Streamlining Information Transfer between Construction and Structural Engineering
Edited by Shiau, J., Vimonsatit, V., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-7-9

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 θ=60° and tri-axial compression test as θ=0°, and set two of the remainder as θ=40°, 20°. 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 θ=40°, 20°, 60°, 0°, 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 θ. 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 ε_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.

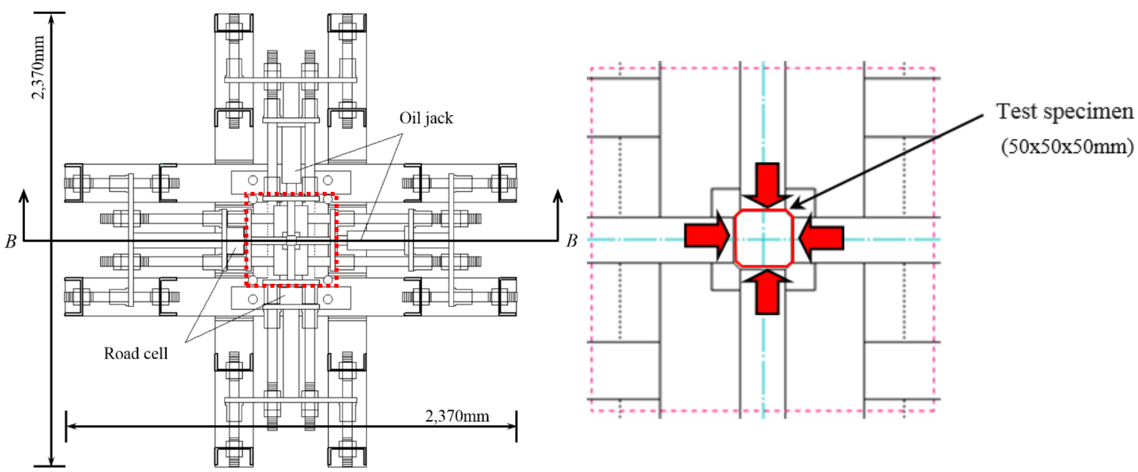


Figure 1. Plan view of high pressure tri-axial compression apparatus, enlarged view of dotted line portion.

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 σ_1, σ_2, σ_3. 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.

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

$$q = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \tag{2}$$

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.

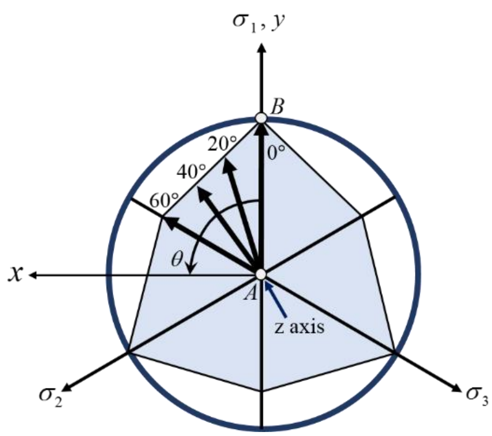


Figure 2. Stress path on the π-plane.

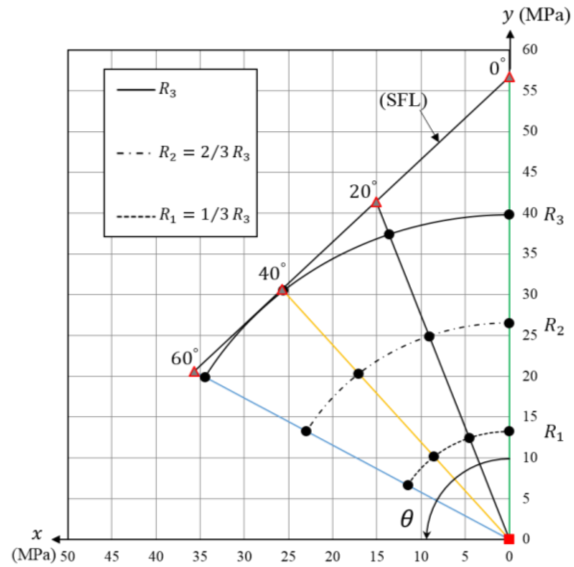


Figure 3. Explanation diagram of stress path in case of C test.

Then, the test of p = 14.5 MPa is called A test, the test of p = 30.0 MPa is B test and the test of p = 50.0 MPa is called C test. For example, experiment with the case of p = 14.5 MPa, the path of θ = 60° and folding back at the point of R_1 is expressed as “A-60°-R_1”.

3 TEST RESULTS AND DISCUSSION

At the start, sieving test was conducted to determine the particle size after particle crushing. Volumetric strain ε_v ~ p relationship and deviatoric strain ε_d ~ 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 ε_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).

