

STRESS-DILATANCY RELATION OF UNDISTURBED CLAY UNDER PRINCIPAL AXES ROTATION

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ABSTRACT

Drained torsion shear tests of anisotropically consolidated undisturbed clay were carried out using hollow cylindrical specimens, in order to investigate the effects of principal axes rotation particularly on the dilatancy characteristics of undisturbed clay. The magnitude of dilatancy is considered to represent the microstructural change of undisturbed clay during the drained torsion shear process. The plastic volumetric strain of clay was experimentally observed to occur just due to the principal axes rotation under constant mean principal stress p' and principal stress difference q drained shear conditions. The plastic volumetric strain increment of undisturbed clay under a magnitude of principal axes rotation was found to be greater than that of reconstituted clay.

KEYWORDS

Clay, Soil Structure, Dilatancy, Torsion, Drained Shear, Stress Path

INTRODUCTION

Stress-strain-strength characteristics of clay are considered to be dependent upon their microstructure. The change of soil microstructure may be caused by the change of total stress system including the rotation of principal axes, which applied to the in-situ soil element in the case of earthquake and wave induced loading (e.g., Saada, 1988). However, the mechanical properties of clay were conventionally investigated using triaxial apparatus, where the principal axes were fixed. The microstructure change, i.e. the dilatancy can be assumed to take place also under the rotation of principal axes.

The microstructure change of soil is considered to be represented by the constitutive law in the geomechanical sense. Most of the successful consti-

tutive laws of geomaterials hitherto proposed, for example *Cam Clay model* (Schofield and Wroth, 1968) and *Sekiguchi - Ohta model* (Sekiguchi and Ohta, 1977) are constructed using the plastic volumetric strain developed during drained deformation as a hardening parameter. Plastic volumetric strain ε_v of *Cam Clay model* is correlated with the magnitude of mean principal stress p' and principal stress difference q , as in Eqn.1.

$$\varepsilon_v = \frac{\lambda}{1 + e_0} \ln \frac{p'}{p'_0} + \frac{\lambda - \kappa}{M(1 + e_0)} \frac{q}{p'} \quad (1)$$

in which λ and κ are compression and swelling indices, M is a critical state parameter and e_0 is the initial void ratio of clay consolidated with the pressure of p'_0 . *Cam Clay model* does not predict the generation of volumetric strain under constant p' and q conditions.

In the case of *Sekiguchi-Ohta model*, the magnitude of mean principal stress p' and stress ratio η^* were used to represent the plastic volumetric strain ε_v during shear as follows.

$$\varepsilon_v = \frac{\lambda}{1 + e_0} \ln \frac{p'}{p'_0} + D\eta^* \quad (2)$$

where

$$\eta^* = \sqrt{\frac{3}{2}(\eta_{ij} - \eta_{ij0})(\eta_{ij} - \eta_{ij0})}$$

$$\eta_{ij} = \frac{s_{ij}}{p'}, \quad \eta_{ij0} = \frac{s_{ij0}}{p'_0}$$

D is a dilatancy constant. s_{ij} is a deviatoric stress tensor and s_{ij0} and p'_0 are the values of deviatoric stress tensor and mean principal stress at the end of K_0 consolidation. Since the value of stress ratio η^* is not constant during principal axes rotation under constant p' and q conditions, *Sekiguchi-Ohta model* is able to predict the generation of plastic volumetric strain.

The quantitative evaluation of open micro-structure of undisturbed natural clay is the aim of this study. A series of drained torsion shear tests on hollow cylindrical specimens of undisturbed and reconstituted clay were carried out, where the magnitudes of p' and q were kept constant throughout the tests. The volume change characteristics of undisturbed and reconstituted clay samples under principal axes rotation were compared.

EXPERIMENTAL PROCEDURES

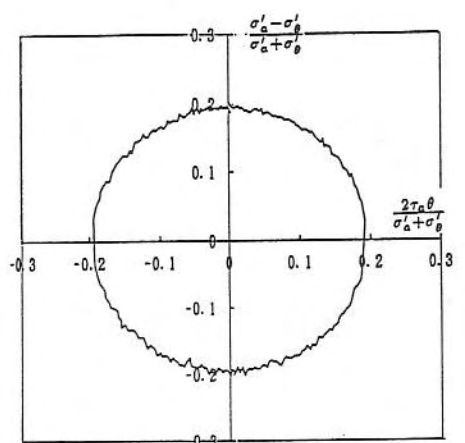
An undisturbed clay sample block used in this study was obtained from a shield tunnelling site in the southern area of Tokyo. The physical properties of the clay sample are listed in Table 1. Hollow cylindrical specimens (external diameter = 7(cm), internal diameter = 3(cm), height = 10(cm)) were prepared using undisturbed clay sample block mentioned above. The value of sensitivity of undisturbed clay determined from unconfined compression test is 7.3.

