In situ testing on shallow landslide scars of Shirasu natural slopes covered by volcanic ash and pumice fall

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ABSTRACT: In Japan, forest occupies about 70% of the country. Approximately 90% of slope failures occurring in Japan are shallow landslides and the trigger is mostly rainfall in Southern Kyushu. In this study, site investigation and in situ tests on shallow landslide scars of Shirasu natural slopes were conducted to investigate the stability of the slopes and the effect of revegetation and soil development of forest topsoils from the viewpoint of forest ecology and geotechnical engineering. In this paper, ground characteristics on shallow landslide scars of Shirasu natural slopes were firstly investigated. Next, field direct shear tests using one surface-shearing testing apparatus and a soil strength probe were applied in situ.

Keywords: Shirasu natural slope; site investigation; in situ test; soil development; field direct shearing test

1. Introduction

Kagoshima Prefecture is located in the southern part of Kyushu Island. The surface ground in Kagoshima Prefecture is almost covered with volcanic products, such as pyloclastic flow deposits including volcanic ash and pumice fall and weathered igneous rock. The non-welded part of pyloclastic flow deposits is called Shirasu in Japanese, which is classified as a sandy soil. The density of Shirasu is lower than most silica sand due to the porous properties of the particles. Thus, Shirasu is relatively susceptible to erosion by the surface flow of rainwater. When heavy rain falls every rainy season, shallow landslides often occur on the slopes composed of Shirasu on which a thin surface humus layer is present. It is well-known that these shallow landslides occur due to the flooding of forest soils, the seepage of rainwater and an increase in self-weight of the soil mass. But it is very difficult to predict these natural disasters due to shallow landslide, quantitatively.

In order to prevent natural disasters due to shallow landslides, six test field points, where past occurrence of landslides due to heavy rainfall was identified, have been determined in the Takakuma experimental forest of Kagoshima University. In this study, site investigation and in situ testings on shallow landslide scars of Shirasu natural slopes were conducted to investigate the stability of the slopes and the effect of revegetation and soil development of forest topsoils from the viewpoint of forest ecology and geotechnical engineering [1, 2]. Firstly, the ground characteristics on shallow landslide scars of Shirasu natural slopes were described in this paper. Next, the field direct shear tests using one surface-shearing testing apparatus and a soil strength probe for the test field points were applied.

2. Test field

Six test field points (Shirasu natural slopes covered by volcanic ash and pumice fall) have been determined in the Takakuma experimental forest of Kagoshima University as shown in Fig. 1. The occurrence of landslides due to heavy rainfalls was identified by investigating past records of the Takakuma experimental forest, aerial photographs and the age of trees. In 2013, the elapsed years after the occurrence of landslides range from 8 to 58 years as shown in Table 1. No.6 point is the minimum and No.4 point is the max. These test fields are situated in the same field as shown in Fig. 1, face the north and the height above the sea level is about 520 m. The average inclination slope is over 37 deg. and the area of landslide scars range from 29 to 114 m^2.

Figure 2 shows the local photograph for No. 6 and No.4 points. As shown in these figures, No. 6 point is composed of various kinds of small trees and weeds, and large trees like evergreen broad-leaved trees are mostly seen in No.4 point.

3. Site investigation

3.1. Physical test

Figure 3 shows the depth of an effective topsoil layer and dry density of topsoils for the elapsed years after the occurrence of landslides. The depth of an effective topsoil layer was measured by soil augers, and the value is the average of test results at intervals of 1 m in vertical and horizontal directions on the area of each test field. As shown in Fig. 3(a), the development of a depth of an effective topsoil layer is relatively slow before approximately 30 years after the landslides, and after that the development becomes rapid. Revegetation developed on the forest soil and had grown to a thickness of approximately 40 cm by the time

