Causes of Shallow Landslides of Weathered Granitic Rocks — From the View Point of Weathering Styles and Petrologic Textures —

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Abstract

Numerous numbers of shallow landslides were induced in granite and granodiorite areas by a heavy rainstorm in July 1972 in Obara village, central Japan, where devastating disaster occurred by large number of landslides during the rainstorm with the precipitation of 218 mm per 5 hours in 12th to 13th July 1972. We analyzed the relationships among the distribution and density of landslides, precipitation, and petrologic types of the granitic rocks quantitatively in the affected area. The landslide density in granite area was 293 /km^2 in maximum and was more than ten times larger than that in granodiorite area (13 /km^2 in maximum), even though both the areas had the same precipitation. Landslide densities increased with the amounts of precipitation in the granite area, but did not in the granodiorite area. We applied successively airborne laser scanner to detect landslides by the 1972 rainstorm and also preceding landslides in an area of 3km^2 in April 2003. The result indicated that the above contrast of landslide densities already existed before the 1972 disaster. The landslide densities during the 1972 disaster thus showed the same trend of landslide densities in a long term.

The difference in landslide density and the relation between landslide densities and precipitations result from the difference in weathering profiles, which reflect the difference of petrologic texture in two rock types. We analyzed the petrologic textures by cutting rock samples, staining potassium feldspar with sodium cobaltinitrite, and processing texture images by computer. The granite and granodiorite had different mineral modes: K-feldspar had modes of 29–50% and 5–17% in granite and granodiorite respectively; plagioclase had modes of 13–34% and 30–45% in granite and granodiorite respectively. In addition, plagioclase connectivity was quite different between these two rocks: it is relatively isolated in granite while well connected to each other to form a framework in granodiorite. Plagioclase is weathered much faster than potassium feldspar and changes into clay minerals such as halloysite and kaolinite. Therefore, clay minerals from plagioclase effectively combine the surrounding minerals in weathered granodiorite but not in weathered granite. In addition, a certain type of granite is micro-sheeted in the surveyed area, which accelerates disaggregating of particles. Consequently, weathered granite easily loosens and slides at its surface part, but weathered granodiorite does not. The binding effect of weathered plagioclase was supported by in-situ shear experiments, and loosening patterns of weathered granite were confirmed in the field.

Keywords: shallow landslide, weathering, granitic rocks

Introduction

Shallow landslides have been frequently induced worldwide by heavy rainstorms in weathered granitoid areas. For example, rain-induced landslides in weathered granitoid areas have been reported in many places, such as Minami-yamashiro in 1952 (Ikeda, 1975), Shimane in 1964 (Oyagi, 1968) and Hiroshima in 1999 (Chigira, 2001). Similar examples were reported in Rio de Janeiro (Durgin, 1977), northeastern Spain (Palacios et al., 2003), southern Italy (Calcaterra et al., 1996) and central Korea (Lee et al., 2002). Granitoid areas are often situated nearby urban areas and are used for land developments. For this reason, rain-induced landslides have been considerable in weathered granitoid areas.

Granitoid is weathered to form landslide materials, so its weathering manner and grade are closely related to the occurrence of landslide. Durgin (1977) indicated that decomposed granitoid is apt to slide more frequently than strongly weathered granitoid. Oyagi (1968) reported that more shallow landslides occurred in areas of moderately weathered granite than in areas of strongly weathered granite. Suzuki et al. (2002) pointed out that surface part of a weathered granite slope loosens more in weakly and/or moderately weathered gruss than in strongly weathered saprolite.

Granitoid consists of different minerals, and each mineral has different rate and manner of weathering. Therefore, different rock types of granitoid may have different weathering styles. Two major rock types in granitoid are granite and granodiorite; the former is rich in K-feldspar and the latter is rich in plagioclase. The

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physical and mechanical properties of these two rock types are similar during fresh rock, but would become very different when weathered because the weathering rate of K-feldspar and plagioclase are very different. Yairi et al. (1973) reported that a rainstorm induced much more landslides in granite area than in granodiorite areas, even though both the areas had experienced the same precipitation in Obara village, central Japan. Similar cases were reported in Shimane in 1964 (Oyagi, 1968) and in Minami-yamashiro in 1953 (Suzuki et al., 2002).