At first, the hollow cylindrical specimens were anisotropically consolidated under constant rate of axial stress increase of 8.17×10^{-4} (kN/m²·s) for about 2(days) up to two different values of axial stress 168.0 and 240.0 (kN/m²). After the completion of anisotropic consolidation, drained torsion shear tests were carried out using the con-

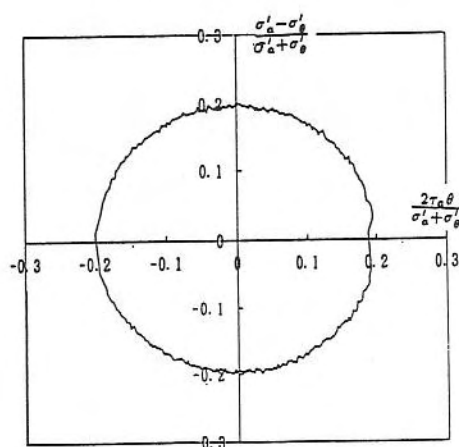
TABLE 1
PHYSICAL PROPERTIES OF CLAY
SAMPLE

Density of soil particles ρ_s (g/cm ³)	2.69
Liquid limit w_L (%)	97.5
Plasticity index I_P	56.6

Figure 1



(a) $p'_0 = 140.0$ (kN/m²)



(b) $p'_0 = 200.0$ (kN/m²)

Effective stress paths

trolled torsion shear loading of 1.14×10^{-3} (kN/m²·s).

During this process, axial stress σ'_a , circumferential stress σ'_θ and radial stress σ'_r were automatically controlled by a personal computer to keep the mean principal stress $p' = (\sigma'_1 + \sigma'_2 + \sigma'_3)/3$ constant and the stress ratio $k = (\sigma'_1 - \sigma'_3)/(\sigma'_1 + \sigma'_3)$ used was 0.2. The intermediate principal stress parameter $b = (\sigma'_2 - \sigma'_3)/(\sigma'_1 - \sigma'_3)$ was almost kept constant at the value of 0.5 throughout the anisotropic consolidation and the drained torsion shear loading, which corresponds to plane strain condition provided that the Poisson's ratio $\nu=0.5$. The values of mean principal stress p'_0 used in the experiments were 140.0(kN/m²) and 200.0(kN/m²).

Consequently, the effective stress path during drained torsion shear became circular shape on the stress diagram between $(\sigma'_a - \sigma'_\theta)/(\sigma'_a + \sigma'_\theta)$ versus $2 \cdot \tau_{a\theta}/(\sigma'_a + \sigma'_\theta)$, as shown in Figs.1(a) and (b). From these figures, the automated stress control system provided by a personal computer can be considered to work as required.

Figures 2(a) and 2(b) demonstrate the variations of three principal stresses and the intermediate principal stress parameter b during drained torsion shear loading. Although the precise control of the intermediate principal stress parameter was very difficult, the value of b was almost kept constant.

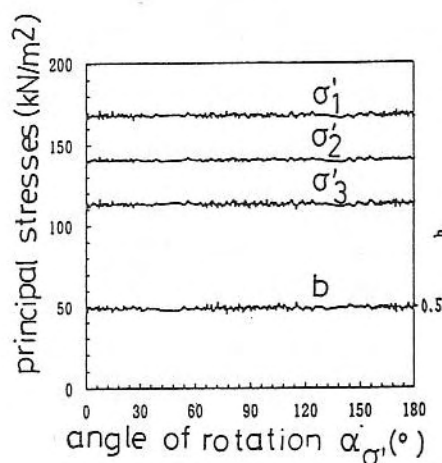
STRESS-DILATANCY CHARACTERISTICS OF UNDISTURBED CLAY

The magnitude of plastic volumetric strain ε_v of undisturbed clay sample under principal axes rotation is plotted against the angle of rotation of principal axes in Fig.3. Although the values of mean principal stress p' and principal stress difference q were kept constant throughout the drained torsion shear process, the compressive volumetric strain ε_v are remarkably increased up to 2(%) of the initial volume of the specimen.

