

Evolution of the particle shape of sands under ring shear

Jianqiao He^{1,2,3 a}, Houzhen Wei^{1, b}, Jianjun Wang^{2 c}, Huodong Chen¹

¹State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan

²Guangxi Road and Bridge Engineering Group Co.,Ltd, Nanning

³University of Chinese Academy of Sciences, Beijing

^aHejianqiao957@163.com, ^bhzwei@whrsm.ac.cn, ^c625445306@qq.com

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Abstract: The particle shape is a key factor in the strength and compatibility of granular material. To investigate the evolution of the particle shape of two kind of sands. The quartz sand from Fujian and the calcareous sand from the South China Sea, were chosen for ring shear tests. The sieving method and laser grain-size analyzer were used to obtain the particle size distribution, and the microscope technique were employed to characterize the particle shape in terms of roundness and flatness. The experimental results indicate that the change of the particle size of the calcareous sand is more significant than the quartz sand. The roundness and flatness of the calcareous sand particles decreased obviously while the roundness of the quartz sand was scarcely changed and the flatness increased. It is shown that the large displacement shear makes the calcareous sand more rounded and quartz sand more roughed.

Introduction

The porous media in the soil consists of grain skeleton and pore. The pore and embedding effect were effected by particle size and shape, thereby impacting the mechanics and distortion characteristic.

Due to the importance of the particle shape, the researchers studied on the shape of non-cohesive soil. fractal theory had been employed first to obtain information on the shape of granular materials by L. E. Vallejo[1]. With image processing tool of matlab, the shape of calcareous sand was analyzed by Chen & Wang[2]. It proposed that fractal dimension of calcareous sand was between 0.95 ~ 1.07. A preliminary study of measurement and evaluation of two sets of limestone grain shapes were examined by Zhang[3]. It found the parameters of length-width ratio, flatness and sphericity could more sensitively reveal the differences. E. T.Bowman[4] analyzed the particle morphology was quantifiably described by use of complex Fourier analysis. It found that breakage of particles by crushing was shown to affect the morphological signature differently depending on the type of sand. With an increase in the level of abrasion, the shape fractal dimension number decreased in value and the fragmentation fractal dimension number increased in value, whereby the gravels were subjected to abrasion in a jar milling test by L.E. Vallejo[5]. Sadrekarimi[6] performed ring shear on Ottawa soil and Illinois River soil found the damage produced that were more angular and rougher than the original particles. In interparticle friction varies with particle texture (or roughness)[7]. Liu[8] investigated the relationship between particle shape and the mechanical property of sands were made up of rounded and angular particles, respectively, using direct shear apparatus. Interestingly, they showed that the critical friction angle reduces linearly with the increase in roundness and particle regularity, while the dilation angle increases with the increase in particles irregularity.

Although the study of the particle shape has been mature, but the law of the particle shape is ambiguous under large-displacement shear. Little comparative study on the law of the particle shape after shearing of different materials. In this paper, in order to reveal the law of the particle shape under large-displacement shear, a series of ring shear tests were tested for Fujian standard sand (quartz sand) and calcareous sand, using image processing techniques.

Material tested and experiment method

Material tested. The soil tested was calcareous sand, taken from the South China Sea and quartz sand, taken from Fujian, respectively. Quantitative analysis of the composition of calcareous sand using D8 ADVANCE X-ray diffractometer, which manufactured by Bruker AXS, Germany. CaCO_3 and MgCO_3 content of 81.08% and 11.55% in calcareous sand respectively, however, SiO_2 content of 96% in quartz sand. The results indicate that mineral composition of calcareous sand are aragonite, dolomite and calcite.

Experiment equipment and method. This paper studied the evolution of shape properties under the large-displacement shear. The triaxial device is the limited available shear displacement. The magnitude of shear displacement that can be imposed on a specimen is also limited by the direct simple shear device. In this paper we tested on DTA-138 geotechnical ring shear, which manufactured by Japan. The ability to shear a sample uninterrupted to virtually unlimited displacement in this ring shear. This sand is tested single sized of 0.5-1mm. Calcareous sand and quartz sand has a maximum (e_{\max}) void ratios of 1.71 and 0.88, respectively. We were tested the maximum void ratios. In this study was prepared by air pluviation as it is a commonly used and reliable method to achieve fairly uniform density[9]. Then all tests are performed on saturated specimens. Consolidation pressure is set to 400kPa. After consolidation, we were sheared to 10m each specimen at a rate of 4.36 cm/min under drained conditions. Considering the content of fines after tests, the particle size distributions are got by the sieving method and laser grain-size analyzer. The shape parameter before and after tests were got by the microscope, and then the characteristics of the particle shape were analyzed.

