

Effect of soil structure disturbance on the shear strength of black volcanic ash soil

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Abstract. The effect of soil disturbance on the shear strength of black volcanic ash soil was investigated using a constant volume direct shear apparatus. Disturbance of soil structure was considered as the pore size distribution which obtained from the soil-water characteristic curve (SWCC). The disturbed sample was used as a representation of soil structure disturbance due to earthquake shakes. A series of cyclic tests were conducted under unsaturated and saturated samples. It was found that the undisturbed samples exhibit a unimodal pore structure, and the disturbed samples indicate to a bimodal pore structure. Since the pore structure of the disturbed sample is unstable, the degradation index value is higher than that of the undisturbed sample and increases with the increasing number of cycles. In other words, the cyclic normalized vertical stress of disturbed samples degrades faster. Furthermore, the degradation index value in the normally-consolidated samples was found to be larger than the overconsolidated. It might be attributed to increasing of the pore water pressure during shearing. Where in the over-consolidated samples is lower than normally-consolidated. On the other hand, the normalized shear stress of unsaturated samples, it is slightly larger due to the suction forces in the total strength of soils.

1 Introduction

Kuro-boku soil is the name for the black volcanic ash soil in Japan and considered as one of the problematic types of soil [1, 2]. Typical of kuro-boku is the organic cohesive volcanic ash soil, which contains the high of allophane and natural water content varying between 65-140% [3]. In general, the black volcanic ash soils are distributed around 31% of the whole area of Japan, largely in the volcanic zones area [4]. The black volcanic ash soils frequently were found in the top layer of the slope above the groundwater table with the saturation degree less than 100 % and can be classified as an unsaturated zone. It has been known that the resistance of soils with the unsaturated condition is higher than the saturated condition. But during the precipitation events, increasing of the pore water pressure results to the reduction of the total shear strength of soil and stability of slope will reduce.

Recently in April 2016 due to the Kumamoto earthquake, several slope failures occurred around the Aso mountain area. It was found that the most common types of soil in the Aso mountain slope failure are the orange-colored pumice deposits and the black volcanic ash soils. According to [5-8], the critical factor is correlated to the reduction of the total shear strength the volcanic soils due to the earthquake loads. Also, it has

been observed that the earthquake shakes give a huge effect on the disturbance of soil structure. It is known that the extent of the damage to soil structure caused by earthquakes is related to the total of soil shear strength. The condition of soil structure during of earthquake shakes is illustrated in Fig. 1.

The soil structure disturbance effect on the total shear strength of soil has been studied by many researchers [9-11]. In general, most of them investigated the relationship between the total shear strength using the series cyclic triaxial test, and comparison with the results of microstructure characteristic from Scanning Electron Microscope (SEM) and X-ray fluorescence analysis (XRF) (before/after shearing). It is well known that methods need special equipment and skill that is not generally available in soils laboratories.

In this paper, the effect of soil structure disturbance on the shear strength of black volcanic ash was evaluated with the simple method using common equipment in the soil laboratories. Disturbance of soil structure was considered as the pore size distribution which obtained from the soil-water characteristic curve (SWCC). The disturbed sample was used as a representation of soil structure disturbance due to earthquake shakes. The constant volume direct shear box with a series of cyclic tests was carried out. In order to clearly understand the black volcanic ash soil behavior is similar to the natural

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condition, the undisturbed samples were used. Furthermore, to examine the effect of precipitation events with changes the moisture content, saturated samples were analyzed.

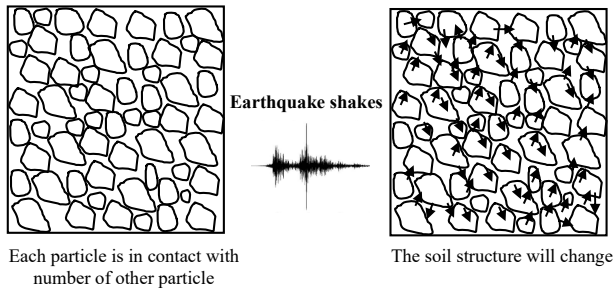


Fig. 1. Soil structure formation during earthquake shakes.

