 1. Regarding the selection of input parameters, some previous researchers proposed qualitative formulas to construct the relationship between the input contact normal stiffness (K^n) and the elastic contact modulus from 2D to 3D.

$$\begin{cases} K^n = \dfrac{\pi}{20} E^* t, E^* = \dfrac{E}{2(1-\nu^2)} & \text{2D Cylinder (Li 2006)} \\ K^n = 2Ed & \text{3D Sphere (Minh and Cheng 2013)} \end{cases} \quad (1)$$

where E^* is the contact elastic modulus of two identical entities, E and v are material Young's modulus and Poisson's ratio, t is the thickness of the 2D disk particles, and d is particle diameter. In the current 2D simulations, the thickness is set as the default value 1 m. From Eq. (1) the input contact stiffness value under 2D condition is insensitive with particle radius. So the selected magnitude of contact normal stiffness 1×10^8 N/m is nearly close to the characteristics of a granular material with $E = 1$ Gpa and $v = 0.2$. Nevertheless, the selection of the magnitudes of contact stiffness is somewhat arbitrary and it may vary in orders as shown in Table 1. Actually, many DEM studies are still carried out to explore the general aspects of material response without having a direct connection with a real granular material [28]. Regarding the