CRUSHING CHARACTERISTICS OF SOIL PARTICLE ON THE EFFECT OF STRESS PATH

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In previous studies, we have conducted tests under various conditions of stress for the particle crushing. Anyway, it is necessary to perform the crushing test that assumed stress conditions in ground under controlled each principal stresses individually, to find the mechanical characteristics of the soil with particle crushing. Therefore, the purpose of this study is to confirm the effect for particle crushing under various stress paths in the combination of principal stresses. We planned four combinations of principal stresses when operate the mean stress p and deviatoric stress q up to the Shear Failure Line (SFL) on the π-plane. First, we set tri-axial extension test as Lode angle \( \theta = 60^\circ \) and tri-axial compression test as \( \theta = 0^\circ \), and set two of the remainder as \( \theta = 40^\circ, 20^\circ \). The crushing tests are carried out using the high pressure true tri-axial compression apparatus under the planned stress paths. As a result, the progress of the particle crushing becomes active in order of \( \theta = 40^\circ, 20^\circ, 60^\circ, 0^\circ \), and found out that deviatoric stress q has essential effect on the particle crushing.

**Keywords**: Mean stress, Deviatoric stress, Lode angle, High pressure, Plastic work, Relative breakage.

1 INTRODUCTION

Sand and gravels are granular materials, which composed of solid particles aggregated. Under the high pressure condition, particle crushing phenomenon occurs in which individual particles constituting the granular material are fractured. It is an important task to investigate the mechanical properties associated with particle crushing of sand under high pressure conditions because the mechanical properties of the soil particles change due to the change in the structure of the granules when particle crushing occurs. In the previous studies, the crushing experiments were conducted under the isotropic compression condition, the \( K_0 \) condition or the tri-axial compression condition, however, the load test should be conducted under conditions close to the actual ground stress conditions \( \sigma_1 \neq \sigma_2 \neq \sigma_3 \). The difference in Relative breakage \( B_r \) should be examined when reaching the same stress state from various stress path. Then, we employed three kinds of experimental parameters; mean stress p, deviatoric stress q and Lode angle \( \theta \). The purpose of this study is to compare the effect of stress path and confirm the influence of stress path and deviatoric stress q on particle crushing. In addition, the volume reduction was discussed in consideration of the relation between mean stress p, deviatoric stress q and plastic volumetric strain \( \varepsilon_v^p \).
2 OUTLINE OF TESTS

In this study, we used high pressure tri-axial compression apparatus (Yokura et al. 2015) to consider the effect of particle crushing under high pressure condition. Figure 1 shows the plan view of apparatus used in this study. As shown in Figure 1, a cubic test specimen with the shape of edge cutting 50 × 50 × 50 mm is installed in the center of this apparatus. The specimen was loaded by oil jack with maximum stress up to 200 MPa through loading plate. All weight of the loading device in the vertical direction are supported by the counterweight passed through the pulleys. Furthermore, in order to load using the reaction force in all directions of the apparatus, loads from the relative loading plate were devised to be equal. In addition, the movable part was supported by a ball bearing to move smoothly and without frictional resistance. In this study, Toyoura sand was used as the specimen in Japan. Toyoura sand is often used in various soil tests. By the general sieving test, the proportion by weight of particles having a particle diameter of 0.125 mm to 0.297 mm is large, and the weight ratio of particles of 0.074 mm or less is extremely small. The specimen was compacted to be initial relative density of 90% or more.

Figure 1. Plan view of high pressure tri-axial compression apparatus, enlarged view of dotted line portion.

Mean stress p, Deviatoric stress q and Lode angle θ are controlled in this study, additionally, it is necessary to make differences only in the stress path with the same mean stress p and deviatoric stress q. For that purpose, it is easy to understand by considering the three-dimensional principal stress space represented by σ1, σ2, σ3. Therefore, experiments were conducted by setting a stress path on the π-plane. Figure 2 shows the stress path on the π-plane. The definitions of mean stress p and deviatoric stress q are shown below.

\[
p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \tag{1}
\]

\[
q = \frac{1}{\sqrt{2}} \left( \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \right) \tag{2}
\]

At the first step, we consider three π planes with mean stress p = 14.5, 30 and 50 MPa. Experiments were also conducted by stress paths with Lode angles θ = 0°, 20°, 40°, 60° for each deviatoric stress levels and the SFL condition, and the isotropic compression cases without deviatoric stress. In total, we conducted 51 cases of experiments as shown Figure 3.
Then, the test of \( p = 14.5 \text{ MPa} \) is called A test, the test of \( p = 30.0 \text{ MPa} \) is B test and the test of \( p = 50.0 \text{ MPa} \) is called C test. For example, experiment with the case of \( p = 14.5 \text{ MPa} \), the path of \( \theta = 60^\circ \) and folding back at the point of \( R_1 \) is expressed as “A-60°-R₁”.

3 TEST RESULTS AND DISCUSSION

At the start, sieving test was conducted to determine the particle size after particle crushing. Volumetric strain \( \varepsilon_v \sim p \) relationship and deviatoric strain \( \varepsilon_d \sim q \) relationship are shown in Figure 4. The Plastic work \( W_p \) are calculated by adding up the area of each painted place (Roscoe et al. 1963). In addition, plastic volumetric strain and deviatoric strain, elastic volumetric strain and deviatoric strain are as shown in the figures. Since this plastic volumetric strain \( \varepsilon_v^p \) is largely related to the volume reduction of the sample, it is considered to be related to the Relative breakage \( B_r \) (Hardin 1985).
Figure 5 shows the relationship between the Lode angles $\theta$ and $B_r$, and the relationship between the Lode angles $\theta$ and $W_p$ obtained by the result of the sieving test. According to $B_r$ and $W_p$ obtained by the test, almost no difference due to the stress path of Lode angle $\theta$ was found. It is also understood that $B_r$ and $W_p$ fluctuate in proportion to the deviatoric stress $q$.