2 Methodology and Materials

2.1 Materials and sampling locations

The undisturbed and disturbed samples were used for the test. Due to the Kumamoto earthquake in April 2016, several slope failures occurred nearby the Aso area. The sample was obtained from the top and middle near the boundaries of the slope failure zone, as shown in Fig. 2. Sampling depth was 1.5 m from the original of the slope surface close to the failures zone borders area and exposed the black volcanic ash soil in the cross-section.

Table 1 illustrated the physical characteristics of the black volcanic ash soils. It can be observed the liquid limit value between 154 % - 214 %. The grain size distribution curve is illustrated in Fig. 3. It was mentioned that the median grain size D_{50} of the black volcanic ash soil is approximately 0.012 mm. According to the Japanese Geotechnical Society (JGS) standards, the black volcanic ash soil is considered as type II of cohesive volcanic soil (VH2)

The consolidation test results with the various degree of saturation illustrated in Fig. 4. It can be seen that the Preconsolidation stress was 105 kN/m² on average for the unsaturated undisturbed sample. Thus, the black volcanic ash soil for this research is classified as over-consolidated soil. With the depth of sampling is about 1.5 m, the overburden pressure smaller than 105 kPa.

2.2 Methodology

The shear strength characteristic and properties of the black volcanic ash soil were evaluated using the direct shear box (constant volume) tests considering both undisturbed and disturbed samples. In the constant volume test, the volume of the samples will keep constant or change in the volume during shearing is not allowed. Fig. 5. shows the schematic of the direct shear box apparatus. The circular sample with 2 cm in height and 6 cm in diameter was provided for the test. Furthermore, evaluation of the shear strength behavior the black volcanic ash soil due to the earthquake loads, the cyclic direct shear box tests with both unsaturated and saturated samples were carried out. The 50 kPa

vertical stress was selected in the cyclic test for the over-consolidated (OC) sample. While 200 kPa vertical stress for the normally-consolidated (NC) sample was applied.

Table 1. Physical properties of the black volcanic ash.

Physical properties		Black volcanic ash
Water content	(%)	111-159
Dry density, ρ_d	(g/cm ³)	0.56-0.58
Wet density, ρ_t	(g/cm ³)	1.18-1.25
Specific gravity		2.28-2.34
Liquid limit	(%)	154-214
Plastic limit	(%)	112-139
Organic matter	(%)	22.9-28.2

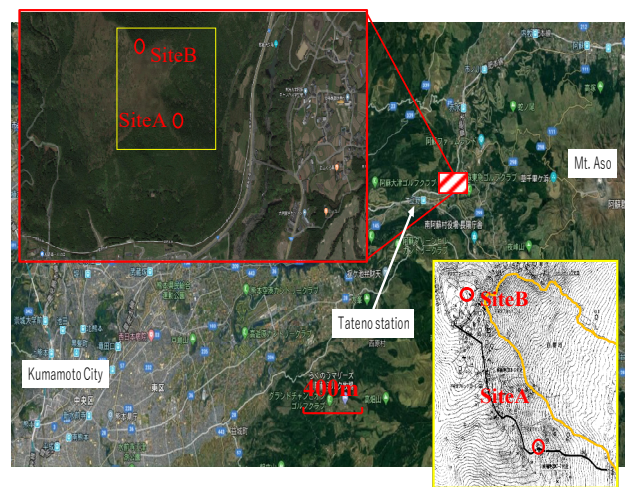


Fig. 2. Detail of sampling location.

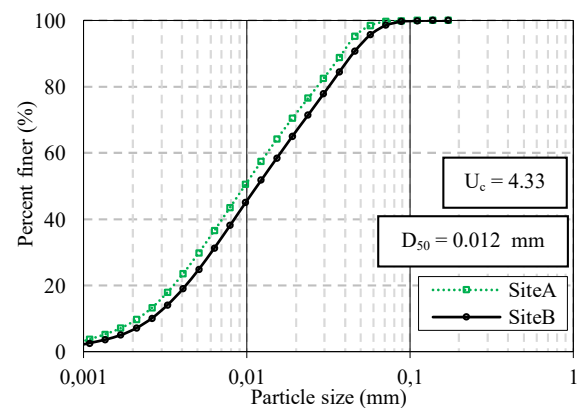


Fig. 3. The grain size distribution of the black volcanic ash.

