Investigation of shallow landslide scars on Shirasu natural slopes from the viewpoint of forest ecology and geotechnical engineering

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ABSTRACT

A non-welded part of pyroclastic flow, Shirasu in Japan, is widely distributed on the ground surface in Kagoshima Prefecture. The slopes composed of Shirasu and other volcanic products often fail due to heavy rain in the rainy season. 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 tests on shallow landslide scars of Shirasu natural slopes are 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 the site investigation, the growth condition of forest trees, the measurement of dry density of topsoil and investigation using soil augers are carried out. Furthermore, simple dynamic cone penetration test and the investigation of slope topsoil using a soil strength probe are performed in situ.

Keywords: Shirasu natural slope, site investigation, in situ test, revegetation, soil development

1. INTRODUCTION

In Japan, forest occupies about 70% of the country. Approximately 90% of slope failures occurring in Japan are shallow landslides and in Southern Kyushu, trigger is usually rainfall. Kagoshima Prefecture is located in the southern part of Kyushu Island. The ground surface in Kagoshima Prefecture is entirely with volcanic products, such as pyroclastic flow deposits including volcanic ash, pumice fall, and weathered igneous rock. The non-welded part of pyroclastic flow deposits is called Shirasu in Japanese, which is classified as a sandy soil. The density of Shirasu is lower than popular 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 this study, site investigation and in situ testing on shallow landslide scars of Shirasu natural slopes are 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.

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. The point No.1 is the minimum and point No.6 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 of the slopes is over 37 deg. and the area of landslide scars range from 29 to 114 m².

In Fig. 2, point No. 1 is composed of various kinds of small trees and weeds, and large trees like evergreen broad-leaved trees are mostly seen in point No.6. Regarding the grain size in all test fields, the percent finer by weight is approximately 100% when the grain size is less than 2.0 mm and the vast majority is coarse.
Table 1. Property 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 | 8     | 12    | 22    | 28    | 40    | 58    |
| Average inclination of slope (°) | 42    | 38    | 41    | 37    | 40    | 39    |
| Area of landslide scar (m²) | 42    | 36    | 29    | 34    | 61    | 114   |

Fig. 1. Test field.

Fig. 2. Local photograph of six test field points

Fig. 3. Number of trees, tree species and tree basal area for the elapsed years after the occurrence of landslides.

Fig. 4. Diversity index of forest trees and appearance rate of evergreen broad-leaved trees for the elapsed years after the occurrence of landslides.

Fig. 5. Depth of an effective topsoil layer and dry density of topsoils for the elapsed years after the occurrence of landslides.
sand (0.85-2.0 mm).

3 SITE INVESTIGATION

The identification of tree species, the growing conditions of forest trees, such as, tree height and diameter at breast height, the measurement of dry density of forest topsoils and investigation using soil augers are carried out. Figure 3 shows the number of trees, tree species and tree basal area for the elapsed years after the occurrence of landslides. The number of trees and tree species peaked approximately 10 years after the occurrence of the shallow landslides, and then decreased with time. Approximately 40 years after the occurrence of the landslides, an apparent steady state was achieved. On the other hand, the tree basal area increases gradually with the time.

The Fisher-Williams' index of diversity (Tagawa 1964) for forest trees and the appearance rate of evergreen broad-leaved trees for all trees are obtained as shown in Fig. 4. In the method of Fisher-Williams' index of diversity, $\alpha$ is calculated by solving the following equation:

$$S = \alpha \log(1 + N / \alpha)$$ (1)

where $N$ and $S$ are the number of all trees and all kinds of tree species. It is found that the tendency obtained from Fig. 4(a) has a good agreement with that from Figs. 3(a) and (b), and $\alpha$ takes approximately 8 when the elapsed years after the occurrence of landslides is over 40. Based on the temporal variation of the Fisher-Williams' index of diversity, the forest located in the shallow landslide scars reached a climax approximately 40 years after the occurrence of the landslides. In Fig. 4(b), the appearance rate of evergreen broad-leaved trees increases with time, and about 80% of all trees are evergreen broad-leaved trees when the forest reached a climax approximately 40 years after the occurrence of the landslides.

Next, Figure 5 shows the depth of an effective topsoil layer and the dry density of topsoils for the elapsed years after the occurrence of landslides. The depth of an effective topsoil layer is 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. 5(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 the forest reached a climax approximately 40 years after the landslides. The average value of point No.6 (58 years have elapsed after the landslides) is 45.3 cm and the rate of development of the depth of an effective topsoil layer is 0.78 cm/year. This value is higher than the average value 0.45 cm/year of shallow landslide scars on Shirasu in Kagoshima city for 80 years (Shimokawa et al. 1989). Because the average inclination of slope is around 50 deg. in Kagoshima city.