We examine the difference in weathering manner between granite and granodiorite, interpret it in terms of petrologic characteristics, and discuss it in relation to landslide generation. The study site is in Obara village, northern Aichi prefecture, central Japan, where a heavy rainstorm with a precipitation of 218 mm per 5 hours induced numerous shallow landslides in 12 to 13 July 1972.

Geomorphological and geological setting

The geomorphology of the study area is characterized by low-relief mountains with elevations from 200m to 600m dissected by small rivers. Slope gradients of the mountains are 15 to 35 degrees. Valley bottoms along small rivers are narrow and have 100 to 200 meters in maximum width.

Nakai (1970) and Ryoke Reserch Group (1972) reported that the bedrock in and around this area is granitoid and Paleozoic strata, which are partly covered by Tertiary strata in the areas from southern Nagano prefecture to northern Aichi prefecture. In the study area the granitoid is monotonously distributed.

Granitoids in the study area are mainly of two types, coarse-grained granite (cGr) and medium-grained granodiorite (mGd); locally present are medium-grained granite (mGr) and aplite (Ap) (Fig.1). The major two type rocks belong to the Sumikawa body and the others to the Naegi body (Nakai, 1970).

Distribution and densities of shallow landslides by the 1972 rainstorm

We divided the study area, which is approximately 140 km^2, into small cells by 250-meter grids to calculate landslide densities for every cell and we allocated rock types to each cell. We divided the precipitations into several ranks that were also allocated to each cell. If a cell contains the boundaries between different rock types and different precipitation ranks, we relegated it to the type or the rank occupying the largest area in