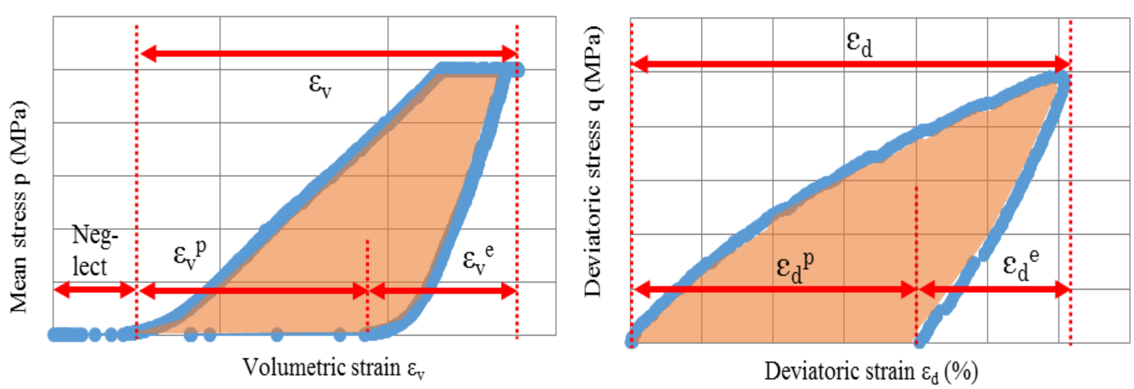


Figure 4. Definition of volumetric and deviatoric strain components.

Figure 5 shows the relationship between the Lode angles θ and B_r, and the relationship between the Lode angles θ 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 θ was found. It is also understood that B_r and W_p fluctuate in proportion to the deviatoric stress q.

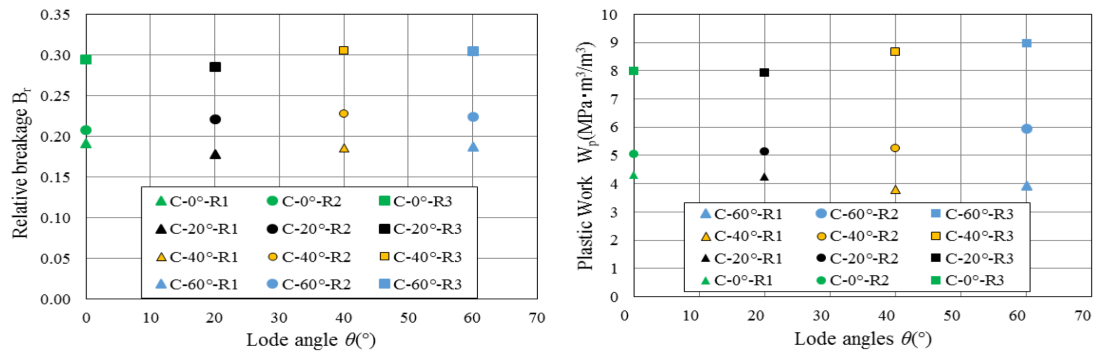


Figure 5. The Relative breakage B_r and the Plastic work W_p for Lode angle θ.

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).

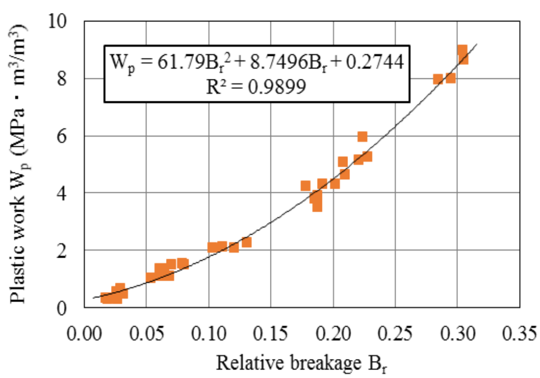


Figure 6. Relationship of $B_r - W_p$.

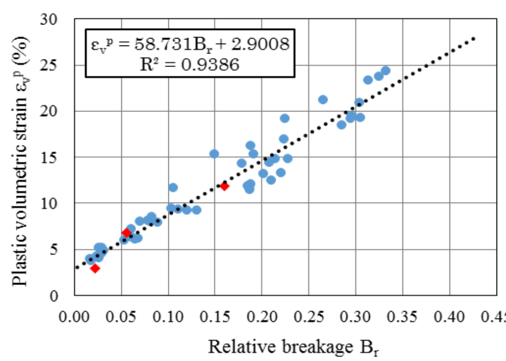


Figure 7. Relationship of $B_r - \varepsilon_v^p$.

4 EXPERIMENTAL FORMULA

In this chapter, the relationship between amount of particle crushing and volumetric strain ε_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 ε_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 ε_v^e and (p, q). According to the paper by (Nakai 1989), ε_v^e is expressed by the following Eq. (3).

$$\varepsilon_v^e = C_e\left[\left(\frac{p}{p_a}\right)^m\right] \quad \text{(In case of } p_0\text{=0)} \tag{3}$$

The unknown coefficients in Eq. (3) are C_e, m (pa is atmospheric pressure). C_e, m derived from the experimental data are shown in Figure 8 and 9. From these figures, it can be assumed that C_e, 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.