The particle breakage parameter. The change of the particle size distribution reflected the particle breakage intuitively. The amount of particle breakage is quantified by means of Hardin's[10] relative breakage, B_r , which is defined as (Eq.1)

$$Br = B_t / B_{p0} \quad (1)$$

Where B_{p0} is the pre-shearing potential for breakage that is area of ABCD (Fig.1), B_t is the amount of total breakage that is area of ABCE. Hardin ignored damage to silt particle. However, in this study, breakage will take into account in the particle greater than 0.01mm.

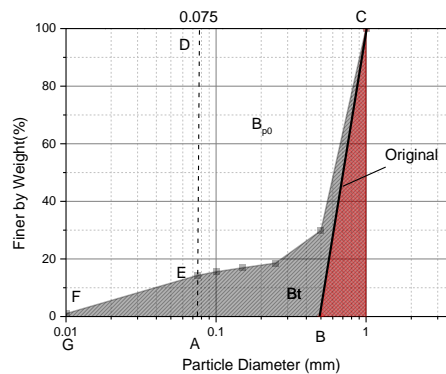


Fig. 1 Illustration for the definition of B_r

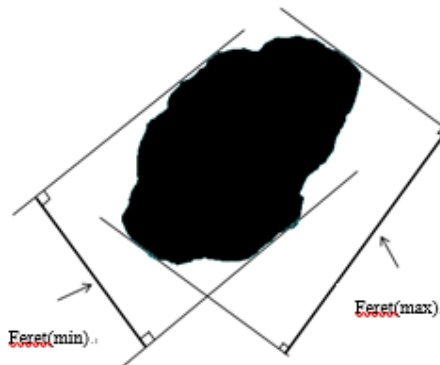


Fig. 2 Illustration for the particle shape parameters

The particle shape parameters. Firstly, the two-dimensional projected images of particle are got by the microscope. Then change the gray image into binary image, thereby got its the geometric parameters, such as maximum and minimum feret's diameter, area and so on. Finally, the particle shape parameter before and after tests are calculated. This paper attempts to describe the particle shape in two level. On one hand, flatness[11], which depicts the particle's outline. Flatness is defined as (Eq.2)

$$e = \text{Feret}(\max) / \text{Feret}(\min) \quad (2)$$

Where $\text{Feret}(\max)$ and $\text{Feret}(\min)$ are maximum and minimum feret's diameter, respectively (Fig.2). On another hand, roundness[12], which depicts the rough on surface proposed by Liu. Roundness is defined as (Eq.3)

$$\text{Roundness} = P^2 / (4\pi A) \quad (3)$$

Where P and A are projected girth and projected area, respectively.

Test results and discussion

The evolution of particle breakage. Particle breakage induced the evolution of grain size distributions in the Shear Band was sheared to 10m (Fig.3). The particle-size distribution curve of quartz sand more steeper than the particle-size distribution curve of calcareous sand after tests. The average particle size (d_{50}) of calcareous sand was reduced from 0.5 mm to 0.349 mm, and quartz sand was reduced from 0.5 mm to 0.475 mm (Table 1). The fines of calcareous sand more than that of quartz sand obviously. It indicate that the change of particle size of calcareous sand larger than that of quartz sand. The amount of crushing also reflects the particle size changes directly. In order to analyze the change of particle size further, quantitative analysis of particle crushing. Calcareous sand was damaged more severely ($Br=0.482$) than quartz sand ($Br=0.166$) that was sheared to 10m (Table 1). The results show that the quantity of particle breakage on calcareous sand is much more than that on quartz sand, further the change of particle size of calcareous sand larger than that of quartz sand.