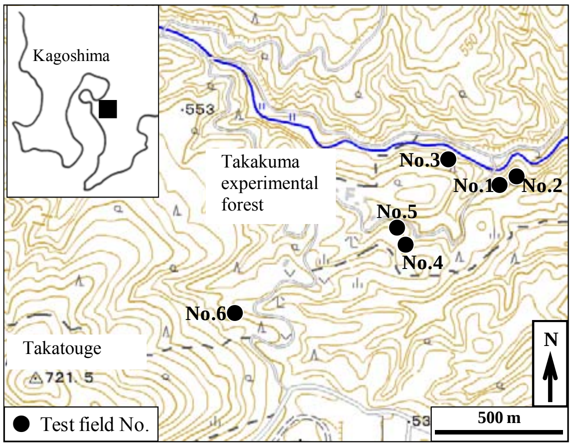


Figure 1. Test field.

Table 1. Properties of shallow landslide scars on six test field points.

Test field point	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Elapsed years after the occurrence of shallow landslide	12	22	40	58	28	8
Average inclination of slope (°)	38	41	40	39	37	42
Area of landslide scar (m^2)	36	29	61	114	34	42

(a) No.6

(b) No.4

Figure 2. Local photograph of test field points.

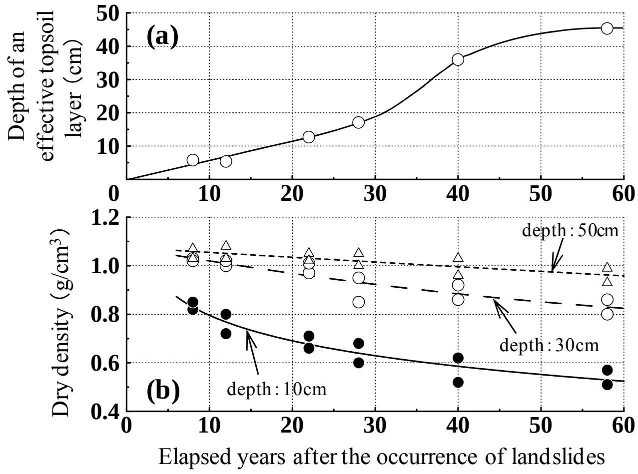
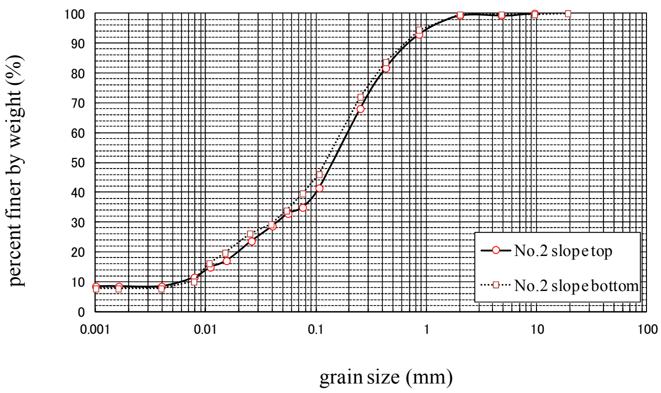
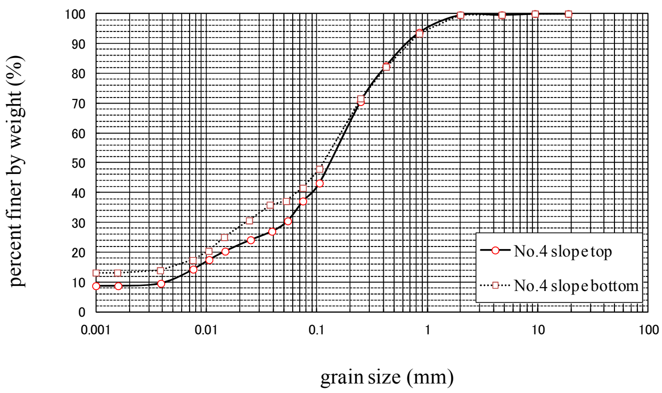


Figure 3. Depth of an effective topsoil layer and dry density of topsoils for the elapsed years after the occurrence of landslides.