Previously, the sample was consolidated with the selected value of the vertical stress for 60 minutes. Then, shear with the undrained condition test under a shearing rate speed of 0.2 mm/min corresponds to the Japanese Geotechnical Society (JGS) standards. Two models of the cyclic test with the shear displacement 1 mm were applied. The first type of model is the one-sided cyclic shearing, while two-sided cyclic shearing was conducted for the second type of the cyclic model. A schematic diagram selected models for the cyclic tests is indicated in Fig. 6.

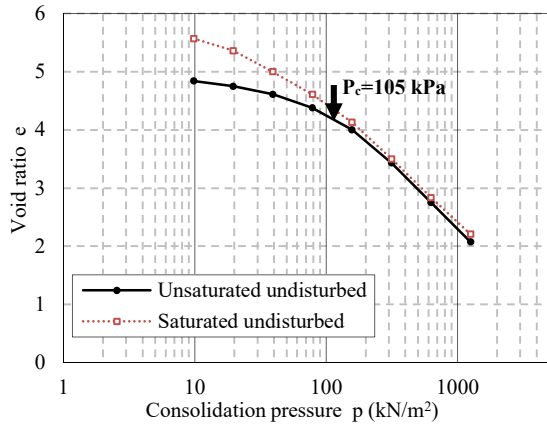


Fig. 4. The consolidation test results of the black volcanic ash.

It can be observed the significant differences between one-sided and two-sided cyclic shearing model. In the one-sided cyclic shearing model, the movement of cyclic was kept in the positive displacement. However, for the two-sided cyclic model, positive and negative displacement of the cyclic movement was adopted. Even though with a different direction, the cumulative displacement in the one cycle of the test for each cyclic model is 2 mm. For each model, the total number of cycles was 10 times. Also, Table 2 illustrated the test program and sample condition for the experimental.

3 Test results and discussion

3.1 Pore size distribution

Soil mass is a collection of soil particles of various sizes and shapes with pores filled with air and water. Pore-size distribution (PSD) is critical in understanding its physical, mechanical, and hydraulic behavior of soils [12]. Mercury Intrusion Porosimetry (MIP) is a well-known technique used to evaluate the pore size distribution (PSD) for porous media, such as soil and rock. In this technique, mercury at increasingly higher pressures is injected into the porous material, and the volume injected is recorded. Further Wang et al. [13] has been developed a simple technique to determine the pore size distribution using soil-water characteristic curve (SWCC) data. The obtained results are compared with MIP tests on the same soil. The PSD of soil is derived from SWCC as well as from MIP. The correlation between the two is seen to be excellent and also indicate the same trend. Also, the determination of PSD from SWCC only may be valid for a drying process.

Based on that, in this paper, the pore size distribution for black volcanic ash soil will also be evaluated by using SWCC for drying data. Different suction pressures correspond to the penetration of air in different pore sizes, which can be determined using the Washburn equation [14]

$$d = (4T_s \cos \alpha) / P \quad (1)$$

Where d is the soil pore diameter; T_s 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.

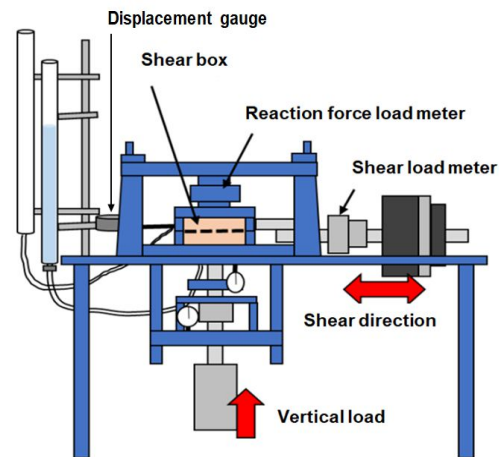


Fig. 5. The schematic diagram of the direct shear box test.

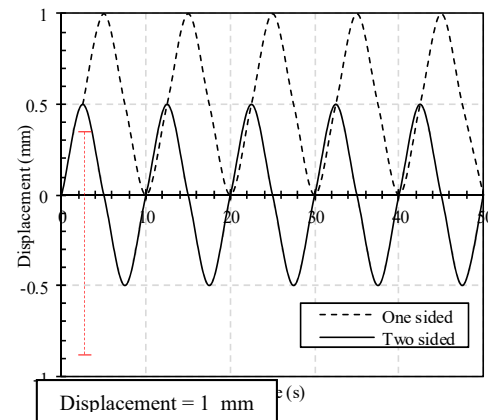


Fig. 6. Models of (one-sided and two-sided) cyclic loading.

