# RESIDUAL STRENGTH OF DIATOMACEOUS SOFT ROCK

Tokai University Student Member ○Dyah Sri Utami, Maki Ikeya
PEC Co.Ltd. Masaru Akaishi
Tokai University Regular Member Motohiro Sugiyama

## 1. INTRODUCTION

It is known that original cam clay can be applied to the elasto-plastic stress strain relationship of diatomaceous soft rock[1]. However, this soft rock shows large compressibility, remarkable time dependency even in over-consolidation and strain softening behavior [1), 2)]. Generally, over-consolidated clay specimens are assumed to be elastic in finite element analysis, but it is controversial whether this is appropriate for stress-strain relationship of the soft rock[2)-4)]. In order to investigate the stress-strain relationship of soft rock, a consolidation undrained (CU) triaxial compression test is generally performed. In this study, consolidation drained (CD) triaxial compression tests were conducted to verify the elasto-plastic stress-strain relationship and examine the residual strength.

## 2. SAMPLES AND EXPERIMENT

A triaxial compression test was performed using diatomaceous soft rock with a specific gravity of 2.18 g/cm$^3$ and natural water content of approximately 120 % taken in Suzu City, Ishikawa Prefecture. A filter paper was placed on the top and , bottom the specimens with a diameter of 5 cm and a height of 10 cm were consolidated. Thereafter, compression was performed at a shear rate of 0.1 %/min in the CU test and at 0.003 %/min in the CD test until the axial strain reached to 15 %. In the drainage test, it was confirmed that the pore water pressure measured at the bottom center of the specimen kept almost zero. During consolidation and shearing tests, a back pressure of 0.5 MPa was applied.

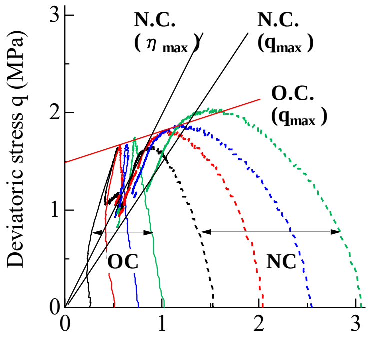


Fig.1 Stress paths of CU test

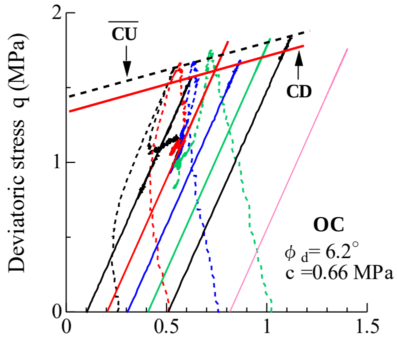


Fig.2 Stress paths of CD test

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

Fig.1 and Fig.2 show the effective stress paths of the CU and the CD tests, respectively. Fig.2 also shows the undrained path of the over-consolidated specimens (Fig.1) with dotted lines. After reaching the maximum deviator stress $q_p$ in the normal consolidation (NC) in Fig. 1, the deviator stress q decreases and the stress ratio η (=q/p) is kept almost constant. For this reason, the critical state line obtained by $q_p$ and $\eta_{max}$ is different. The critical state line estimated by $q_p$ in the over-consolidation (OC) region in Fig. 2 is considered almost the same regardless of drainage conditions. From these results, the strength constant of the over-consolidated specimen used for finite element analysis was set to $\varphi_d \fallingdotseq \varphi' \fallingdotseq 6.2°$, $c_d \fallingdotseq 0.66$ MPa.