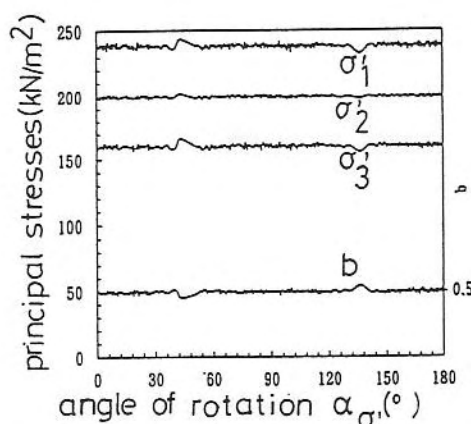
The plastic volumetric strain of undisturbed clay accumulates with the variations of the magnitude of plastic shear strain ε_s , as shown in Fig.4.

Reconstituted clay samples were prepared by remoulding disturbed clay samples obtained from excavation sites in Tokyo. Figures 5 and 6 de-

Figure 2



(a) $p'_0 = 140.0$ (kN/m²)



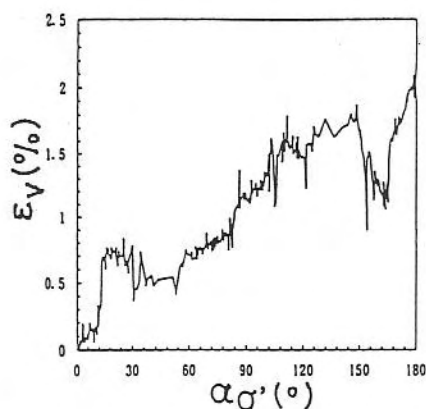
(b) $p'_0 = 200.0$ (kN/m²)

Variations of principal stresses and b parameter

mostrate the volumetric strain ε_v developed during the drained torsion shear process under variable and constant b loading against the angle of rotation of principal axes. The variation of the mean principal stress p' and the intermediate principal stress parameter b are plotted in the same figures (Akagi and Saitoh, 1994). Although the value of mean principal stress p' was kept constant throughout the drained torsion shear process of these reconstituted clay samples, the compressive volumetric strain ε_v are increased up to 4(%) of the initial volume of the specimen in the case of stress ratio $k = 0.4$. The magnitude of this negative dilatancy becomes greater, when the stress ratio k becomes greater. The dilatancy characteristics of reconstituted clay observed during drained torsion shear loading is assumed to be less influenced by the variation of intermediate principal stress parameter b . Although the types of clay samples are different, the comparison of the magnitudes of volumetric strain ε_{vf} observed at the final stages of drained torsion shear under the same stress ratio $k = 0.2$ is conducted between undisturbed and reconstituted clay samples. The magnitude of ε_{vf} of undisturbed clay amounts to approximately 2 (%) as shown in Fig.3, but in the case of reconstituted clay ε_{vf} is just 0.5 (%) as shown in Fig.6(a).

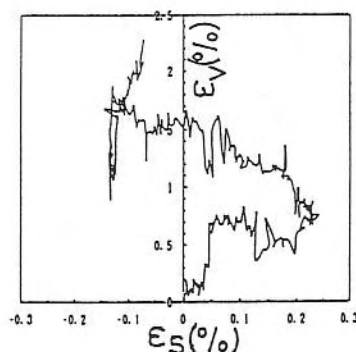
Figure 7 compares the volume contraction during principal axes rotation between undisturbed clay and different type of reconstituted clay. Although the values of initial specific volume v_0 of undisturbed clay samples are smaller than those of reconstituted clay samples, it is observed that the volume contraction of undisturbed clay is equal to or greater than that of reconstituted clay. Therefore, the magnitude of plastic volumetric strain increment $\Delta\varepsilon_v = \Delta v/v_0$ of undisturbed clay is greater than that of reconstituted clay. Since the number of successful experimental results using undisturbed clay samples and their reconstituted samples are limited, it is difficult to compare the dilatancy characteristics between undisturbed clay and reconstituted one directly. However, the differences of plastic volumetric strain increment observed in these experiments can be considered to represent the difference of clay microstructure between undisturbed clay and reconstituted clay quantitatively.

