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Shear stress behavior of unsaturated undisturbed black volcanic ash soil under cyclic loading

Kyushu University, Student member, ○ OKRI ASFINO PUTRA
Kyushu University, Fellow member, YASUFUKU Noriyuki
Kyushu University, Regular member, ISHIKURA Ryohei
NEXCO West, Regular member, KAWAGUCHI Yuko

1. Introduction

Black volcanic ash soil which is known as Kuro-boku soil in Japan that is a problematic type of soil [1]. Distribution of black volcanic ash soil covers approximately 31% of the total area of Japan, mainly within the volcanic zones [2]. Black volcanic ash soils are generally found near the slope surfaces above the groundwater table which can be generally as an unsaturated zone. Recently Kumamoto earthquake 2016 triggered many slope failures around the Aso area. The black volcanic ash soils and orange-colored pumice deposits are the most common types of soils that experienced failure in the Aso area. Many researchers have studied the volcanic ash soil in Kumamoto slope failures especially the orange-colored pumice [3]. However, small attention was given to the shear strength and characteristic of the black volcanic ash soil. In this paper, the shear stress behavior of unsaturated undisturbed black volcanic ash soil was evaluated. A series of cyclic tests using the constant volume direct shear box was performed. Furthermore, to consider the effect of overconsolidation ratio, normally consolidated and over-consolidated samples were tested.

2. Materials and sampling locations

Tests were conducted using undisturbed sample and collected at the middle and the top of the slope failure zone at the boundaries in Kumamoto slope failure. Samples were collected 1.5 m, from the original surface next to the failures zone boundaries and the cross-section mainly showed the black volcanic ash.

The median grain size D_{50} of black volcanic ash soil is approximately 0.012 mm. Based on that, the black volcanic ash soil can be classified as volcanic cohesive soil type II (VH2) according to the JGS standards. The yield stress in the unsaturated undisturbed sample was 105 kN/m^2 in average. Based on the consolidation test results, the black volcanic ash used in this research is considered as over-consolidated soil. Where the sampling depth is around 1.5 m, thus overburden pressure less than 105 kPa.

3. Methodology

In order to examine the shear stress behavior of the black volcanic ash soil under earthquake shakes, a series of constant volume direct shear box tests were carried out. In a cyclic test for overconsolidated sample 50 kPa vertical stress was applied. On the other hand, for normally consolidated sample 200 kPa vertical stress was adopted. Before the shearing start, specimens were consolidated under the designated vertical stress each condition for 1 hour. Then, sheared with the shear rate of 0.2 mm/min according to the JGS standards. The cyclic test under two pattern with displacement 1 mm were adopted. First type of pattern, cyclic one-sided shearing was applied. Where shearing was started from 0.5 mm to 1 mm, from 1 mm moving back to 0 mm and again to 0.5 mm. The total of displacement for one cycle was 2 mm. On the other hand, for the second type of pattern two-sided shearing was conducted. Where shearing was started from 0 mm to 0.5 mm, then from 0.5 mm moving back to -0.5 mm and again to 0 mm. The total of displacement for one cycle was also 2 mm. The schematic diagramof cyclic loading and test program were applied is shown in **Fig. 1.** and Table 1.

4. Results of shear stress (one-sided and two-sided) shearing

An empirical relationship of the overconsolidation ratio and the shear stress ratio in the static test was developed [5]. The relationship for the black volcanic ash soil [6] is shown

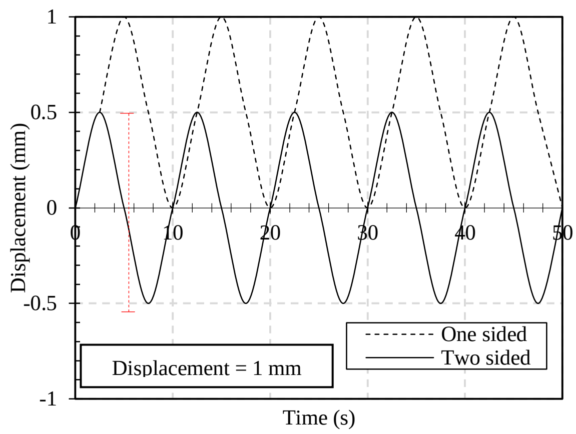

Fig. 1. Schematic of (one-sided and two-sided) cyclic loading.

Table 1. Test program for static and cyclic.

Test ID	Sample	Void Ratio (e_0)	Sr_0 (%)	Initial Suction* (kN/m^2) [4]	Vertical stress (kN/m^2)
One-sided cyclic					
C101	Unsaturated	4.03	67.8	100	50
C102	Unsaturated	4.01	69.5	100	200
Two-sided cyclic					
C201	Unsaturated	4.73	74.1	97	50
C202	Unsaturated	4.96	82.9	8	200

* Initial suction before shearing

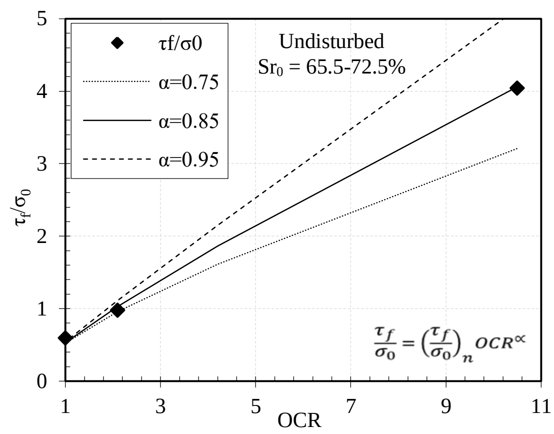

Fig. 2. Relationship of normalized shear stress and OCR.

in Fig. 2. The line represents an empirical model, while the scatter represents the experimental data. For OCR = 1 the shear stress ratio was 0.55, and the shear stress ratio increases as the increasing number of OCR. These obtained results are in well agreement with the kaolin clay behaviour [7].