It is considered to the consume energy when particles break. Therefore, it can be inferred that there is a unique relationship between Relative breakage $B_r$ and Plastic work $W_p$. Figure 6 shows the relationship between Plastic work $W_p$ and Relative breakage $B_r$. The curve is convex downward as shown the figure. Also, since the increment of $B_r$ gradually decreases, it seems that $B_r$ has an upper limit. This is a proportional relationship as shown in Figure 7, the order of approximation is good ($R^2=0.939$).

4 EXPERIMENTAL FORMULA
In this chapter, the relationship between amount of particle crushing and volumetric strain $\varepsilon_v$ was derived by experiments. The final goal is to be able to estimate the strain increment from the pressure on the soil particles by establishing these relationships. As shown in Figure 4, the volumetric strain $\varepsilon_v$ is a sum of a plastic and elastic component. Therefore, each components are represented by mean stress $p$ and deviatoric stress $q$. At first, it is explained the relationship between elastic volumetric strain $\varepsilon_v^e$ and $(p, q)$. According to the paper by (Nakai 1989), $\varepsilon_v^e$ is expressed by the following Eq. (3).
The unknown coefficients in Eq. (3) are $C_\varepsilon$, m (pa is atmospheric pressure). $C_\varepsilon$, m derived from the experimental data are shown in Figure 8 and 9. From these figures, it can be assumed that $C_\varepsilon$, m are constants, therefore we regard the average value of experimental data as coefficients. In these Figures, rhombic marks are regarded as singularities with largely deviated from the average and are excluded when taking the average.

![Figure 8. Relationship of $p - C_\varepsilon$.](image)

![Figure 9. Relationship of $p - m$.](image)

Figure 10 shows the relationship between the Relative breakage $B_r$ and mean stress $p$. The increasing tendency of Relative breakage $B_r$ gradually increases as the mean stress $p$ increases in the case where the deviatoric stress $q$ is small. On the other hand, we can see that the increasing tendency of Relative breakage $B_r$ gradually decreases with increase in the mean stress $p$ in the case where the deviatoric stress $q$ is large. In addition, we can find that the influence on the increase of particle crushing is larger in the deviatoric stress $q$ than the mean stress $p$. Based on the above tendency, an approximate expression of $B_r - (p, q)$ relationship shown in the Eq. (4) and (5) are assumed. Also, stress path is not considered in this estimation. Figure 11 compares the estimated $B_r$ with experimental data. Incidentally, $B_r$ was obtained by substituting the coefficients $A_0$, $r_c$ and $c$ determined by the least-squares method into the Eq. (4) and (5). The order of approximation is good ($R^2=0.974$) by using this relational expression and Relative breakage $B_r$ can be estimated from the combination of $(p, q)$. Figure 12 is a three-dimensional image of this experimental formula. Experimental equations derived from the above calculations are shown in Table 1. Accordingly, the volumetric strain can be represented by the mean stress $p$ and the deviatoric stress $q$.

![Figure 10. $B_r$ - mean stress $p$.](image)

![Figure 11. Estimation accuracy of $B_r$.](image)
From the experimental results of particle crushing tests, it was found that there is little influence of the Lode angle $\theta$ on the crushing property, and $B_r$, $W_p$ increase in proportion to the deviatoric stress $q$. We derive an experimental formula to calculate the volumetric strain $\varepsilon_v$ by mean stress $p$ and deviatoric stress $q$. In addition, formulating the relation $\varepsilon_v \sim (p, q)$, $B_r \sim (p, q)$ and $\varepsilon_v \sim (p, q)$ were achieved success in the case of Toyoura sand. However, we have unfinished works to future studies as followings.

1) Applicability of the experimental formula for the different type of sand.
2) Examine the effect of different stress paths.
3) Experimental formula on the deviatoric strain $\varepsilon_d$.

Thereafter, these works will be confirmed by experiments; using different type of sand (e.g. weathering granite and Shirasu) and passing through different stress paths. Experimental equation of deviatoric strain $\varepsilon_d$ will be estimated with same method as the case of volumetric strain $\varepsilon_v$.

5 CONCLUSION

Table 1. List of estimated experiment formula.

<table>
<thead>
<tr>
<th>Volumetric strain components</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_v = C_e \times (p/p_a)^m$</td>
<td>$C_e = 0.6725$ $m = 0.4863$ $p_a = 0.1$ (MPa)</td>
</tr>
<tr>
<td>$\varepsilon_v = a_1 \times B_r(p, q) + b_1$</td>
<td>$a_1 = 58.731$ $b_1 = 2.9008$</td>
</tr>
<tr>
<td>$B_r = A \times {1 - \cos(\pi/2 \times r/r_c)}$</td>
<td>$A = 0.31$ $r_c = 107$ (MPa) $c = 1.7$</td>
</tr>
</tbody>
</table>

$B_r = A \cdot \{1 - \cos(\pi/2 \cdot r/r_c)\}$

$r^2 = p^2 + (c \cdot q)^2$, $c$ : Magnification factor $c \geq 1.0$

References