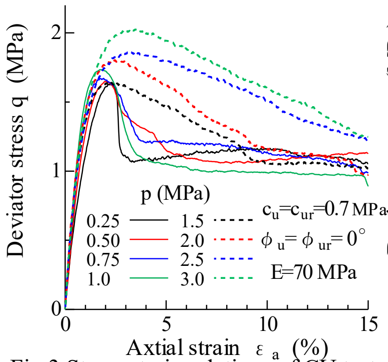


Fig.3 Stress strain relations of CU test

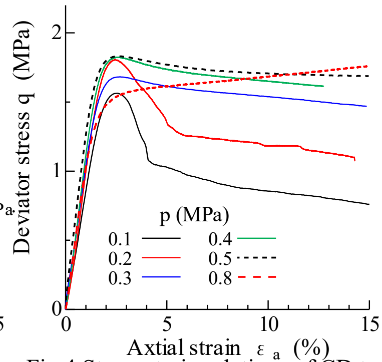


Fig.4 Stress strain relations of CD test

Fig.3 and Fig.4 show the relationship between deviator stress q and axial strain $\varepsilon_a$ in the CU and the CD tests, respectively. From Fig.3, it can be seen that $\varepsilon_a$ reaching the peak stress $q_p$ is slightly smaller in the OC specimens drew as solid line than in the NC ones. The peak drop after reaching $q_p$ is also different between the NC specimens and the OC ones. While the q of the NC specimens decreases with the axial strain, the OC specimens decrease instantaneously to the residual strength $q_r$.

Fig.5 shows the ratio $q_r/q_p$ of the residual strength at axial strain 15 % to $q_p$. In the CU test, the ratio was about 0.6 regardless of the OC and NC specimens.

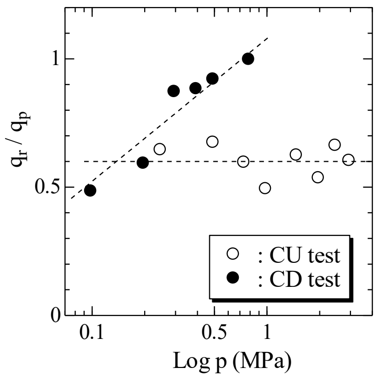


Fig.5 $q_r/q_p$ – p relations

Keywords: Soft rock, Triaxial CD test, Strain softening, Elasto-plastic, FEanalysis
Contact address: Kitakaname 4-1-1, Hiratsuka-shi, Kanagawa, 259-1292, +81-463-58-1211,sugi@keyaki.cc.u-tokai.ac.jp

As shown in Fig.4, the peak drop is observed in the CD test with a large over-consolidation ratio (OCR) and the ratio $q_p/q_r$ tends to change depending on the OCR

## 4. RESULTS OF FINITE ELEMENT ANALYSIS

Elasto-plastic FE analysis using the finite element program GA3D.f published by the Geotechnical Society is performed and compared with the results of the CD tests. The elasto-plastic soil model is incorporated in GA3D.f, the constitutive law is perfect elasto-plasticity, the yield criterion is the Mohr-Coulomb failure criteria, and the plastic potential is the Drucker-Prager equation. GA3D.f is characterized in that excess stresses exceeding the yield criterion is returned to the yield surface at a constant effective mean stress. However, since this program cannot reproduce the decrease in the deviator stress after yielding, the residual strength was expressed by changing the constant of the Mohr-Coulomb equation after yielding.

