Particle breakage and its influence on soil behavior under undrained condition

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ABSTRACT

This paper presents particle breakage and its influence on soil behavior under undrained shear condition. First the pre-crushed sand was produced by triaxial tests under 3MPa confining pressure on dense samples. It was revealed that particle breakage increased with increasing axial strain and particle breakage in shear band was found to be much more substantial than outside shear band. Thereafter the pre-crushed sand and original sand were used separately in new triaxial tests under 0.2MPa and 3MPa confining pressures to investigate the influence of particle breakage on soil behavior under undrained condition. It was found that particle breakage deteriorated the stress-strain curves in reduction of peak strength of soil and resulted in more substantial development of excess Pore Water Pressure (PWP) with a higher residual excess PWP. Particle breakage resulted in more contractive behavior of soil in depression of dilatancy. The effective friction angle at peak strength and the deformation modulus at 0.002 axial strain were analyzed with respect to particle breakage. It was concluded that the particle breakage resulted in reduction of friction angle and deformation modulus.

Keywords: particle breakage, grain size distribution, soil behavior, pre-crushed sand, undrained condition

1 INTRODUCTION

Granular materials are comprised of particles whose characteristics and gradation govern its mechanical properties. Particle breakage occurs in granular materials subjected to high pressure exceeding the material strength of particles, leading to new gradation of soil. The change of grain size distribution has a significant influence on the mechanical properties of soil. Particle crushing depends on many factors such as particle shape, state of effective stress, effective stress path, void ratio, particle hardness etc. (Hardin, 1985; Lade et al., 1996; Lade and Yamamoto, 1996; Ueng and Chen, 2000; Coop et al., 2004; Donohue et al., 2009; Kikumoto et al., 2010). A new method to quantify the extent of particle breakage and the equation to estimate the total breakage considering many influence factors were proposed by Hardin (1985). Particle breakage results in the increase of fines content. Kikumoto et al. (2010) concluded that the broadening gradation induced by particle breakage lowered the critical state line and changed the contractive characteristics of soil, which was adopted in the Severn-Trent sand model. To provide a single unifying parameter for all types of soil tests, a new particle breakage factor $B_{fr}$ was proposed to estimate the permeability computation in using total input energy on soil, which is significant for application in the effect of particle breakage on pore water pressure distribution and seepage in reality (Lade et al., 1996). Coop et al. (2004) conducted ring shear tests to investigate the development of particle breakage, and it was thereby found that the soil reached a stable gradation at very large displacement where the volumetric compression ceased. Sadrekarimi and Olson (2010) preformed further ring shear tests to three kinds of sand with different mineralogical compositions, the dominant particle damage mechanism was found to strongly depend on the soil response, particle hardness and particle-size distribution, and the influence of particle breakage on the hydraulic conductivity, liquefaction resistance, stress-strain response, friction angle and critical state were briefly discussed as well.

Most of the previous researches about the particle breakage mainly focused on the evolution of particle breakage and particle crushing mechanism in compression or shearing. In order to investigate the direct influence of particle breakage on soil behavior under undrained condition, the pre-crushed sand and original sand were used in triaxial tests in this study.

2 MATERIAL AND METHOD

Triaxial tests were carried out by a high-pressure triaxial apparatus with maximum 3MPa confining pressure. Silica sand No.5 with properties of $e_{max}=1.215$, $e_{min}=0.766$ and $G_s=2.76$ was used in triaxial tests. The original grain size distribution curve of silica sand No.5 is shown in Fig. 1. All specimens
in dimension of diameter 75mm and height 160mm were prepared by dry rodding method in air pluviation into a mound with a 1mm-thick membrane in eight layers with necessarily tamping. Herein the 1mm-thick membrane was used to avoid being pierced by sharp edge of soil particles under high effective pressure and minimize membrane penetration under high effective stress. All triaxial tests were conducted on saturated specimens with Skempton’s B value over 0.98. The pre-crushed sand were produced by drained triaxial tests under 3MPa confining pressure on original sand. For getting different extents of pre-crushed sand, the triaxial tests were terminated at various specific axial strain levels ranging from 10% to 50% by 10% increment. Then the relevant grain size distribution curves were obtained by sieve analysis on pre-crushed sand after drying. The new specimens were prepared by pre-crushed sand and original sand separately for new triaxial tests in order to demonstrate the effect of particle breakage on soil behavior under undrained condition.

![Original grain size distribution curve](image1)

**Fig. 1. Original grain size distribution curve**

The new specimens made of pre-crushed sand and original sand were prepared separately by air pluviation with necessarily tamping. Triaxial tests were conducted after isotropic consolidation under Consolidated Undrained condition (CU) on pre-crushed sand and original sand under 0.2MPa confining pressure to examine the effect of previous particle breakage on soil behavior. Herein the 0.2MPa confining pressure as a relatively low confining pressure was used in triaxial tests for trying not to crush the sand any more. Consequently the difference curve after loading can be called the total breakage $B_T$, and the area between initial grain size distribution curve and the vertical line of 0.074mm sieve size is regarded as the breakage potential $B_p$. The relative breakage $B_r$ is defined as a ratio of the total breakage $B_T$ over the breakage potential $B_p$ as illustrated in Fig. 2.