(a) No.2



(b) No.4

Figure 4. Grain size distribution curves (No.2 and No.4).

the forest reached a climax approximately 40 years after the landslides. The average value of No.4 point (58 years have elapsed after the landslides) is 45.3 cm and the rate of development for a depth of an effective topsoil layer is 0.78 cm/year. This value is higher than the average value 0.45cm/year of shallow landslide scars on Shirasu in Kagoshima city for 80 years [3]. Because the average inclination of slope is around 50 deg. in Kagoshima city.

The sampling point was set for the upper and lower parts (2 points) of each shallow landslide scar to measure the dry density of forest topsoils. The dry density for each soil profile was measured by extracting the undisturbed sample at the depth of 10, 30 and 50cm using 100 ml cylindrical sampling. Note that the data is composed of a pair of plots (the upper and lower parts of each shallow landslide scar). As shown in Fig. 3(b), the dry density of forest topsoils tends to decrease with time after the occurrence of the landslide. Thus, the development of forest topsoils originates from shallow to deep depths due to the growing tree roots and the supply of organic substances followed by the revegetation of forest.

Figure 4 shows the grain size distribution curves for No. 2 and No.4 points. The sample was extracted at the depth of 30 cm from the ground surface. From these figures, the proportion of sand, silt and clay is approximately 70 %, 20 % and 10%, respectively for No.2 point. The grain size ranges of sand, silt and clay are 0.075-2.0 mm, 0.005-0.075 mm and less than 0.005 mm, respectively. Also, the proportion of silt and clay for No.4 point (Fig. 4(b)) is increased, comparing with No.2 point shown in Fig. 4(a). In both Fig. 4(a) and 4(b), the grain size distribution of slope bottom is finer than that of slope top.

To investigate the effect of soil permeability due to the development of a topsoil layer, the soil permeability test was conducted by setting 12 spots (2 spots for each test field), where the depth of an effective topsoil layer was different on shallow landslide scars. The spot was 1.0 m length in the slope direction and 0.5 m width, and the water was sprinkled over the ground surface. The details of the test can be found in [1]. Figure 5 shows the relationship between the depth of an effective topsoil layer (*ED*) and soil permeability (*Ir*). The straight line of this figure is the regression line and is as follows:

$$Ir = 1.21ED + 69.5 \ (r = 0.90) \tag{1}$$

where r is a multiple correlation coefficient. There is a good positive correlation and the soil permeability increases with the development of the depth of an effective topsoil layer. This fact is related with the increase of soil void that has a decrease of dry density due to the development of the depth of an effective topsoil layer, as shown in Fig. 3(b).

3.2. Soil analysis

The measurement of pH and contained-element concentration was conducted for the eluate of soil sampled from a topsoil in the test field. The soil sample was extracted at the depth of 10, 30 and 50cm from the ground surface in the slope top and bottom of test field points. In order to make the eluate for the measurement of pH, distilled water 50 g was added to the soil 20 g in natural drying and stirring for about 3 minutes by magnetic stirrer. After leaving as it is for 10 mininutes, the transparent part of supernatant liquid was measured.

Figure 6 shows the variation of pH for the elapsed years after the occurrence of landslides. There is a tendency, in which pH values decrease with the increase of time as shown in Figs. 6(a) and (b). On the whole, the pH values of slope bottom are smaller than those of slope top. This is because the acidification of soil due to the effect of humic acid. Also, the substances flowed from the top of slope would be accumulated at the bottom of slope by the effect of soil erosion. It is confirmed that the humus is progressed well and the color of samples become blackish as a whole from visual observations. Furthermore, from the results of measurement for contained-element concentration, the silicon, calcium, sulfur and iron were detected at every field points.

Table 2 shows the soil particle density and ignition loss in the test field. The soil sample was extracted at the depth of 30 cm from the ground surface in the slope top and bottom of test field points. The ranges of soil particle density ρ (g/cm^3) and ignition loss L_i (%) are 2.467-2.589 and 2.5-4.3, respectively, except for the ignition loss of No.2 slope top. It is therefore confirmed that the soil particle density in the test field is lower than that of most slica sand and the content of organic substances is relatively small.