Table 2. Test program for cyclic loading

Test ID	Sample Condition	Sr ₀ (%)	Void ratio (e ₀)	Vertical stress (kN/m ²)
One-sided cyclic				
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
Two-sided cyclic				
C201	Unsat-Undisturbed	74.1	4.73	50
C202	Unsat-Undisturbed	82.9	4.96	200
C203	Sat-Undisturbed	100	4.43	50
C204	Sat-Undisturbed	100	4.77	200
CD201	Unsat-Disturbed	81.6	4.54	50
CD202	Unsat-Disturbed	82.2	4.64	200
CD203	Sat-Disturbed	100	4.49	50
CD204	Sat-Disturbed	100	4.23	200

The SWCC of the undisturbed and disturbed sample of the black volcanic ash soil, according to Alowaisy et al. [15] is illustrated in Fig.7. It can be seen that the SWCC of the undisturbed samples has different the typical shape. Furthermore, the disturbing samples have a larger air entry value [16]. It is known that is related to the pore size distribution of black volcanic ash.

Fig. 8. illustrates the pore size distribution of the black volcanic ash soil. There is a significant difference between undisturbed and disturbed sample. The cumulative pore volume the undisturbed samples were found to be larger than that the disturbed samples. On the other hand, the dominant pore diameter of the undisturbed sample is observed only at one point that is 72750 nm. While in the disturbed sample, the dominant pore diameter was obtained on two points that are 41571 and 4850 nm. That behavior can be translated into the pore structure characteristic. Where the undisturbed samples exhibit a unimodal pore structure, and the disturbed samples indicate to a bimodal pore structure. In addition, a unimodal distribution representing only the inter pore. While a bimodal distribution representing both inter pore and intra pore. The inter pore represents the water molecules bounded between soil aggregates whereas the intra pore represents the water molecules bounded within the soil aggregated and on the clay surface. Thus, it can be concluded that the pore structure of the disturbed sample is unstable. The obtained results and tendency agree very well with the results obtained by Niu and Saranya [17, 18].

3.2 The behavior of cyclic shearing (one-sided and two-sided)

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

$$\delta = \frac{\sigma_{SN}/\sigma_0}{\sigma_{S1}/\sigma_0} = \frac{\sigma_{SN}}{\sigma_{S1}} \quad (2)$$

$$t = - \frac{\log \delta}{\log N} \quad (3)$$

In general, for the one-sided cyclic shearing, the normalized vertical stress reduces with the increasing the number of cycles. With the reduction of normalized vertical stress, the total shear strength of soil will also be reduced [19]. The reduction of normalized vertical stress might be associated with the increase of the pore water pressure during the shearing test. The relationship between the degradation index of cyclic normalized vertical stress and number of cycles is illustrated in Fig. 9 and Fig. 10.