### 3 TEST RESULTS AND DATA ANALYSIS

Triaxial tests were conducted in Consolidation Drained (CD) condition under 3MPa confining pressure for crushing sand. Therein the axial compression for each test was terminated at specified axial strain from 10% and 50% with 10% increment, and crushed sand was collected and called pre-crushed sand subsequently. Fig. 3 shows the CD test results and relevant grain size distribution curves obtained by sieving around 200g sand of specimen after shearing. It is seen herein that the grain size distribution curves evolved toward the increase of fines content and more particle breakage occurs in shear band, along which the sand around 200g sand were picked out to sieve for getting the grain size distribution curve as shown in Fig. 3(d). Particle crushing ($B_p = 0.0059$) occurred just after isotropic consolidation as shown in Fig. 3(c). The grain size distribution curves were quantified by relative breakage as a single parameter to assess the amount of particle breakage as shown in Fig. 3(c).

The shear band in specimen was formed as the axial strains reached 50%. Particle crushing in shear band was investigated as well in comparison with the particle crushing outside shear band. Herein, three parts of the specimen, namely top, middle and bottom as shown in Fig. 3(d), were picked out about 200g separately to get the relevant grain size distribution curves by sieve analysis, where the 200g at the top or bottom parts in specimen was picked up along the central axis of the specimen but at the middle part of the specimen 200g of sand was picked up along the shear band. Fig. 3(d) shows the grain size distribution curves in shear band and at top & bottom parts of the specimen. It can be seen herein clearly that the particle crushing in shear band is slightly more substantial than in top or bottom parts of the specimens. However there is no big difference about particle crushing between top and bottom parts of the specimen.

In the present paper, the Relative Breakage (subsequently abbreviated as $B_r$) developed by Hardin (1985) is introduced to assess the extent of particle breakage, where the area between initial grain size distribution curve and the grain size distribution curve after loading can be called the total breakage $B_T$, and the area between initial grain size distribution curve and the vertical line of 0.074mm sieve size is regarded as the breakage potential $B_p$. The relative breakage $B_r$ is defined as a ratio of the total breakage $B_T$ over the breakage potential $B_p$ as illustrated in Fig. 2.

![Definition of relative breakage](image2)

**Fig. 2. Definition of relative breakage (after Hardin, 1985)**

In the present paper, the Relative Breakage (subsequently abbreviated as $B_r$) developed by Hardin (1985) is introduced to assess the extent of particle breakage, where the area between initial grain size distribution curve and the grain size distribution curve after loading can be called the total breakage $B_T$, and the area between initial grain size distribution curve and the vertical line of 0.074mm sieve size is regarded as the breakage potential $B_p$. The relative breakage $B_r$ is defined as a ratio of the total breakage $B_T$ over the breakage potential $B_p$ as illustrated in Fig. 2.
stress-strain curve and pore water pressure increases with the increase of particle breakage. The stress-strain curve on original sand in Fig. 4(a) has the highest peak strength and the strength decreases gradually with the increase of particle breakage. Moreover the axial strain at the peak strength of soil increases with the increase of particle breakage. Fig. 4(b) shows that the influence of particle breakage on development of excess PWP, where particle breakage is found to result in more substantial development and slower dissipation of excess PWP in increased contractancy in pre-crushed sand than that in original sand.

Fig. 3. CD test results on original sands and relevant grain size distribution curves

Fig. 4. CU test results under 0.2MPa confining pressure

The soil behavior at high pressure was investigated as well in comparison with the soil behavior at low pressure, where during shearing the particle breakage can be assumed to cease at low pressure but during shearing at high pressure the particle crushing may continue to occur. The undrained behavior subjected to high pressure between pre-crushed sand and original sand were investigated by another undrained triaxial tests under 3MPa confining pressure. Fig. 5 shows the CU test results under 3MPa confining pressure. It can be seen herein that the particle breakage resulted in the reduction of peak strength of soil and increase of excess PWP, which are consistent with the findings under low pressure in trend. In comparison with the results at 0.2MPa confining pressure, it has a more evident softened process in the
stress-strain curve on original sand at 3MPa confining pressure. It may be caused by the synthesized combination of the continuous particle breakage during shearing at high pressure and the depressed dilatancy behavior under high pressure.

The increase of particle breakage, which is consistent with that the particle breakage deteriorates the stress-strain curve, meanwhile including the deformation modulus.

4 CONCLUSIONS

The triaxial tests were conducted at designated axial strain from 0% to 50% by 10% increment on dense samples under 3MPa confining pressure to produce the pre-crushed sand. The relevant grain size distribution curves were obtained by sieve analysis and quantified by relative breakage. The pre-crushing sand and original sans were employed in triaxial tests to investigate the effect of particle breakage on soil behavior. The major findings are as what follows.

(a) Particle breakage increases with the increase of axial strain and the particle breakage still can be caused during isotropic consolidation. Particle crushing in shear band was much substantial than that outside shear band and there is no big difference about particle crushing between top and bottom parts of the specimen.

(b) Undrained tests on pre-crushed and original sand under 0.2MPa and 3MPa confining pressure showed that the particle breakage deteriorated...
stress-strain curves in reduction of peak strength and resulted in the more substantial development and slower dissolution of excess pore water pressure with higher residual excess pore water pressure.

(c) Particle breakage resulted in reduction of the effective friction angle and the deformation modulus substantially.

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