The sampling point is 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 is measured by extracting the undisturbed sample at the depth of 10, 30 and 50 cm 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. 5(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.

4 IN SITU TESTING

The simple dynamic cone penetration test and the investigation of slope topsoil using a soil strength probe ("dokenbou" in Japanese) are performed in situ (Sasaki 2010). Figure 6 shows the results of simple dynamic cone penetration test for points No. 1 and No. 6. As shown in Table. 1, 8 and 58 years have elapsed after the landslides for points No. 1 and No. 6, respectively. In Fig. 6(a), the amounts of penetration are 9 and 25 cm when the number of blows is 0 and 1, respectively. After that, the amount of penetration decreases and the value of $N_d$ tends to increase. Thus, it is supposed that the depth of an effective topsoil layer is approximately 9 cm. Also, the penetration is stopped when the penetration reached 1.5 m. This is because the amount of penetration is less than 20 mm even when 10 blows are applied. On the other hand, the amount of penetration is 6 cm when the number of blows is 0 and, the value of $N_d$ increases until the penetration depth is 10 cm as shown in Fig. 6(b). After that, $N_d$ decreases when the penetration depth is approximately 60 cm. Thus, the depth of an effective topsoil layer is around this depth. It is observed that the $N_d$ value increases suddenly when the penetration depth is approximately 3.3 m. Generally, the amount of penetration is relatively large even at few blows due to the forest topsoil, and the simple dynamic cone penetration test could generally be continued until the penetration depth is 5.0 m.

Next, Figure 7 shows the results of vane cone shear test using "dokenbou". This figure is the correlation between vertical load $W_{vc}$ (N) and torque $T_{vc}$ (N·m) when the shear test is conducted by changing the vertical load at least 4 times. These cases have quite a good agreement and the strength parameters $c$ and $\phi$ of soils are calculated by the following conversion formula:

$$c=10.16 \cdot Y_0$$ (2)

$$\tan \phi =12.04 \cdot X$$ (3)

where $c$ and $\phi$ 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 the reference (Sasaki 2010).

Figure 8 shows the variation of cohesion, $c_{dk}$ and internal friction angle, $\phi_{dk}$ obtained from "dokenbou"
Fig. 6. Results of simple dynamic cone penetration test.

Fig. 7. Results of vane cone shear test.

Fig. 8. Variation of $c_{dk}$ and $\phi_{dk}$ for the elapsed years after the occurrence of landslides.
for the elapsed years after the occurrence of landslides. The data are all test field points and the subscript letter \( d_k \) denotes the "dokenbou". The values of \( c_{dk} \) and \( \phi_{dk} \) decrease with the elapsed years after the occurrence of the landslides due to the effect of weathering, the growing tree roots and the soil development of forest topsoil followed by the revegetation of forest. In general, the strength parameters and dry density tend to become smaller from the surface layer when the elapsed years after the occurrence of the landslides are high. Additionally, it is found that the mixing of pumice and tree roots has a great effect on the results of the shear test when the test is actually conducted in situ.

5 SOIL ANALYSIS

The measurement of pH, electrical conductivity and contained-element concentration was conducted for the eluate of soil sampled from the topsoil of points No. 1, 3, 5 and 6 in the test field. In order to make the eluate for the measurement of pH and electrical conductivity, distilled water 50 g is added to the soil 20 g in natural seasoning and stirring for about 3 minutes by a magnetic stirrer. After leaving as it is for 10 minutes, the transparent part of supernatant liquid is measured.

Figure 9 shows the variation of pH and electrical conductivity for the elapsed years after the occurrence of landslides. The pH values decrease and electrical conductivity increases monotonously with time. This is because acidification of soil is occurring and conducts the electricity well by increasing the electrolyte due to the effect of humic acid. It is therefore confirmed that the humus is progressing well and the color of samples become blackish as a whole from visual observations. In addition, from the results of measurement for contained-element concentration, the silicon, calcium, sulfur and iron are detected at every field points. Thus, the test field would include the material resources of carbonate and silicate.

6 CONCLUSIONS

It was possible to conduct a follow-up survey of forest trees on Shirasu natural slopes, since the period of shallow landslides is short, the age of some kinds of trees which cover the final stage of transitions is long and the growth of trees is relatively fast due to the geomorphological warm climates of the Southern Kyushu region. Most of the shallow landslides involve forest trees in Japan. Thus, several indicators can be proposed, such as, the diversity index of forest trees, the appearance rate of evergreen broad-leaved trees and the depth of an effective topsoil layer quantitatively. From the viewpoint of forest ecology and geotechnical engineering, a judgment regarding the stability of slopes and the effect of revegetation and soil development could be made. Furthermore, shallow landslides do not tend to occur regularly after 20 years have elapsed since the last landslide, this is due to the growing tree roots having a stabilising effect on the topsoil.

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