4. In situ testing

4.1. Field direct shear apparatus

A field direct shearing apparatus was developed to conduct the direct shear test using an undisturbed big sample in situ, as shown in Fig. 7. The dimension of sample is 20 cm length, 20 cm width and 10 cm height. The volume of soil is 4000 cm^3. It is possible to conduct the test including pumice, gravel and thin tree roots by extracting the undisturbed sample in the field, due to the scale effect [4]. The shear and vertical loads is applied by a manual screw-jack mode and a manual wheel using a vertical stress loading device. Their maximum load is 2 kN. The rate of shearing is at the slow speed of 1.0 mm/min and conducted until the shear displacement reaches 25 mm. The measurement of shearing displacement is conducted by a dial gauge which indicates 1 mm in one cycle. At the same time, the shear and vertical loads are recorded every 1 mm of the shear displacement by checking their indicators.

4.2. Field direct shear test

The undisturbed soil sample was extracted at the depth of 30 cm from the ground surface in the slope top and bottom of test field points, as shown in Fig.8. Also, Figure 9 shows the vane cone shear test using a soil strength probe, which are described in section 4.3.

Figures 10-11 show the relationships between shear displacement and shear stress, and normal stress and shear strength for No.4 slope top obtained from the field direct shear test using one surface-shearing testing apparatus. In Fig.10, the initial vertical (normal) stresses (σ_n) are set as 4.02 kN/m^2, 9.02 kN/m^2 and 19.02 kN/m^2 by

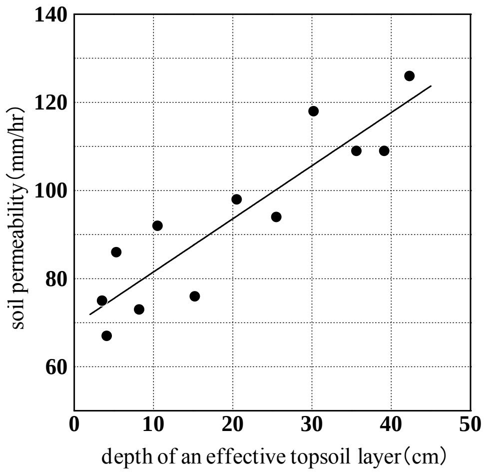
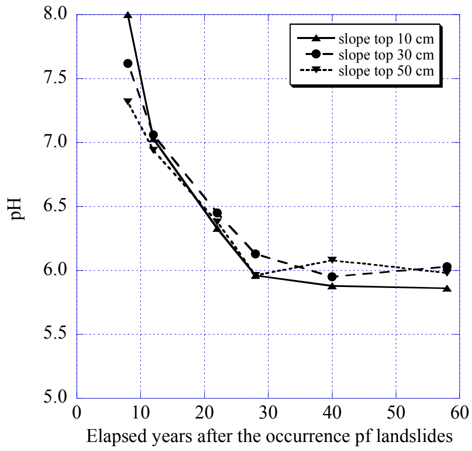
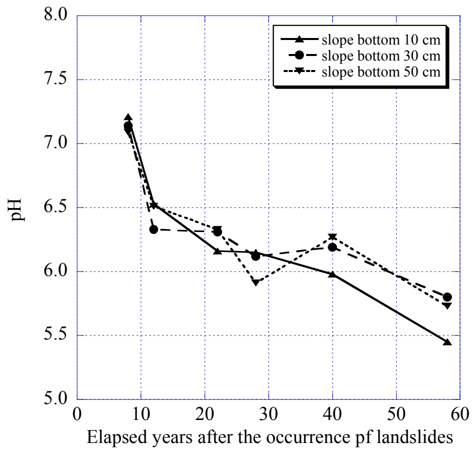


Figure 5. Relationship between depth of an effective topsoil layer and soil permeability.



(a) slope top



(b) slope bottom

Figure 6. Variation of pH for the elapsed years after the occurrence of landslides.

Table 2. Soil particle density and ignition loss.

