Undrained strength-deformation properties of anisotropically consolidated diatomaceous mudstone

Tokai University Student Member ○ Najibullah
Tokai University Member Motohiro Sugiyama

1. Introduction

Due to the development of public hard infrastructure and deep underground structures, the mechanical characteristics of sedimentary soft rocks have been investigated[1)-4)]. Most previous research on the strength-deformation properties of soft rocks has involved triaxial compression tests using isotropically consolidated specimen. In the present study, undrained triaxial compression tests were conducted to investigate the strength-deformation properties of anisotropically consolidated diatomaceous mudstone at a specified consolidation pressure and the results were compared with the results of isotropically consolidated specimen at the same consolidation pressure. The undrained creep properties of the overconsolidated condition that exhibits notable strain softening behavior were also examined.

2. Test specimens and experimental methods

Diatomaceous mudstone[1),2)] collected at Suzu city, Ishikawa prefecture was used for the experiment. Specimens of 5 cm in diameter and 10 cm in height were formed from blocks that were free of cracks and surface irregularities. The blocks were cut off from a cube with approximately 50 cm in side length. Table 1 lists the measured physical properties of the milled fine-grain fraction (<420 μm). There was a maximum spread of approximately 20% in the natural water content. Therefore, the consolidated undrained triaxial compression and undrained creep tests were performed using specimens with 120% ± 5% natural water content. Diatomaceous mudstone has high associative strength due to cementation but is an extremely porous sedimentary rocks[1].

Table 1 Physical properties of diatomaceous

ρ_s (g/cm^3)	w_n (%)	w_L (%)	w_p (%)
2.183	108～128	172.7	94.7

Consolidated undrained triaxial compression test:

The specimens were sheared at a strain rate of 0.1%/min after isotropic and anisotropic consolidation by an intermediate-capacity triaxial compression apparatus (maximum lateral pressure 4.92 MN/m^2) at a specified consolidation pressure p' (=(σ'$_1$+2σ'$_3$)/3). Eight values of p, ranging from 0.25 MN/m^2 to 2.94 MN/m^2 was selected. For anisotropic consolidation, only axial pressure was applied. While measuring the graded dissipation of water pressure after isotropic consolidation, the effective stress ratio η (= q/p') was 0.75. Water pressure dissipated within 24 hours for isotropic and anisotropic consolidation of $p \leq 1.47$ MN/m^2. However, water pressure for anisotropic consolidation of $p \geq 1.96$ MN/m^2 required one week to be dissipated.

Undrained triaxial creep test:

A creep test was performed in which a specified creep stress q_c was held constant. The specimen was sheared in an undrained condition with the same method and condition as the consolidated undrained test until q_c was reached. The creep strength and residual strength according to isotropic/anisotropic consolidation were compared with consolidation pressure p at 0.49 MN/m^2 and creep stress q_c ranging from 75% to 96% of the maximum strength q_p (= $\sigma_{1max} - \sigma_3$) acquired from the consolidated undrained test. In addition, in both tests, a backpressure of 0.49 MN/m^2 was applied throughout the duration of the test.

Keywords: diatomaceous mudstone, triaxial compression test, anisotropic consolidation, residual strength, undrained creep
Contact details: 4-1-1 Kitakaname, Hiratsuka-shi, Kanagawa 259-1292, Japan Tel.: 0463-58-1211,e-mail : sugi@keyaki.cc.u-tokai.ac.jp

3. Results and discussion

3.1 Consolidation and strength-deformation characteristics of the consolidated undrained test

First, we consider the isotropic and anisotropic consolidation process of the consolidated undrained test. Figure 1 shows the *e*-log*p* relationship described by the void ratio of each specimen after consolidation. Although there is a 5MN/m^2 difference in the consolidation yield stress p_c between isotropic and anisotropic consolidation, the sudden decrease in void ratio after p_c is a characteristic shared by both consolidation types and the decrease of the anisotropic consolidation being larger is because of the rupture of the mudstone[1] is further promoted by negative dilatancy in shear. Figure 2 shows the results of investigating the relationship between the ratio of axial strain ε_a over volumetric strain ε_v; ($\varepsilon_a/\varepsilon_v$) and consolidation pressure *p*. The ratio is around 0.45 for isotropic consolidation, irrespective of consolidation pressure. This implies that this specimen has anisotropy with respect to deformation[1]. $\varepsilon_a/\varepsilon_v$ for anisotropic consolidation increases linearly from the vicinity of isotropic consolidation and when exceed to p_c, becoming almost 1 at $p \geq 24.53$ kN/m^2 which is close to K_0 consolidation conditions.

