Microscopic Geometrical Characteristics of the Granular System and the Evolution Rules under Complex Loads

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Abstract—An accurate quantification of the grains’ arrangement and structure is the key to establish the relationship between microscopic and macroscopic properties for granular media, which is also of vital importance for precisely predicting macro-deformation and mechanical behavior using the system’s microscopic properties. In order to further reveal the structural characteristics of the granular media, a special loading device was designed and developed; then, the polycarbonate disk grains with the diameters of 3 mm and 5 mm were prepared for photo-elastic tests under complex loads. The relationship of the distribution frequency of the contact angle between grains with grain scale, grain combination as well as the magnitude and direction of the external load was explored. Results reveal that: (1) for granular media consisting of a single component, the geometrical structure shows obvious initial anisotropy without the application of load, the initial structure determines the transfer of force in the granular system; during the shearing process, the frequency distribution of the contact angle increased significantly along the directions of great main stresses but decreased along the directions of small main stresses. (2) for the mixed granular system consisting of grains with two different diameters, the anisotropy was not obvious, whether under initial conditions or under compression and shearing loads.

Index Terms—granular medium; geometrical characteristics; contact angle; photo-elastic test

I. INTRODUCTION

Granular matter mechanics is a science that focuses on the equilibrium and motion laws of the complex system consisting of a great number of discrete solid particles and the related applications. In this complex system, the particles, with the diameter over 1 μm (d>1 μm), interact with each other and the interstitial fluid and show low viscosity and saturation (the saturation is generally smaller than 1, i.e., S<1); additionally, the strongly dissipative contact friction dominates the interaction among these particles, while the thermal motion can be neglected [1], [2]. For last two decades, researchers began to notice the fine mechanical behavior in the granular matter system and focused on the physical mechanisms behind them [3], [4]. In the granular system’s multi-scale structural framework, both the theoretic studies based on the contact mechanics of solid particles and the numerical simulation methods based on discrete element method have achieved great progress [5]-[8]. The researchers have made breakthroughs in dissipative particle gas, granular discrete element, mixing & grading, vibration and shear dynamic mechanisms [9]-[11]. However, it was also realized that solid mechanics based on continuum hypothesis falls short in explaining the granular matter’s mechanical behavior, and the phenomenological relations based on macroscopic prototype tests cannot take into account the effects of a single grain’s physical properties [10], [12].

The test methods and techniques of the granular matter’s internal stress and strain are particularly important in validating theoretical and numerical calculation results and exploring the interaction mechanisms in the granular matter. Photo-elastic testing may be the only one experimental measure so far that can visually reveal the internal force distribution in granular matter [6], [13]-[15].

In 1957, Dantu first used photo-elastic technique to observe force propagation model in the granular matter. Oda et al. focused on the two-dimensional (2D) pillared photo-elastic materials and investigated the contact force distribution, fabric change and anisotropy in 2D granular materials [16]. Nagel, S R and Majumdar, S [17] simulated the non-uniform distribution of force in a granular pile and found the load’s exponential decay
law when the internal force between the grains exceeded the average contact force. R. R. Hartley and R. P. Behringer [18] constructed a 2D shearing system using a photo-elastic disk and then conducted slow shear tests on the granular material to examine the correlation between stress and shearing rate. They found that the average stress showed a logarithmic relationship with the shearing rate in plastic deformation, and the increase of shearing rate would lead to the increase of the strength of force chain network and the fluctuating amplitude of stress, and simultaneously change the distribution rules of stress concentration and relaxation. Through photo-elastic disk tests on the granular system, T. S. Majmudar and M. Sperl [19] verified that the average coordination number increased rapidly when the model’s volume fraction reached the critical value; as the model’s volume fraction exceeded the critical value, the average distribution number and uniform load increased exponentially with the volume fraction. R. W. Yang and X. H. Cheng [20] focused on a mixed granular system that was composed of two kinds of grains with different diameters and also used photo-elastic tests for preliminary research of the system’s force chain distribution and the geological structure change under 2D direct shear tests; then, they processed the photo-elastic experimental results using digital image technology, attempted to characterize the bearing force on the granular materials using color gradient algorithm and acquired the force chain with average strength.