Table 1 The parameters of particles

Material	d_{50} (before test) /mm	d_{50} (after test) /mm	Br
calcareous sand	0.50	0.349	0.482
quartz sand	0.50	0.475	0.166

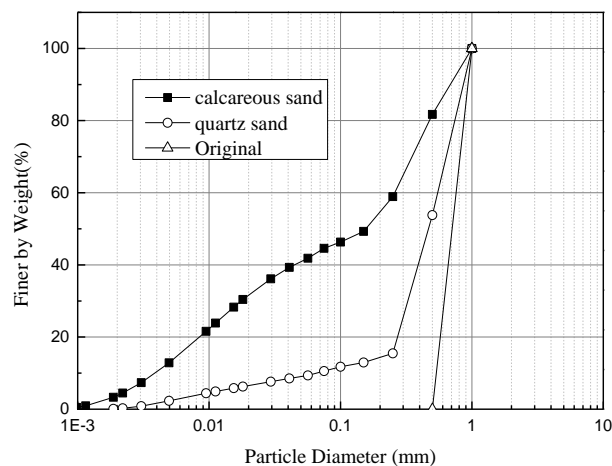


Fig. 3 the particle size distribution before and after tests

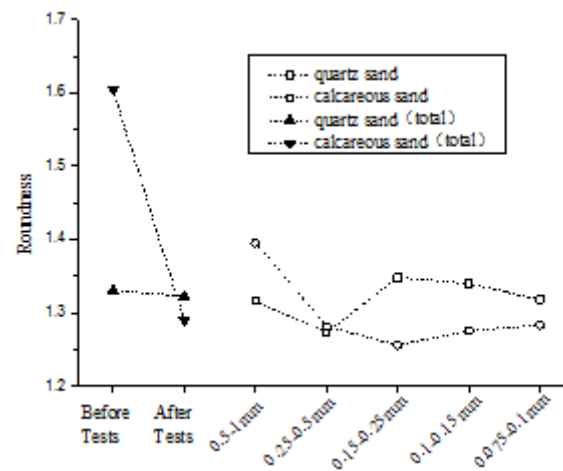


Fig. 4 The change of roundness before and after tests

The change of particle shape. According to statistics the particle shape before and after tests, it suggested that roundness of calcareous sand larger than that of quartz sand before tests (Fig.4). The roundness of calcareous sand and quartz sand decreased that was sheared to 10m. However, the roundness of the quartz sand was little decreased. It indicated that performed large-displacement shear the calcareous sand was more rounded, and quartz sand was more rougher than the original particles. It was found that the roundness of the particle size of 0.15-0.25mm was the smallest, and the largest of the roundness of the quartz sand was particle size of 0.15 to 0.25mm. During shearing, the prolate of irregular particles were subjected to particle breakage, that caused by stress concentration, and produced particle more rounded. This could be a result of intense rolling and abrading on the calcareous sand of the particle size of 0.15-0.25mm and mild rolling and abrading on the quartz sand of the particle size of 0.15-0.25mm.

Table 2 The change of the roundness before and after tests

Material	Before tests			After tests		
	Mean	CI of Mean	SD	Mean	CI of Mean	SD
calcareous sand	1.605	1.517-1.693	0.304	1.289	1.275-1.303	0.146
quartz sand	1.331	1.300-1.362	0.155	1.323	1.293-1.353	0.330

Note: The CI of Mean is lower 95% CI of mean and upper 95% CI of mean, SD is standard deviation of sample.

Table 3 The change of the flatness before and after tests

Material	Before tests			After tests		
	Mean	CI of Mean	SD	Mean	CI of Mean	SD
calcareous sand	1.560	1.437-1.683	0.374	1.410	1.383-1.437	0.275
quartz sand	1.388	1.349-1.427	0.198	1.401	1.375-1.427	0.282

Note: The CI of Mean is lower 95% CI of mean and upper 95% CI of mean, SD is standard deviation of sample.