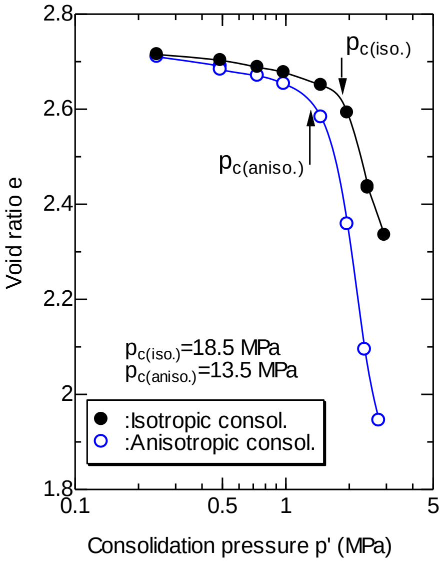


Fig. 1 *e*-log*p* curves of the triaxial tests

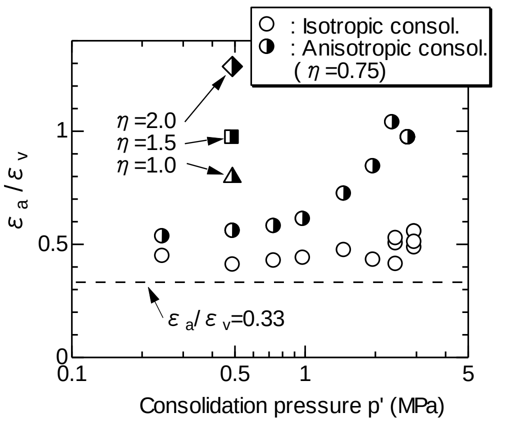
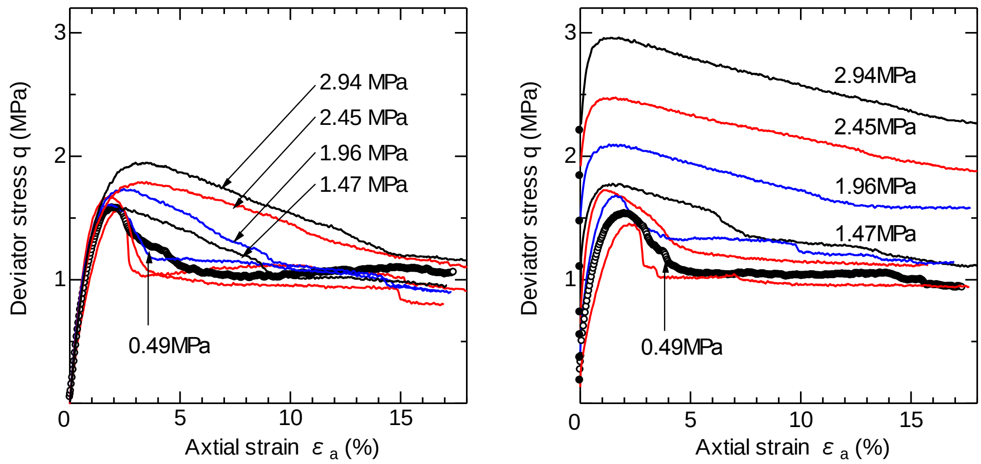


Fig. 2 Strain ratio and consolidation pressure relation



(a) Isotropic consolidation (b) Anisotropic consolidation

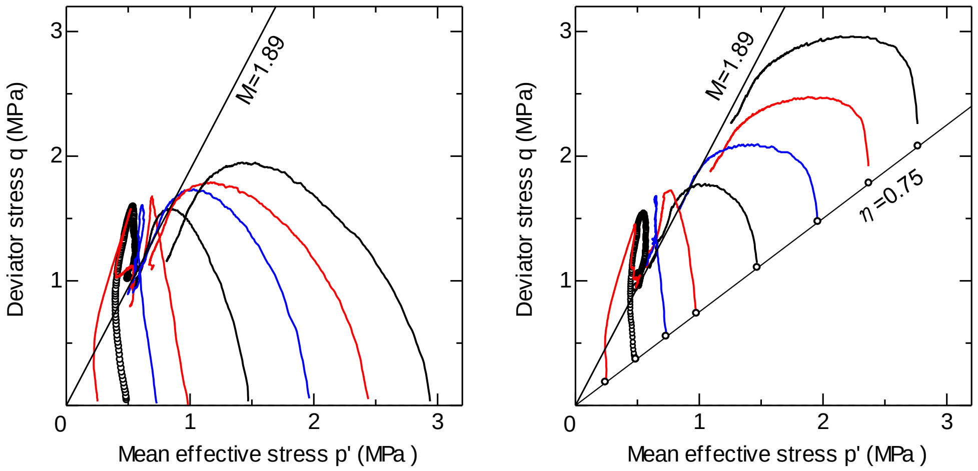
Fig. 3 Stress strain relations for consolidated undrained test resulted from isotropic and anisotropic consolidation samples