As stated above, these studies regarding granular materials based on photo-elastic tests have greatly advanced the development of granular dynamics in both theory and numerical calculations [14], [21], [22]. For gaining a better understanding of the granular system’s geometrical features, this study designed and developed a compressive/direct-shearing loading device for photo-elastic granular materials. Two kinds of polycarbonate disk grains with two diameters—3 mm and 5 mm, were processed, and the photo-elastic tests were performed on these granular media. The granular medium’s geometrical characteristics and evolution patterns under complex loads were investigated by statistically analyzing the relationships of contact angle with grain size, grain configuration, external load’s magnitude and direction.

II. EXPERIMENTS

A. Experimental Model

(1) In order to study the photo-elastic grains with high-transparency, small size and excellent photosensitivity, this study used polycarbonate sheet with a thickness of 5 mm produced in Japan; then, using the numerical-control (NC) carving machine for plastics, the disks with the diameter of 3 mm and 5 mm were cut out. Since the cutting face is parallel to the light direction, the propagation of light is not affected by the processing and the processed disks were characterized by high transparency. High machine stress was produced at the edge of grains during the cutting process, and therefore, annealing should be performed on the polycarbonate disks for eliminating the machine stress.

(2) In order to overcome the shortcomings of the existing photo-elastic experimental system, this study made use of the advantages of a digital photo-elastic device, as well as designed and developed a special loading device suitable for this work. As shown in Fig. 1, the device is light and convenient so that small grains can be easily placed in it; moreover, the planar photoelastic compression tests, shearing tests and the related simulations of engineering structures can be conducted using this device.

![Figure 1. Illustration of the developed loading device](image)

1-Shell frame; 2-Base; 3-Digital display instrument; 4-Upper shell of the container; 5-Lower shell of the container; 6-Axial loading system; 7-Shearing loading system; 8-Axial loading screw; 9-Shearing loading screw; 10-Cover plate for loading; 11-Screw for lateral fixing; 12-Sliding rail board; 13-Rolling block; 14-Wire for data transmission; 15-Pin; 16-Photo-elastic granular medium

![Figure 2. Schematic diagram of the test device](image)

B. Experimental Setup and Procedures

(1) Experimental setup

The granular materials are with a diameter of 5 mm and 3 mm, respectively; and amixof these two disk grains wasselected for this study. The materials were put into the above-described experimental device; then, compression and shearing were applied for investigating the materials’ photo-elastic properties under complex loads. The acquired photo-elastic pictures were then processed using mean square grayscale (color) gradient method and image digitalization technique.

(2) Experimental procedures
Firstly, after annealing, the disk grains with a diameter of 3 mm were manually placed in the container in a random way, during which the smooth surface of the granular material should be parallel to the loading box’s glass plate. Then, the container was placed in the loading device, with

the loading device and the loading box parallel to the photo-elastic device’s lens, and the loading box located at the center of the photo-elastic device’s optical source. Next, the axial loading screw was rotated so that the loading cover plate was exactly touching the disk grains. At that moment, the test started and the digital display instrument was reset.

The positive loading was applied by slowly rotating the screw at a speed of 2 mm/min. The positive load and displacement were recorded once after each advance for a certain distance; meanwhile, two pictures were taken, a photo-elastic picture of the granular materials under dark conditions and another showing the geometrical positioning of the disk grains. At that moment, the test started and the digital display instrument was reset.

Similarly, the photo-elastic tests under shearing action were then performed.

For the disk grains with a diameter of 5 mm, the above steps were repeated in order to investigate their microscopic structural properties.

Finally, for the mixed disk grains, the same steps were performed.

III. RESULTS AND DISCUSSION

The pictures of the granular media after the removal of rotationally polarized lens were then processed using image processing software, and the distribution frequencies of the grain’s contact angle for different grain sizes, grain configuration sand load under compression as well as the combined action of compression and loading were investigated.

A. Evaluation Laws of the Contact Angle between Grains under Different Compression Loads

(1) Results for the disk grains with a diameter of 3 mm

As stated above, the disk grains with a diameter of 3 mm were put into the container, and the positive loads were applied by rotating the axial loading screw. The pictures under the positive load of 0 N, 30 N, 50 N and 70 N were selected for statistical analysis of the contact angle, as the results is shown in Fig. 5. Since the contact angles were symmetrical, the contact angles within the range of 0~180° were selected and 9° intervals were set as the analysis range. The angles with the frequencies no smaller than 0.018 were defined as the polarized angles, and the polarized angles under the initial state were defined as the initial polarized angles.