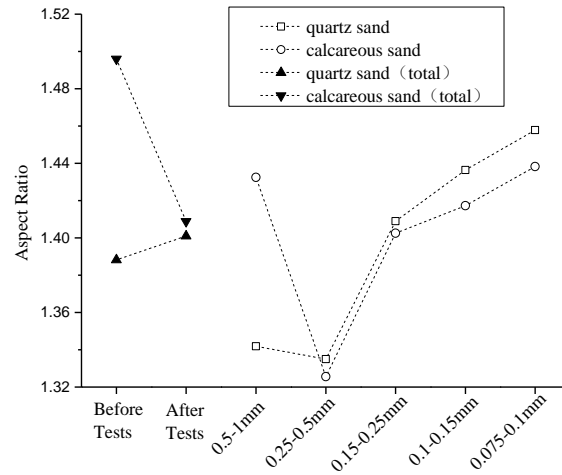


Fig. 5 The change of flatness before and after tests

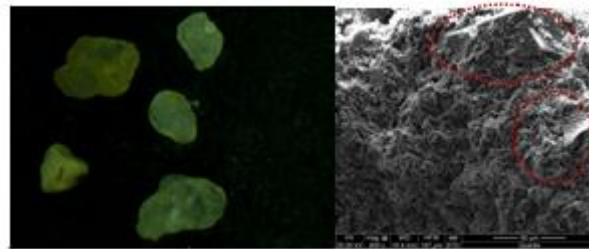


Fig. 6 The image of quartz sand before and after tests

According to the statistical method to get the flatness both before and after test (Table 3). A significant difference in the flatness of the two specimens (calcareous sand and quartz sand) were shown in Fig.5. The flatness of calcareous sand reduces (more rounded or square) obviously (from 1.496 to 1.409). Conversely, the flatness of calcareous sand increases (more flat). To better visualize the particle after shearing, the sheared sand was observed on scanning electron microscope (SEM). The SEM photos illustrates that the quartz sand had more roughed and flatness is shown in Fig.6.

The flatness of the quartz sand with particle size of 0.25-0.5mm was the smallest. While the flatness of the <0.25mm particles was larger than the original. During large-displacement shearing, grain skeleton consist of coarse particles that primarily subjected to shear loading(Fig.7 & Fig.8). So the roundness and flatness of coarse particles decreased, that caused by rolling and abrading. The damaged fines (<0.25mm) fall into the skeleton pores, not the part of the skeleton, the fines in the pores had not been rolling and abrading (Fig.8). Therefore the flatness of the fines larger than original. Due to calcareous sand particle is prone to crush under stress, with increasing shear displacement, the skeleton could not withstand the external load and failure. Particle crushing produced the pore compression, and a part of broken particle become the skeleton again. Circularly, the particles unremitting rolling and abrading, and the particle trended to regular continuously.

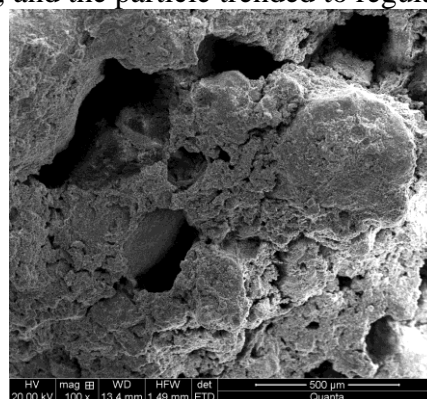


Fig. 7 The SEM image of shear band

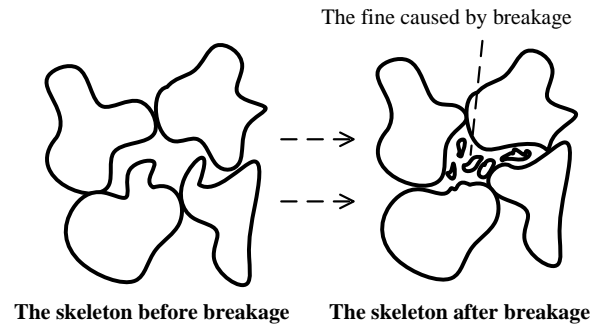


Fig. 8 Illustration for the skeleton before and after breakage

After large-displacement shear, the flatness of calcareous sand and quartz sand had the same trend in each size. By using SEM, obtaining a particle distribution on the shear band used to making a simple model about breakage process (Fig. 8), the external load of the grain skeleton broken and the fines fall into the pore preventing from breakage; after the original grain skeleton (the previous process) was failure, the new skeleton composed of part of original grain skeleton and part of particle in pore, the flatness kept decreasing along with increasing shear displacement. Therefore, the particle shape change was related to the severeness of breakage.

Conclusions

In this study, we performed a series of ring shear tests on calcareous sand and quartz sand. Particle damage and shape change could be observed in the shear band of the tests. The following conclusions can be drawn based on the finding of this study:

- (1) The calcareous sand was damaged more severely ($B_r=0.482$) than quartz sand ($B_r=0.166$) in large-displacement shearing, and the particle size of the calcareous sand changed more than the quartz sand;
- (2) After large-displacement shear, the shape of calcareous sand tends to be more regular, in contrast, quartz sand tends to be more irregular;
- (3) After large-displacement shear, the flatness of calcareous sand and quartz sand have the same trend for full particle size range.

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