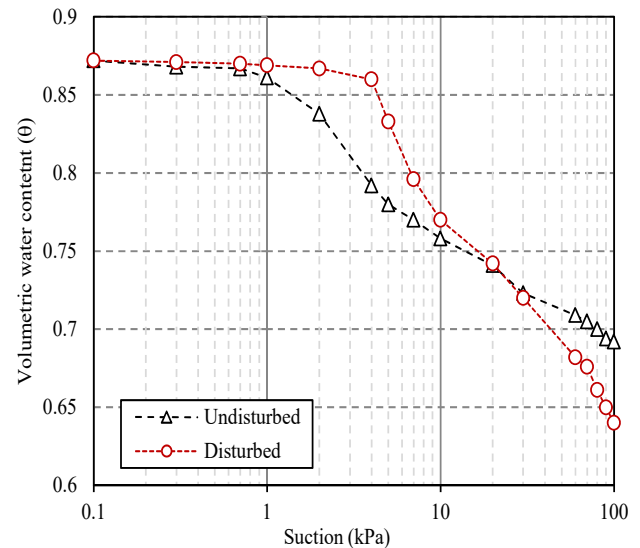


Fig. 7. SWCC of the black volcanic ash soil

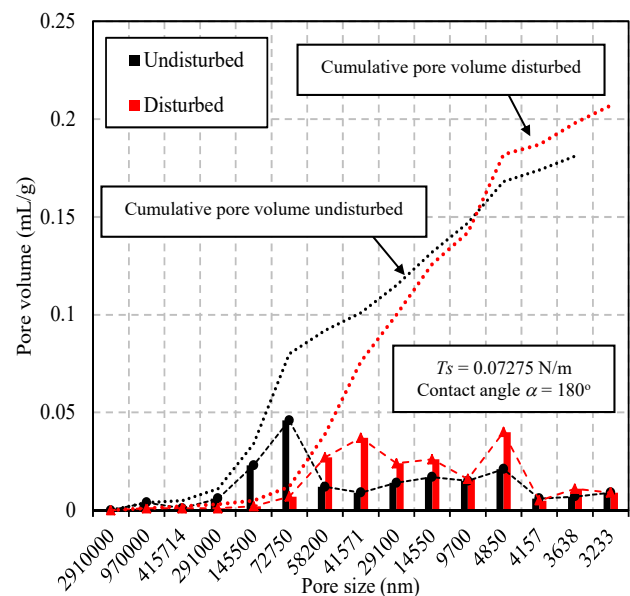


Fig. 8. The pore size distribution of the black volcanic ash soil

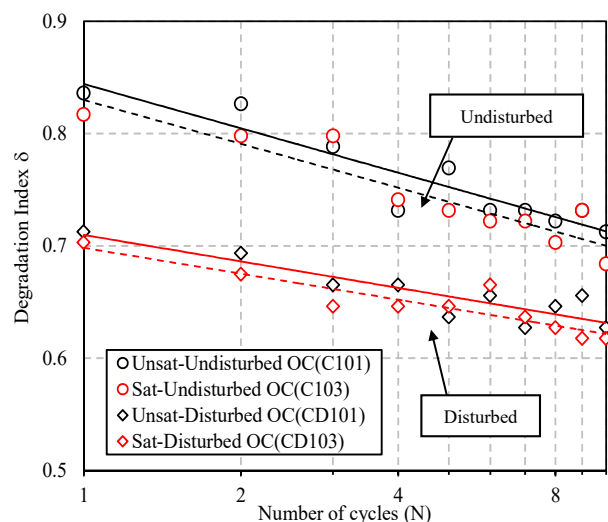


Fig. 9. Degradation index (δ) over-consolidated sample

There is a significant difference between undisturbed and disturbed samples. The degradation index value in the disturbed sample is higher than that of the undisturbed sample and increases with the increasing number of cycles. In other words, the cyclic normalized vertical stress of disturbed samples degrades faster than that of the undisturbed samples under cyclic loading. It must be noted that for both over-consolidated and normally-consolidated samples, the normalized vertical stress showed a similar reduction tendency. The normalized vertical stress decreases immediately at the beginning of shearing. It can be concluded that the effect of soil structure disturbance observed in the cyclic normalized vertical stress degradation. Since the pore structure of the disturbed sample is unstable, the reduction degradation index of cyclic normalized vertical stress will be higher.

On the other hand, the degradation index of cyclic normalized vertical stress in the normally-consolidated samples was found to be larger than that the overconsolidated samples. It might be related to the increase of the pore water pressure during shearing. Where in the over-consolidated sample is lower than that of the normally-consolidated samples.

The degradation parameter, t versus cumulative displacement are shown in Fig. 11 and Fig. 12. It can be seen that the degradation parameter, t increases with the increasing of cumulative displacement. It must be noted that for both over-consolidated and normally-consolidated samples the degradation parameter, t tends to be lower for unsaturated samples than for saturated samples. It can be said that the total shear strength of the soil strongly depends on the water content, which can be translated into the suction force contribution to the total shear strength. Thus, small degradation parameter, t values correspond to low degrees of cyclic normalized vertical stress degradation.

