Effect of soil structure disturbance on the vertical stress degradation black volcanic ash soil under cyclic loading

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1. Introduction

Recently in April 2016 an earthquake with a magnitude of 7.0 has struck the Kumamoto area and induced several slope failures around Aso mountain area. It was reported that orange-colored pumice deposits and the black volcanic ash soil are dominant in the affected area. According to (Miyabuchi, 2016), the critical factor that has led to those failures is the reduction in the total shear strength of the volcanic soil due to the earthquake load. Also, it has been observed that the earthquake caused a significant disturbance on the soil microstructure. Through this paper, the effect of soil structure disturbance on the vertical stress characteristics of black volcanic ash was evaluated using a simple methodology where the disturbance on soil structure was indirectly considered by studying the pore size distribution which was reflected from the soil-water characteristic curve (SWCC) using disturbed and undisturbed samples.

2. Materials and sampling locations

Samples were 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.

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. The shearing rate was 0.2 mm/min according to the JGS standards. The cyclic test with displacement 1 mm were adopted. The schematic diagram of cyclic loading and test program were applied is shown in **Fig. 1.** and Table 1.

4. Results of pore size distribution and vertical stress degradation

The pore size distribution for black volcanic ash soil was evaluated using SWCC for the drying phase. Different suction pressures correspond to the penetration of air in different pore sizes, which can be determined using the Washburn equation (Nimmo, 2014) as follows:

$$d = 4Ts\cos\alpha/P \qquad (1)$$

where d is the soil pore diameter; Ts is the surface tension; α is the contact angle between the soil particles and the fluid, and P is the applied pressure or the capillary/suction pressure.

The SWCC corresponding to the undisturbed and disturbed samples of black volcanic ash soil was reported by (Alowaisy et al., 2019) as illustrated in **Fig.2.** It can be observed that the disturbed sample has a larger air entry value in comparison to the disturbed sample.

Fig. 3 illustrates the pore size distribution of the black volcanic ash soil. It can be seen that there is a significant difference between the undisturbed and disturbed samples, where the cumulative pore volume corresponding to the undisturbed

Table 1. Test program for cyclic test

Test ID	Sample condition	Sr %	Void ratio (e_0)	Vertical stress (kPa)
C101	Unsat-Undisturbed	67.8	4.03	50
C102	Unsat-Undisturbed	69.5	4.01	200
C103	Sat-Undisturbed	99.5	4.41	50
C104	Sat-Undisturbed	96.8	4.45	200
CD101	Unsat-Disturbed	80.7	4.82	50
CD102	Unsat-Disturbed	79.4	4.61	200
CD103	Sat-Disturbed	100	4.96	50
CD104	Sat-Disturbed	100	4.90	200

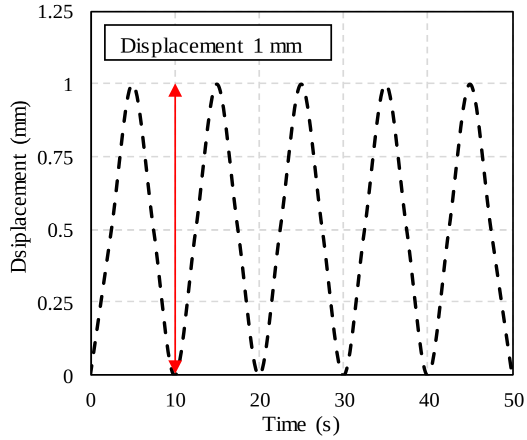

Fig. 1. Schematic diagram of the cyclic loading.

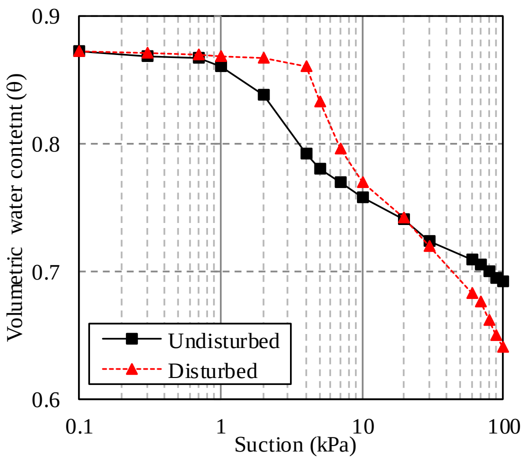

Fig. 2. The SWCC of the black volcanic ash soil

samples was found to be larger than that of the disturbed sample. The dominant pore diameter (one peak) of the undisturbed sample is observed with an average diameter of 72.8 µm. While for the disturbed sample, two dominant pore diameters (two peaks) were obtained with diameters of 41.6 and 4.9 µm respectively. That behavior can be attributed to the pore structure disturbance, where the undisturbed sample exhibits a unimodal pore structure, while the disturbed sample exhibits a bimodal pore structure. It must be noted that unimodal distribution indicates the existence of inter pore water only. While a bimodal distribution reflects both an inter pore and intra pore morphology. The inter pore represents the water molecules bounded between soil aggregates whereas the intra pore represents the water molecules bounded within the soil aggregates and on the clay particles surface. Consequently, it can be concluded that the pore structure of the disturbed sample is relatively unstable.