Figure 3



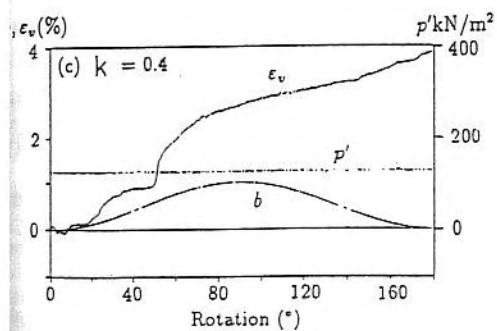
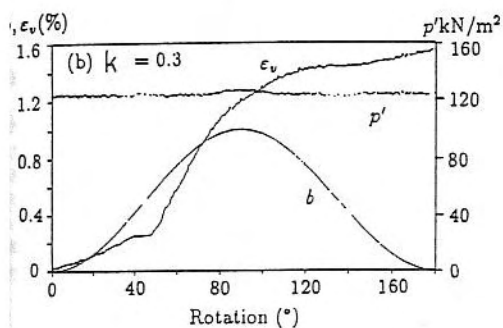
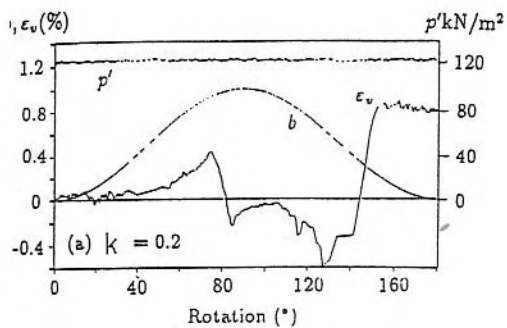
Generation of plastic volumetric strain during principal axes rotation

Figure 4



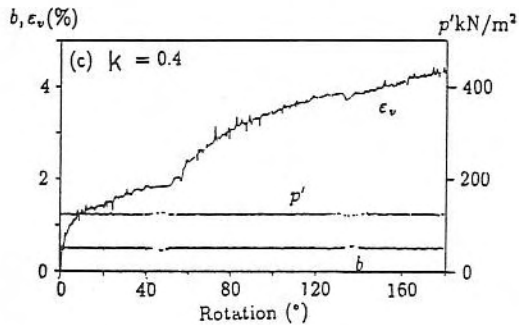
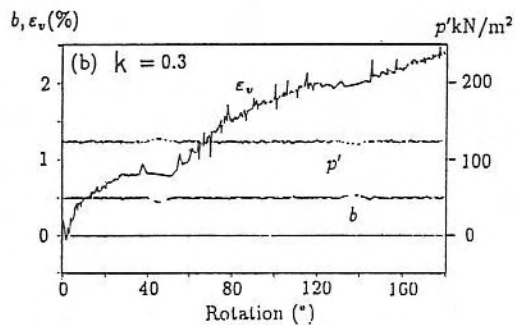
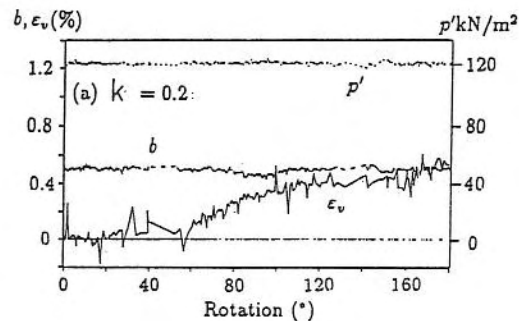
Relation between plastic volumetric strain and shear strain

Figure 5



Dilatancy characteristics under variable b loading (Akagi and Saitoh, 1994)

Figure 6



Dilatancy characteristics under constant b loading (Akagi and Saitoh, 1994)

CONCLUDING REMARKS

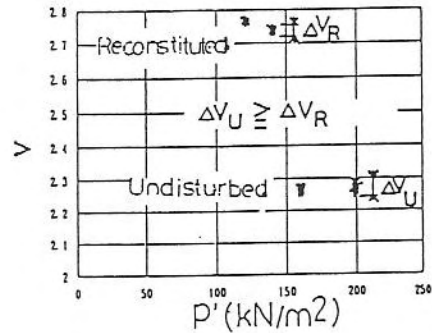
From these limited ranges of experimental results, it was concluded that:

- (1) the plastic volumetric strain of clay did occur due to the principal axes rotation under constant p' and q drained torsion shear conditions.
- (2) the plastic volumetric strain increment of undisturbed clay under a magnitude of principal axes rotation was greater than that of reconstituted clay.

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Figure 7



Comparison of volume contraction between undisturbed and reconstituted clay