Test field	soil particle density ρ (g/cm^3)	ignition loss L_i (%)
No.1 slope top	2.537	3.6
No.1 slope bottom	2.558	4.3
No.2 slope top	2.534	12.0
No.2 slope bottom	2.576	3.7
No.5 slope top	2.589	3.7
No.5 slope bottom	2.467	2.5
No.4 slope top	2.573	4.3
No4 slope bottom	2.567	3.1

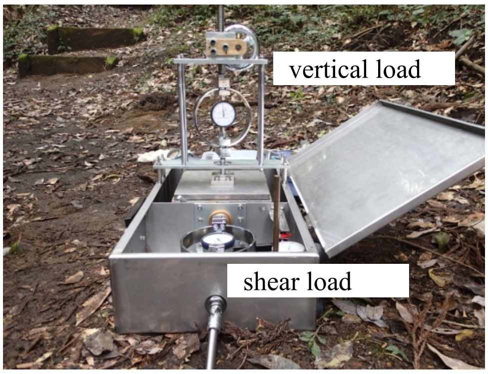


Figure 7. Developed field direct shearing apparatus.

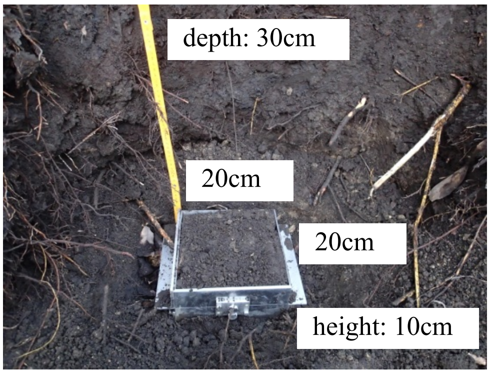


Figure 8. Sampling in the test field (No.4 slope top).

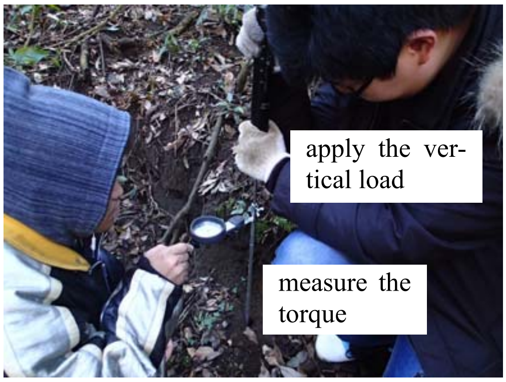


Figure 9. Vane cone shear test using a soil strength probe.

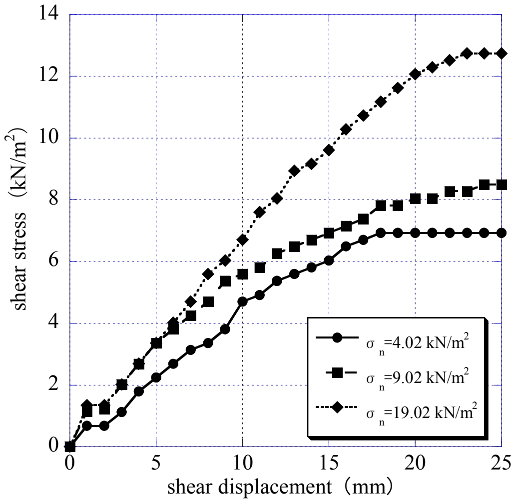


Figure 10. Relationship between shear displacement and shear stress (No.4 slope top).