Figs 3 and 4 show comparisons of the stress-strain relationship and effective stress path at all consolidation pressures respectively. The stress-strain relationship demonstrates strain hardening-softening type of brittle behavior, with all relationships reaching residual strength by an axial strain of 18%. For anisotropic consolidation, the amount of strain at peak strength decreases and hardness increases however for isotropic consolidation the strain is increasing with enlarging consolidation pressure. The rate of decrease of deviator stress (the gradient of the straight line) moves from peak strength to residual strength at $p \geq 1.96$ MN/m^2 differs because of differences between isotropic and anisotropic consolidation. In addition, from the effective stress path of Fig. 4, a difference in dilatancy characteristics is apparent, as seen in cohesive soil at the boundary of consolidation yield stress p_c. Furthermore, the value of *M* noted in the diagram is the average value found from the maximum stress ratios of all tests.

Figure 5 shows the relationship between peak strength q_p and residual strength q_r (at ε_a=18%), and the mean effective stress on a double logarithmic scale. In previous researches on soft rocks, the results were arranged to approximate the maximum and residual strength for the overconsolidated and normally consolidated conditions with almost straight lines, and the result of this diagram approximately agrees with the approximation. However, the results shown by the dotted line have a higher correlation for the residual strength of the anisotropic normally consolidated condition. With this regard, further data collection and investigation are needed.

3.2 Residual strength and creep strength

Figure 6 demonstrates the ratio q_r/q_p plots against consolidation pressure for the consolidated undrained test. Regardless of the consolidation pressure, q_r/q_p of isotropic consolidation is around 0.6, with all values for anisotropic consolidation being larger than those for isotropic consolidation, and the values increase rapidly to 0.75 as soon as consolidation pressure was beyond p_c. Figs 7 and 8 show the creep test results for creep time and strain, and time and strain rate, respectively. As indicated in the legend, the results show that creep failure



(a) Isotropic consolidation (b) Anisotropic consolidation

Fig. 4 Stress paths for consolidated undrained test results from isotropic and anisotropic consolidation samples

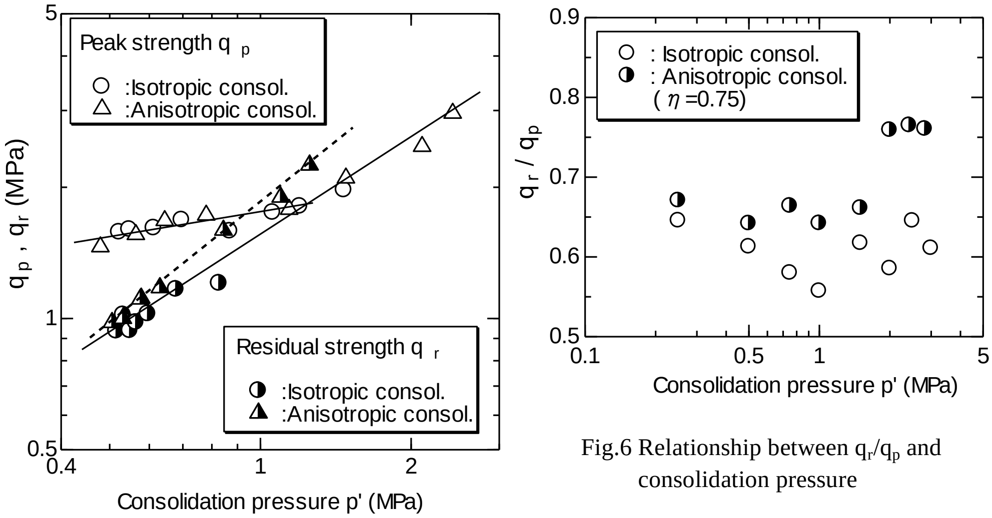
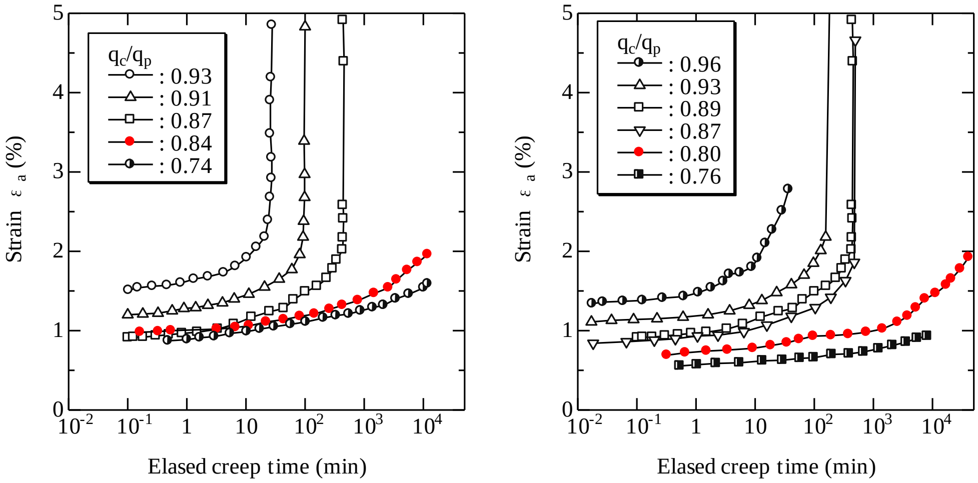