The relationship between the normalized shear stress and number of cycles in the one-sided and two-sided as illustrated in **Fig. 3.** It can be observed on the one-sided cyclic that the normalized shear stress value decreases with the increasing number of cycles. On the other hand for the two-sided cyclic shearing test, the normalized shear stress value is higher than the one-sided cyclic shearing and increases with the increasing number of cycles. In other words, the stiffness of black volcanic ash soil changed during the cyclic test. It can be seen clearly the stiffness degrades with the increasing number of cycles in the one-sided shearing. However, for two-sided shearing the stiffness value increases with the increasing number of cycles till reaching the maximum value at the 10th cycles (final cycles).

Furthermore in the one sided shearing, it can be seen that the normalized shear stress for both normally and over-consolidated samples decrease with N indicating the cyclic shear stress degradation. For the cyclic strain controlled mode, the cyclic shear stress degradation with N can be quantified with degradation index, δ and degradation parameter, t. Where, τ_{SN} and τ_{S1} are the normalized shear stress after N cycles and first cycle at constant shear strain amplitude respectively.

$$\delta = \frac{\tau_{SN}/\sigma_0}{\tau_{S1}/\sigma_0} = \frac{\tau_{SN}}{\tau_{S1}} \quad ..(1) \qquad t = -\frac{\log \delta}{\log N} \quad ..(2)$$

The relationship between degradation index of cyclic shear stress and number of cycles is illustrated in **Fig. 4.** There is a significant difference between over-consolidated and normally consolidated samples. The degradation index value in the normally consolidated sample is higher than the over-consolidated sample and increases with the increasing number of cycles. In other words, the cyclic shear stress of normally consolidated samples degrades faster than over-consolidated samples under cyclic loading. It can be concluded that the rate of cyclic shear stress degradation decreases with increasing overconsolidation ratio.

The degradation parameter, t and cumulative displacement is shown in **Fig. 5.** It can be seen that the degradation parameter, t increases with the increasing of cumulative displcement. The degradation parameter, t tends to be lower for over-consolidated samples than for normally consolidated ones. Thus, small degradation parameter, t values correspond to low degrees of cyclic shear stress degradation.

5. Conclusions

The main conclusions are as follows:

1. The cyclic shearing pattern and direction significantly affect the shear stress behavior of black volcanic ash soil.
2. The cyclic shear stress of normally consolidated samples degrades faster than over-consolidated samples under cyclic loading. It can be seen in the degradation index and degradation parameter.

6. Acknowledgement

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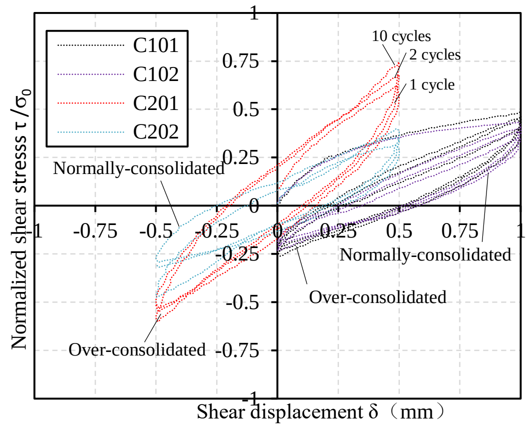

Fig. 3. Cyclic shear stress - displacement behavior under one-sided and two-sided shearing

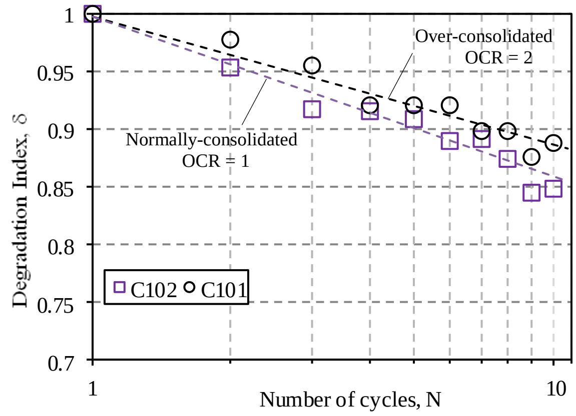

Fig. 4. Degradation index of cyclic shear stress in the one-sided shearing

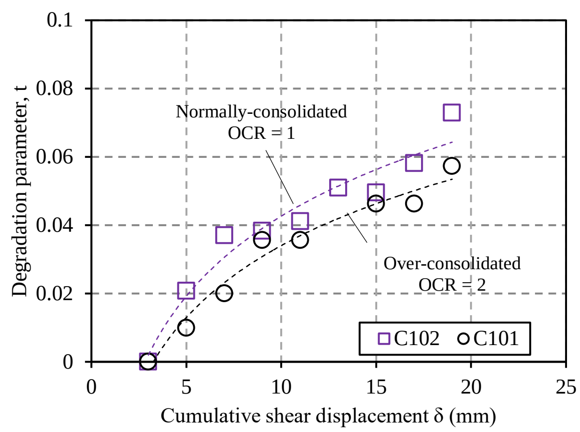

Fig. 5. Degradation parameter of cyclic shear stress in the one-sided shearing

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