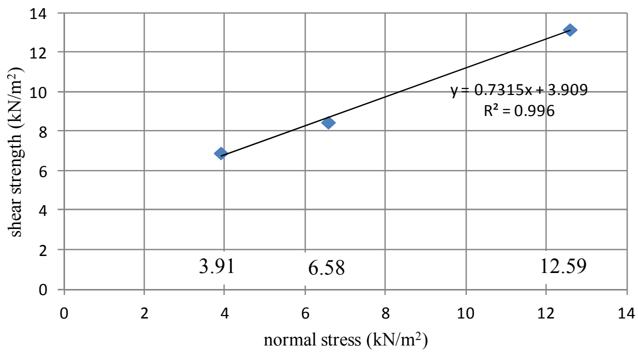
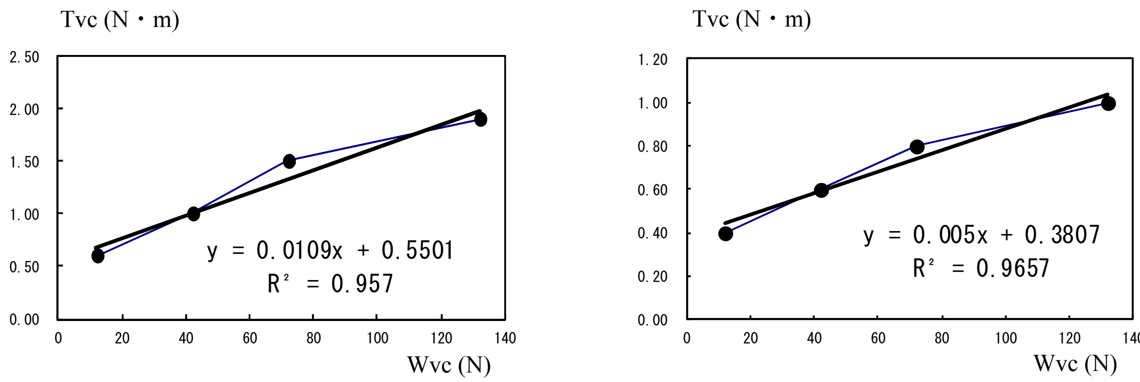


Figure 11. Relationship between normal stress and shear strength (No.4 slope top).



(a) slope top (b) slope bottom

Figure 12. Results of vane cone shear test (No.4).

Table 3. Strength parameters of soils obtained from field one surface-shearing test and its soil property.

Test field	field one surface-shearing test		soil property		
	cohesion c (kN/m^2)	internal friction angle ϕ (°)	wet density (g/cm^3)	dry density (g/cm^3)	water content (%)
No.1 slope top	3.3	28.5	1.37	1.00	37.0
No.1 slope bottom	2.9	36.3	1.45	1.05	37.5
No.2 slope top	4.6	36.2	1.20	0.75	61.2
No.2 slope bottom	4.0	30.7	1.30	0.88	47.2
No.5 slope top	4.3	35.2	1.29	0.91	42.0
No.5 slope bottom	4.9	29.4	1.23	0.85	44.4
No.4 slope top	3.9	36.2	1.24	0.87	42.7
No4 slope bottom	2.4	43.3	1.18	0.77	54.2

Table 4. Strength parameters of soils obtained from soil strength probe test and its soil property.

Test field	soil strength probe		soil property		
	cohesion c (kN/m^2)	internal friction angle ϕ (°)	wet density (g/cm^3)	dry density (g/cm^3)	water content (%)
No.1 slope top	4.8	5.1	1.12	0.74	50.5
No.1 slope bottom	4.4	6.3	1.07	0.74	43.9
No.2 slope top	5.2	7.4	1.23	0.79	55.1
No.2 slope bottom	4.2	4.3	1.21	0.81	49.2
No.5 slope top	10.1	7.8	1.46	1.02	43.6
No.5 slope bottom	10.3	7.0	1.14	0.89	27.8
No.4 slope top	5.6	7.5	1.39	1.04	33.1
No4 slope bottom	3.9	3.5	1.52	1.15	32.4

assuming shallow landslide phenomena. It is found that from Fig. 10 that the shear stress increases as the increase of the shear displacement and normal stress. Regarding the axes shown in Fig. 11, the shear strength is the maximum value of shear stress, and the normal stress means the stress when the shear strength is caused. Note that the initial normal stresses are reduced to 3.91 kN/m^2, 6.58 kN/m^2 and 12.59 kN/m^2 as shown the horizontal axis in Fig. 11. From Fig.11, the shear strength is increased as the increase of normal stress and there is a good correlation (the coefficient of determination, R^2=0.996). By obtaining the intercept and slope of the regression line, the strength parameters of the soils are c=3.9 kN/m^2 and ϕ=36.2°, respectively.

