UNDRAINED SHEAR CHARACTERISTICS AND PARTICLE BREAKAGE OF SILICA SAND AT LOW AND HIGH PRESSURES

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1. INTRODUCTION

Investigations on particle crushing in drained conditions have gained more attention than those in undrained cases. However, the liquefaction of weak-grained sand in port island areas was observed during the Hanshin earthquake in Kobe, Japan in 1995. The influential parameters affecting the particle crushing of sand in undrained monotonic and cyclic tests are not well examined in previous investigation.

This study presents an experimental study on the undrained monotonic and cyclic shear response of silica sands at two relative densities at a wide range of confining pressures. To clarify the evolution of particle crushing, undrained monotonic and cyclic tests were terminated at several distinctive stages and the amount of particle crushing is quantified. Further, the correlation between the relative breakage and plastic work for undrained monotonic and cyclic tests are established and its differences due to loading mode is intercepted.

2. TESTED SAND AND TEST METHOD

Tested Aio sand is a silica sand from the Yamaguchi prefecture and contains many sub-angular to angular hard grains. The specific gravity G_s and uniform coefficient U_c of Aio sand are 2.64 and 2.74, respectively, and the maximum and minimum void ratios are 0.958 and 0.582, respectively.

Tests were conducted using a high-pressure triaxial testing apparatus. All specimens were formed by air pluviation methods to attain the relative densities of 50% (medium-dense state) and 80% (dense state) and an initial density ρ_d = 1590 kg/cm^3. The specimens had a diameter of 50 mm and a height of approximate 100 mm. The specimens were isotropically consolidated to different effective mean stresses of 0.1 MPa, 3 MPa, and 5 MPa. A series of undrained monotonic and cyclic triaxial tests were performed and terminated at several distinctive stages at confining pressures from low to high. The particle crushing is quantified using the relative breakage Br proposed by Einav (2007) based on the fractal theory.

3. UNDRAINED MONOTONIC SHEAR RESPONSE AND PARTICLE CRUSHING

Fig. 1 shows the void ratio plotted against the isotropic consolidation pressure for Aio sand at two relative densities under isotropic consolidation pressures from 0.02 MPa to 10 MPa. The yield stresses p_y' located at the point of the maximum curvature on the isotropic consolidation curve for medium-dense and dense sands are around 2 MPa and 3 MPa, respectively. To clarify the evolution of particle crushing in undrained monotonic loading, the tests terminated after consolidation (AC), at phase transformation (PT) state point and at the steady state (SS) point, were performed. Fig. 2 presents that relative breakage increases as the consolidation pressure increases. The amount of particle crushing significantly increases after the PT point and continues to increase until the SS point regardless of initial relative density. The variant tendencies of the relative breakage with the confining pressures for both medium-dense and dense sands are quite similar. Fig. 3 demonstrates that the relative breakage linearly increases with the increasing axial strain at all confining pressures. Moreover, this increasing tendency of relative breakage with the axial strain is remarkable at higher confining pressures. Less particle crushing occurs at a low confining pressure of 0.1 MPa. A small amount of particle breakage before the PT point is believed to result from the specimen reaching the PT point at an earlier stage with a small axial strain.

Fig .4 describes that the undrained shear strength at the PT point of the medium-dense Aio sand initially increases, as the confining pressure varies from 0.1 MPa to 3 MPa, and subsequently decreases at a confining pressure of 5 MPa. However, the undrained shear strength of dense sand at the PT point decrease with increasing confining pressure σ_c'. The normalized pore pressure ratios exhibits the opposite tendency to the normalized shear strength. The normalized pore pressure ratio

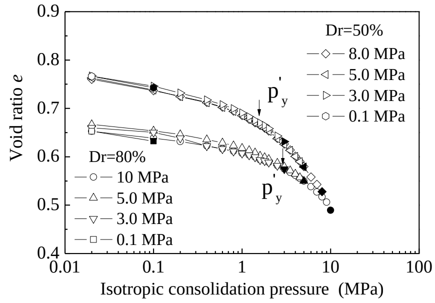

Fig.1 Isotropic compression curves of Aio sand

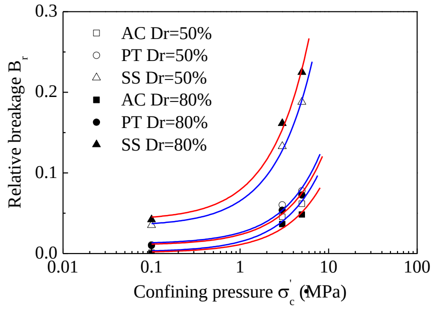

Fig.2 Br after several stages of Aio sand in monotonic tests

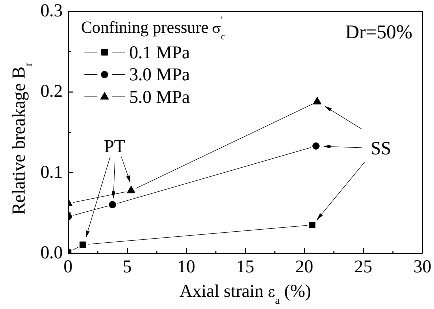

Fig.3 Br plotted against the axial strain

Keywords: Undrained shear behaviour, particle breakage, relative density, phase transformation state, cyclic stress ratio
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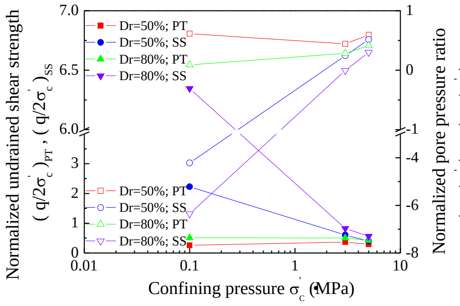