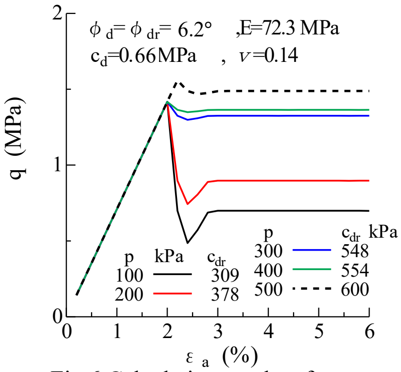

Fig.6 Calculation results of q - $\varepsilon_a$

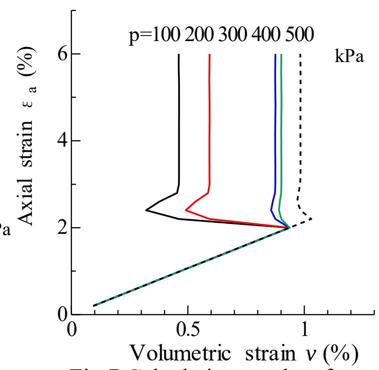

Fig.7 Calculation results of q –υ

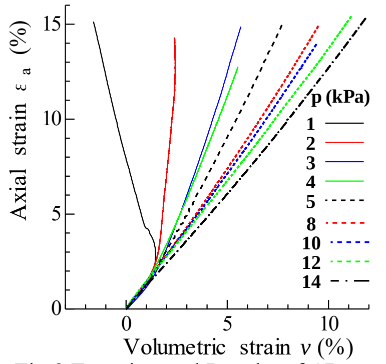

Fig.8 Experimental Results of CD test

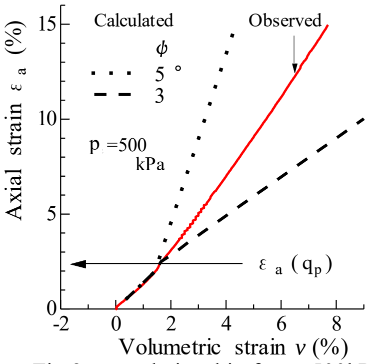

Fig.9 $\varepsilon_a$-υ relationship for p=500kPa

For the calculation, the results of the CD test in the over-consolidation region were used. The bulk modulus K=dp/dv (average value ≒0.34 MPa) and the elastic modulus $E=d\sigma_y/d\varepsilon_a$ (≒72.3 MPa) were determined from the CD test results of the OC specimen. The Poisson's ratio *v* was determined from K and G calculated as 0.14.

Fig.6 and Fig.7 show the calculation results of q - $\varepsilon_a$, and $\varepsilon_a$ - υ relationships of the CD test, respectively. In Fig.6, the residual strength corresponding to the $c_{dr}$ / $c_d$ ratio is calculated. As shown in the experimental results, it is easy to consider the decrease in deviator stress q as $\varepsilon_a$ increases, but this is not taken into account in the calculation. Also, since the dilatancy angle ψ related to the plastic potential is assumed to be zero, the volume change after yield is calculated to be zero as shown in Fig.7. This is different from the experimental results in Fig.8.

Since the soil constant used for the calculation was determined from the experimental results, the calculation results up to $q_p$ correspond to the experimental results. The over-consolidated diatomaceous soft rock shown in Fig.8 undergoes significant volume changes even after yielding, which is also affected by OCR. Fig.9 shows the $\varepsilon_a$-υ relationship (measured values) for p =500 kPa (red line) in Fig.8 and the calculation results with a dilatancy angle ψ of 3 or 5 degrees. If ψ after yielding can be set appropriately, it is possible to calculate the $\varepsilon_a$ -υ relationship that is close to the measured value. The plastic potential that controls strain components after yielding is a topic for future study.

## 5. CONCLUSIONS

The results obtained from characteristics of the residual strength of diatomaceous over-consolidated soft rock in the undrained / drained triaxial compression test are as follows:

1) Strength parameter $c_d$ and $\varphi_d$ determined by the maximum of deviator stress $q_p$ are almost the same as c' and φ'.
2) Residual strength $q_r$ depends on the over-consolidation ratio and drainage conditions during compression. The residual strength at an axial strain of 15 % is about 60 % of the maximum deviator stress.
3) The volumetric changes after yielding is affected by the over-consolidation ratio.

## REFERENCES


1) Liao,H.J., M. Hayashi and M. Akaishi: Residual Strength Characteristics of Diatomaceous Soft Rock with Discontinuous Surfaces, Journal of JSCE, No.529, pp.103-111, 1995.
2) M. Hirata et. al.: Deformation Behavior Factors of Road Embankment on Ultra Soft Ground and Countermeasures, Journal of JSCE (C), Vol. 66, No. 2, pp.356 -369, 2010.
3) H. Maekawa and K. Miyakita: Mechanical Properties of Diatomaceous Soft Rock, Journal of JSCE, No.334, pp.135-143, 1983.
4) N. Adachi and F. Oka: Strain Softening Elasto-plastic Constitutive Equation for Soft Rock, Journal of JSCE, No.445 / III-18, pp. 9-16, 1992.
5) Japan Geotechnical Society: "The elasto-plastic finite element method", FEM series ③, GA3D.f, 2003.