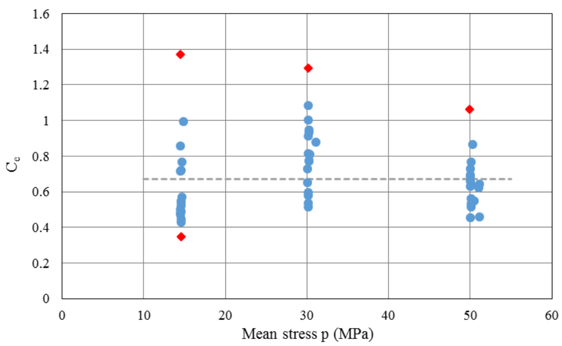


Figure 8. Relationship of p - C_e.

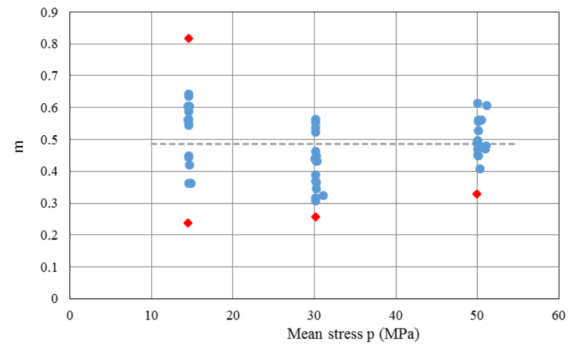
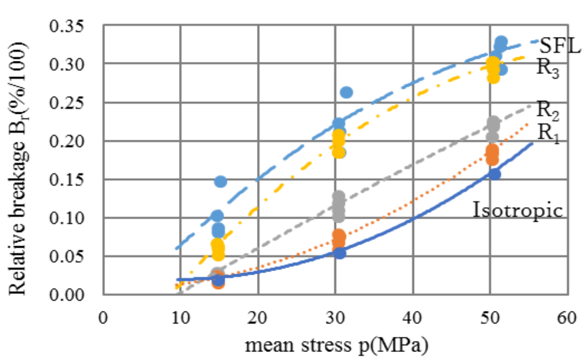


Figure 9. Relationship of p - m.

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 be seen 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.



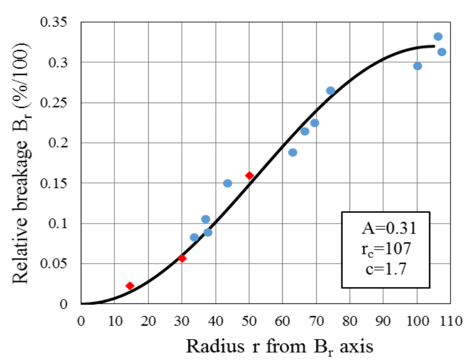
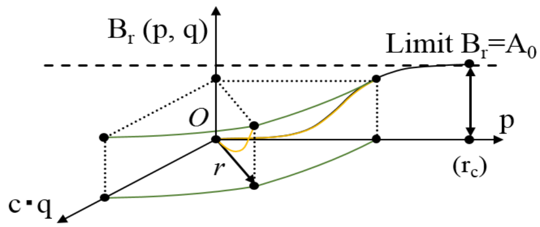


Figure 10. B_r - mean stress p.

Figure 11. Estimation accuracy of B_r.



$$B_r = A \cdot \{1 - \cos(\pi/2 \cdot r/r_c)\} \tag{4}$$

$$r^2 = p^2 + (c \cdot q)^2,\ c\ ;\ \text{Magnification factor}\quad c \geqq 1.0 \tag{5}$$

Figure 12. Conceptual diagram of B_r, p and q in three-dimensional space.

Table 1. List of estimated experiment formula.

Volumetric strain components	**Coefficients**
$\varepsilon_v^e = C_e \times (p/p_a)^m$	$C_e = 0.6725$ $m = 0.4863$ $p_a = 0.1$(MPa)
$\varepsilon_v^p = a_1 \times B_r(p, q) + b_1$	$a_1 = 58.731$ $b_1 = 2.9008$
$B_r = A \times \{1 - \cos(\pi/2 \times r/r_c)\}$ $r = \sqrt{p^2 + (c \times q)^2}$	$A = 0.31$ $r_c = 107$(MPa) $c = 1.7$

5 CONCLUSION

From the experimental results of particle crushing tests, it was found that there is little influence of the Lode angle θ 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 ε_v by mean stress p and deviatoric stress q. In addition, formulating the relation ε_v^e ~ (p, q), B_r ~ (p, q) and ε_v^p ~ (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 ε_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 ε_d will be estimated with same method as the case of volumetric strain ε_v.

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