4.3. Soil strength probe

The field direct shear test using a soil strength probe ("dokenbou" in Japanese) were performed to measure the strength of soil layer in situ. The testing method is to measure the torque of the soil strength probe, applying the vertical load at the top of the probe. Figure 12 shows the results of vane cone shear test using "dokenbou". This figure is the correlation between vertical load Wvc (N) and torque Tvc (N・m) when the shear test is conducted by changing the vertical load at least 4 times. The working scene is shown as Fig. 9. These cases have quite a good agreement (the coefficients of determination are around 0.96) and the strength parameters c and ϕ of soils are calculated by the following conversion formula:

$$c_{dk} = 10.16 \cdot Y_0 \quad (2)$$

$$tan\,\emptyset_{dk} = 12.04 \cdot X \quad (3)$$

where c and ϕ are the cohesion and internal friction angle, and Y_0 and X are the intercept and slope of approximate equation. Note that this conversion formula is based on [5]. Thus, c_{dk}=5.6 kN/m^2 and ϕ_{dk}=7.5° are obtained for Fig.12(a) and c_{dk}=3.9 kN/m^2 and ϕ_{dk}=3.5° for Fig.12(b). The subscript letter dk denotes the "dokenbou".

5. Test results and discussion

Table 3 shows the strength parameters of soils obtained from the field one surface-shearing test and its soil property. For the cohesion, similar values are calculated for both slope top and bottom of each test field. But, there is a difference for the internal friction angle between slope top and bottom, because higher values are obtained. The soil properties for each test field were measured by extracting the undisturbed sample at the depth of 30 cm using 100 ml cylindrical sampling. The quality of these soil properties varies widely due to the undisturbed sample in the field. Table 4 shows the strength parameters of soils obtained from the soil strength probe and its soil property. Regarding the strength parameters of soils, similar values are calculated for both slope top and bottom of each test field, except the cohesion for No.5. Retest of the soil strength probe will be required for checking the cohesion for No.5.

From the comparison of strength parameters shown in Tables 3 and 4, it is found that there is relatively a good agreement for the values of cohesion except the cohesion for No.5 shown in Table 4, but the internal friction angle obtained from the field one surface-shearing test is much higher than that from the soil strength probe "dokenbou". This is because the soil strength probe "dokenbou" cannot load higher vertical stress and the vertical stress is applied by manpower in the field. Thus, the properties of confining pressure dependency are evaluated low in the soil strength probe "dokenbou", comparing with that in the field one surface-shearing test.

6. Conclusions

The ground characteristics and strength parameters of soils on shallow landslide scars of Shirasu natural slopes have investigated in this paper. The strength parameters of soils could be obtained in the test field using both field one surface-shearing test and the soil strength probe "dokenbou". The main conclusions drawn from this study are as follows:

1) The development of forest topsoils originates from shallow to deep depths due to the growing tree roots and the supply of organic substances followed by the revegetation of forest. Thus, the dry density of forest topsoils tends to decrease with time, and the soil void has the reverse tendency.
2) The pH values for the eluate of soil sampled from forest topsoils decrease with the increase of elapsed years after the occurrence of landslides, due to the acidification of soil.
3) The soil particle density for forest topsoils in the test field is lower than that of most slica sand and the content of organic substances for forest topsoils is relatively small.
4) From the comparison of results of both field one surface-shearing test and the soil strength probe "dokenbou", it is found that there is relatively a good harmony for the values of cohesion, but the internal friction angle obtained from the field one surface-shearing test is much higher than that from the soil strength probe "dokenbou".

As one of the future work, we would like to propose a new conversion formula of the strength parameters in the field direct shear tests using a soil strength probe "dokenbou" for each local soil.

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