Fig. 5 Peak strength and residual strength lines

Fig.6 Relationship between q_r/q_p and consolidation pressure

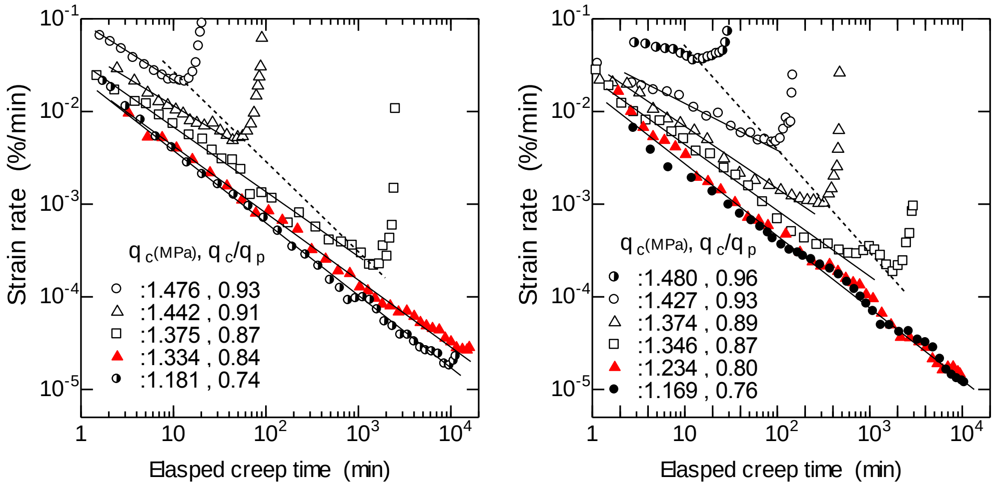


(a) Isotropic consolidation (b) Anisotropic consolidation

Fig .7 Creep time and strain (p = 0.49 kN/m^2) in the undrained creep test does not occur at q_c/q_p < 0.84, which is less than 84% peak strength, for either isotropic or anisotropic consolidation. Although there are reports that the creep strength of soft rocks is almost equivalent to the residual strength[4], the present result shows that the creep strength of the tested specimens is much higher than their residual strength.

4. Conclusion

Most previous researches on the strength-deformation properties of soft rocks have involved triaxial compression tests using the isotropically consolidated specimen. We demonstrated that, the ratio of residual strength to peak strength q_r/q_p becomes larger than isotropic consolidation for diatomaceous mudstone due to the anisotropic consolidation and specifically remarkable increases in normal consolidation condition. However, there are reports that the creep strength of soft rocks is almost equivalent to the residual strength[4], and the creep strength of mudstone is almost equal to residual strength. The finding of this research shows that the creep strength of diatomaceous mudstone used in this study is larger about 20% than residual strength.



(a) Isotropic consolidation　　(b) Anisotropic consolidation

Fig .8 Creep time and strain rate (p = 0.49 kN/m^2) in the undrained creep test

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