The relationship between normalized shear stress and the number of cycles in the normally-consolidated samples for one-sided and two-sided shearing is shown in Fig. 13 and Fig. 14. There is a significant difference between undisturbed and disturbed samples. The normalized shear stress in the undisturbed sample is higher than that of the disturbed samples. On the other hand, a significant discrepancy among one-sided and two-sided cyclic shearing was acquired. On the one-sided cyclic shearing, the test results showed that the normalized shear stress reduces since the beginning of the cyclic.

The obtained results are seen to be excellent and also indicate the same pattern with the Takanodai pumice under cyclic loading using direct shear box test [20]. While the higher of normalized shear stress value was obtained under the two-sided cyclic shearing test in comparison with the one-sided cyclic shearing test. It can be seen that the increasing number of cyclic associated with the increase of normalized shear stress value till achieving the maximum value at the 10th cycles (last cycles).

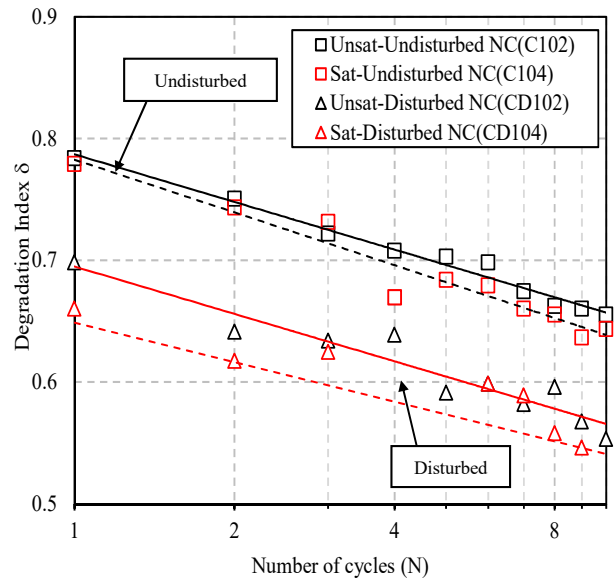


Fig. 10. Degradation index (δ) normally-consolidated sample

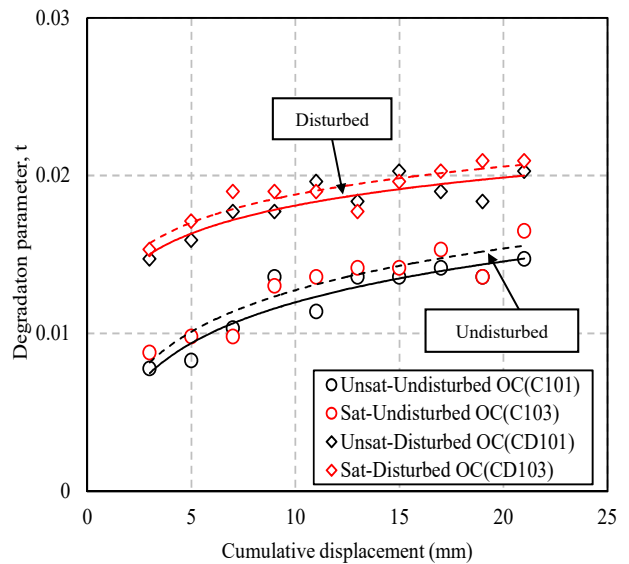


Fig. 11. Degradation parameter over-consolidated sample

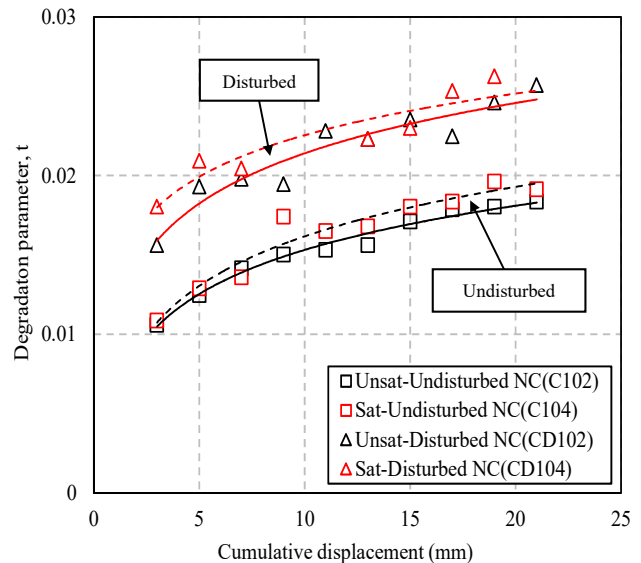


Fig. 12. Degradation parameter normally-consolidated sample

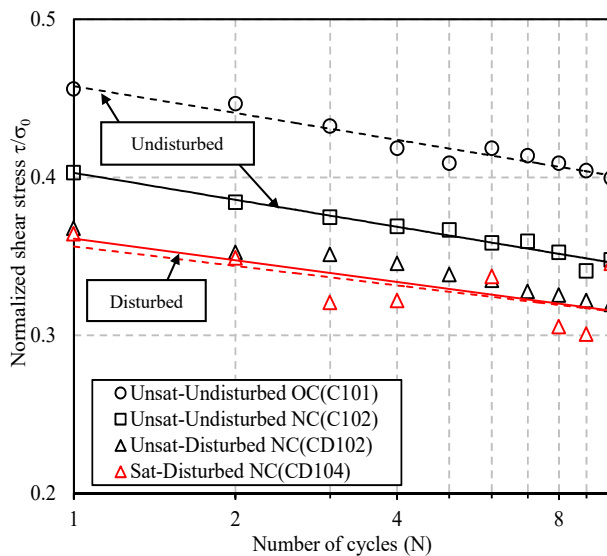


Fig. 13. Normalized shear stress for one-sided shearing

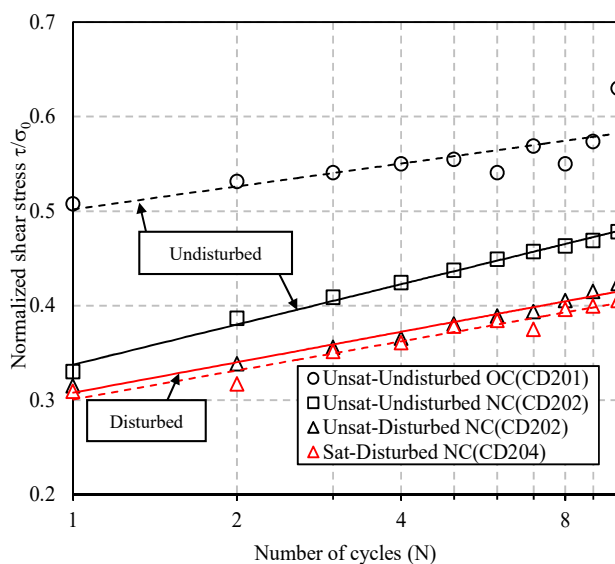


Fig. 14. Normalized shear stress for two-sided shearing

It might be confirmed to be a result increase in frictional resistance of soils. The results also indicate the same pattern with the two-sided cyclic shearing direct shear box test results reported by Putra [21]. It has been reported that the increasing number of cyclic associated with the increase of normalized shear stress for the strain-controlled test. Eventually, it can be concluded that the cyclic shearing pattern and direction significantly influence the total shear strength of the soil.

Also, it can be recognized that the normalized shear stress of unsaturated condition, it is slightly larger. The obtained results indicate a good correlation with the normalized vertical stress behavior in the cyclic shearing. It can be associated with the suction forces contribution to the total strength of soils.

4 Conclusions

Through this paper, the effect of soil structure disturbance on the shear strength of black volcanic ash

soil was examined using a constant volume direct shear box apparatus. A series of cyclic tests were carried out. Also, pore size distribution according to the soil-water characteristic curve (SWCC) data has been done. The main conclusions are as follows:

1. The undisturbed samples exhibit a unimodal pore structure and the disturbed samples indicate to a bimodal pore structure.
2. Since the pore structure of the disturbed sample is unstable, the degradation index value is higher than that of the undisturbed sample and increases with the increasing number of cycles. In other words, the cyclic normalized vertical stress of disturbed samples degrades faster under cyclic loading.
3. The degradation index value in the normally-consolidated samples was found to be larger than that of the over-consolidated samples. It might be associated with the increase of the pore water pressure during shearing. Where in the over-consolidated sample is lower than that of the normally-consolidated samples.
4. The normalized vertical stress and shear stress of the unsaturated samples are larger. This can be related to the influence of the matric suction contribution in the total shear strength of soils.

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