For the cyclic strain-controlled mode, the normalized vertical stress degradation with the number of cycles (N) can be quantified using the degradation index (δ). Where S_1 and S_N are the initial normalized vertical stress and the normalized vertical stress after N cycles at constant shear strain amplitude.

$$\delta = \left(1 - \frac{\sigma_{SN}/\sigma_0}{\sigma_{S1}/\sigma_0}\right) = \left(1 - \frac{\sigma_{SN}}{\sigma_{S1}}\right) \qquad (2)$$

The relationship between the degradation index of the cyclic normalized vertical stress and the number of cycles for the over-consolidated and normally consolidated samples are illustrated in **Fig. 4** and **Fig. 5** respectively. A significant difference between the undisturbed and disturbed samples can be observed. The degradation index value corresponding to the disturbed sample is 20 % higher than that of the undisturbed sample, where for both conditions the degradation index increases by increasing the number cycles. In other words, the cyclic normalized vertical stress of disturbed samples degrades faster than that of the undisturbed samples under cyclic loading. It can be concluded that the effect of soil structure disturbance can be observed in the cyclic normalized vertical stress degradation, where the degradation index of the cyclic normalized vertical stress is higher for the disturbed samples which can be attributed to the unstable micro-pore structure of the disturbed samples.

On the other hand, the degradation index of the cyclic normalized vertical stress in the normally consolidated samples was found to be larger than that of the over- consolidated samples. This trend can be attributed to the increase in the pore water pressure during shearing, where, the generated pore water pressure is significantly lower for over-consolidated samples in comparison to the normally consolidated samples. Furthermore, the degradation index tends to be lower for the unsaturated condition than that of the saturated conditions for both over-consolidated and normally consolidated samples. It can be related to the water content, which can be translated into the suction force which contributes to the total shear strength.

5. Conclusions

The undisturbed samples exhibit a unimodal pore structure and the disturbed samples exhibit a bimodal pore structure. Since the pore structure of the disturbed sample is unstable, the degradation index value is around 20 % higher than that of the undisturbed sample. In other words, the cyclic normalized vertical stress of disturbed samples degrades faster under cyclic loading.

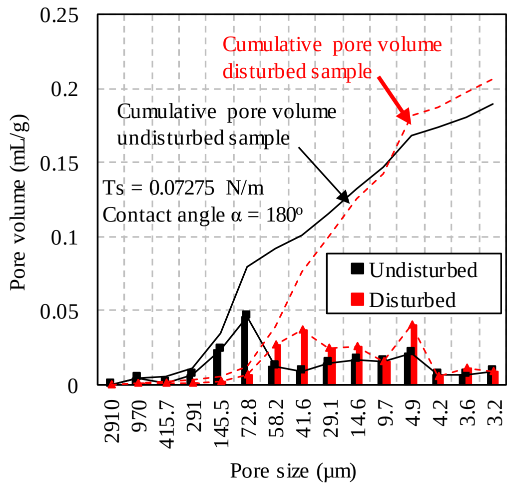

Fig. 3. Pore size distribution of the black volcanic ash soil

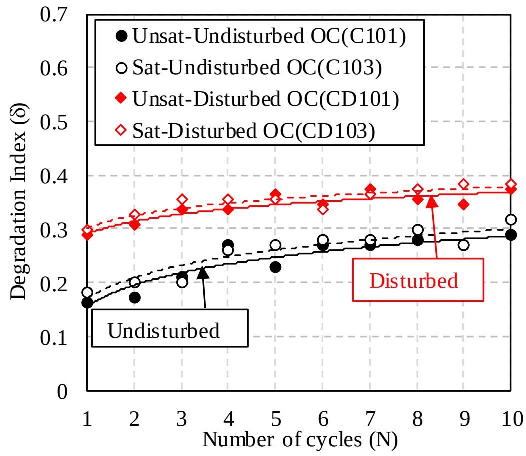

Fig. 4. Degradation index of over-consolidated sample

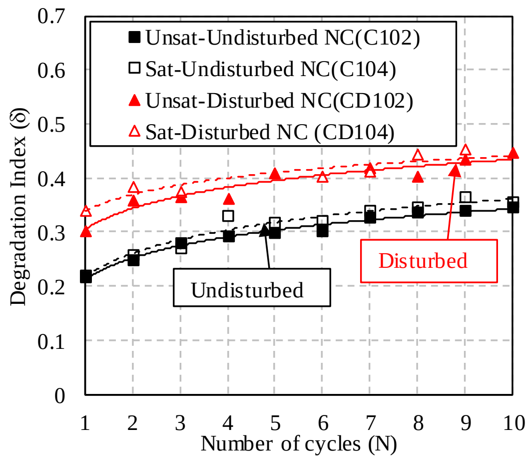

Fig. 5. Degradation index of normally consolidated sample

6. Acknowledgment

The authors express their gratitude to Laboratory Assistant Mr. Michio Nakashima for the assistant and support in the experimental test.

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