(a) under a positive load of 0 N
(b) under a positive load of 30 N
(c) under a positive load of 50 N
(d) under a positive load of 70 N

Due to the effects of boundary and sample loading, the frequency distribution of the contact angle between grains in each angle range shows strong randomness. Therefore, in this study, we neglected the specific values of frequency but focused on the overall evolution patterns of the frequency distributions of the contact angle, as the results shown in Fig. 6.
greatly from the distributions along the other directions, suggesting that the grains show obvious initial anisotropy in the overall geometrical structure.

(3) As shown in Fig. 6 (b), with the increase of positive compression load, the frequency of the contact angle along the vertical direction increased rapidly while decreasing to varying degrees along the other directions, suggesting an enhanced anisotropy in granular medium’s geometrical structure. However, as shown in Fig. 5(c), the frequency distribution of contact angle shows a different tendency with the increase of applied load. The deformation of grains and slippage and dislocation between the grains can be observed under a large load, which further caused the compaction and recombination of grains and thereby changed the variation tendency of geometrical structure.

B. Results for the Disk Grains with a Diameter of 5 mm

The pictures under the applied loads of 0 N, 50 N, 100 N and 150 N were selected for analyzing the variation tendency of the distribution frequency of the contact angle, with the results shown in Fig. 6.

![Figure 6. Overall variation tendency of the frequency distribution of the contact angle between the grains with a diameter of 5 mm](image)

(1) It can be observed that, for the grains with a diameter of 5 mm, their geometrical structure shows obvious initial anisotropy; however, the polarized angle ranges increased and the distribution appeared to be an eight-pointed star. The grains with a diameter of 5 mm differ greatly from those with a diameter of 3 mm in the contact angles with higher frequencies.

(2) With the increase of load along the vertical direction, the frequency of contact angle increased significantly along the vertical direction or in the polarized angle range near the vertical direction, but decreased significantly along the horizontal direction. With increasing load, the frequency distribution of contact angle almost remained unchanged, which is unlike the variation tendency of the grains with a diameter of 3 mm. This is due to the fact that, as the grain diameter increased, slippage and dislocation between the grains occurred was reduced due to the limitations of model size, and accordingly, the entire grain system was difficult to be recombined. 3. Results for the mixed grains at a ratio of 3-mm grains to 5-mm grains of 2:3

The grains with the diameters of 3 mm and 5 mm were mixed at a ratio of 2:3, and then randomly placed in the container. The positive load was applied by rotating the axial loading screw, and the pictures under the positive loads of 0 N, 50 N, 100 N and 150 N were selected for statistical analysis of the contact angle, with the results shown in Fig. 7.

![Figure 7. Overall variation tendency of the frequency distribution of the contact angle between the mixed grains](image)

(3) As shown in Fig. 8, for the mixed grains, the contact angles show quite a different frequency distribution with respect to the results for the grains with a single component. Specifically, the polarized angle ranges decreased in number, and the difference of the distribution frequency between the polarized angle ranges and the non-polarized angle ranges decreased. The overall distribution pattern falls in between a six-pointed star and an eight-pointed star; overall, the grains show no obvious anisotropy in geometrical structure.

(4) With the increase of load, the distribution frequency of the contact angle within the polarized angle range decreased gradually rather than increased; the number of polarized angles also decreased. Finally, as reflected by the contact results, the grains show approximate isotropy in geometrical structure. Through experimental observations, for the mixed granular media consisting of two grains with different diameters, the slippage and dislocation between the grains more easily occurred, i.e., the smaller grains more easily moved to the gap between larger grains.

IV. CONCLUSIONS

(1) For the granular media consisting of a single component (i.e., the grains with an identical diameter), the contact angle distribution implies that the internal structural characteristics are uniform and symmetrical and appears to be a six-pointed star along several directions. This suggests that the granular system’s overall geometrical structure shows an obvious initial anisotropy. This anisotropy was increased gradually after the application of compression loads, with the initial anisotropy important for determining the evolution of the system’s geometrical structure after the application of load (the contact angle distribution remained unchanged in pattern, but the frequency distribution in the initial polarized angle ranges increased).

(2) For the granular media consisting of a single component, under the application of shearing load, translation, rolling-over and climbing can be observed. The geometrical structures show significant changes, the frequency distributions of the contact angles increased remarkably along the large main stress directions but decreased steadily along the small main stress directions,
and the outer contour changed from approximate circles to ovals.

REFERENCE