Fig. 4 Normalized undrained shear strength and pore pressure ratio plotted against confining pressure

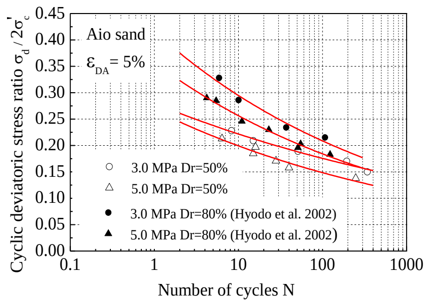

Fig. 5 Liquefaction resistance strength

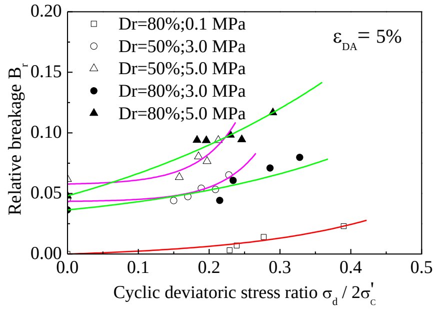

Fig. 6 Br plotted against cyclic deviatoric stress ratio

at the SS point varies from a negative value to a positive value with the rise in σ_c'. A positive pore water pressure indicates the contractive behaviour. The increasing mean stress suppresses the dilation behaviour by a rapid rise in pore water pressure, thus resulting in the occurrence of particle crushing and a remarkable contractive behaviour of specimen.

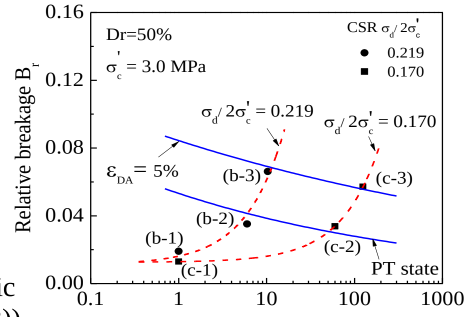

Fig. 7 Br versus number of cycle N

4. UNDRAINED CYCLIC SHEAR RESPONSE AND PARTICLE CRUSHING

Two representative failure patterns of Aio sand, subjected to undrained cyclic loading at a wide range of confining pressures, are identified (Hyodo *et al.* (2002)). Fig. 5 presents the liquefaction resistance strength plotted against the cycle number of medium-dense and dense Aio sands. The cyclic resistance strength of medium-dense and dense Aio sands tend to decrease as the applied confining pressure σ_c' is increased. Particle crushing has been identified as the major contributor to this tendency. A rise in cyclic deviatoric stress ratio increases the relative breakage of specimens regardless of initial relative densities and this increasing tendency becomes remarkable when the confining pressures σ_c' is approximately equal to or greater than the yield stress p_y', as shown in Fig.6.

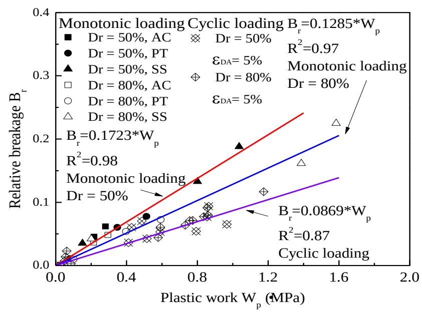

Fig. 8 Br plotted against the plastic work

Fig.7 shows the evolution of the relative breakage B_r of medium-dense sand with increasing cycle number N at two cyclic stress ratios and a confining pressure σ_c' = 3 MPa. At a specific cyclic stress ratio, the relative breakage increases as the cycle number N progresses. Majority of particle crushing is produced and the stiffness of specimen decreases after the specimen passes through the PT point. It is noted that shear strain amplitude plays a preponderant role in the amount of particle crushing subjected to the undrained cyclic loading.

5. RELATIONSHIP BETWEEN PLASTIC WORK AND RELATIVE BREAKAGE

Fig. 8 displays that the relative breakage exhibits a linear relationship with the plastic work Wp subjected to undrained monotonic and cyclic loadings. A large amount of plastic work is dissipated during shearing process in comparison with those in isotropic consolidation. The increasing rate of relative breakage with the plastic work decreases with a rise in the relative density because that a larger amount of plastic work is consumed for particle crushing and a higher deviatoric stress is obtained. In undrained cyclic tests, the slope of linear relation between relative breakage and plastic work is less dependent on the relative density and lower than that determined from monotonic loading due to a relatively smaller amount of particle breakage.

6. CONCLUSIONS

In undrained monotonic tests, the majority of the particle crushing occurs between the PT point and the SS point. The relative breakage linearly increases with the axial strain at each confining pressure, and the rate of increase is dependent upon the confining pressure. The increasing mean stress suppresses the dilation behaviour accompanied by a rapid rise in pore water pressure, thus resulting in the occurrence of particle crushing and a remarkable contractive behaviour of specimen. In undrained cyclic tests, the relative breakage increases with the amplitude of the cyclic stress ratio, regardless of the relative density. At a given cyclic stress ratio, confining pressure, and relative density, the relative breakage increases as the cycle number N progresses. This is due to the high-level axial strain induced by the particle transformation and rotation. The relative breakage can be approximately linearized with plastic work in undrained conditions.

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