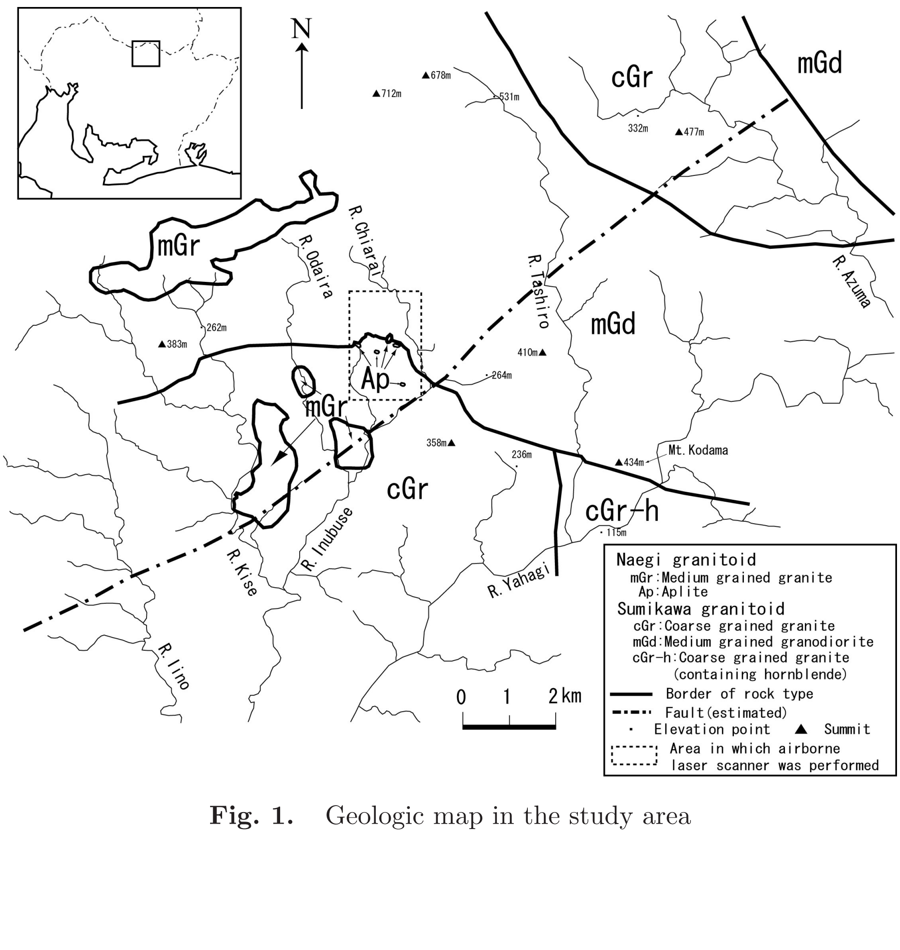

Fig. 1. Geologic map in the study area

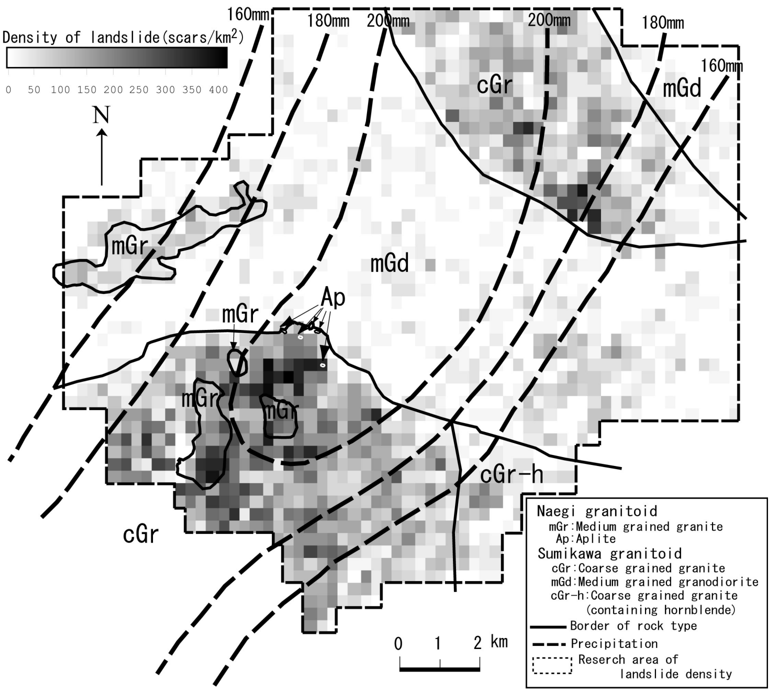

Fig. 2. Distribution of landslide densities in the 1972 event

the grid.

By using the aerial photographs (1/6000) taken 26 days after the disaster, which occurred on July 13 1972, we identified many landslide scars that occurred at this event. All the white scars except for artificial ones were regarded as the landslide by this event. This assumption was made because of the following reason. White scars in the aerial photographs taken in 1972 and those in 1969 did not coincide except for only one in the area of most intensive precipitation and no rainstorm occurred between 1969 and 1972. This assumption was extended to the surrounding areas with less precipitation.

The distribution of landslides in 1972 was dependent on rock types (Fig.2). In areas with the same precipitation, landslide densities in granite area were much larger than those in granodiorite area. In addition, the densities in granite area became larger with increasing the amounts of precipitation, but those in granodiorite area did not. The qualitative relationships among landslide density, rock type, and precipitation had been indicated by previous researchers (Yairi et al., 1973), but we clarified it quantitatively. Aplite areas were recognized as small bodies and no cell was relegated to aplite, therefore aplite was excluded from not only this analysis but also the following analyses.

Trend of landslide densities in a long term

We applied airborne laser scanner in April in 2003, obtaining 1-m grid DEMs and a high-resolution topographic map. The surveyed area, which stretches for 1.5 km in east and west and 2.1 km in north and south, is located in the largest precipitation area (Fig.1). Granite occupies the southern part of the area, and granodiorite in the northern part (Fig.3). By examining the map in comparison with the aerial photographs taken after the disasters, we identified many landslide scars by the 1972 event only from the map. This high-resolution map enabled us to identify many old landslide scars that already existed at the time of the disaster but was difficult to identify in aerial photographs. Aerial photographs taken in 1948, 1964, 1969, 1974, 1979, 1989, 1993,and 1998 were used to determine the time of the occurrence of old landslides. These photographs showed that almost all of the old landslides occurred before 1948. The precision of the airborne laser scanner is 30 cm in the horizontal distance and 15 cm in the vertical. Arc View GIS made by Environmental System Research Institute was used for the analysis.

Extracted landslides by the 1972 event and by previous events were both concentrated in granite area (Fig.3). We calculated landslide densities per square kilometers of slopes steeper than 20° and obtained landside densities of 293/km^2 in granite area and 13/km^2 in granodiorite area at the 1972 event. The average landslide densities of the cells corresponding to the laser scanning area were 218/km^2 in granite area and 11/km^2 in granodiorite area. The differences in the landslide densities between two measurements were due to that the

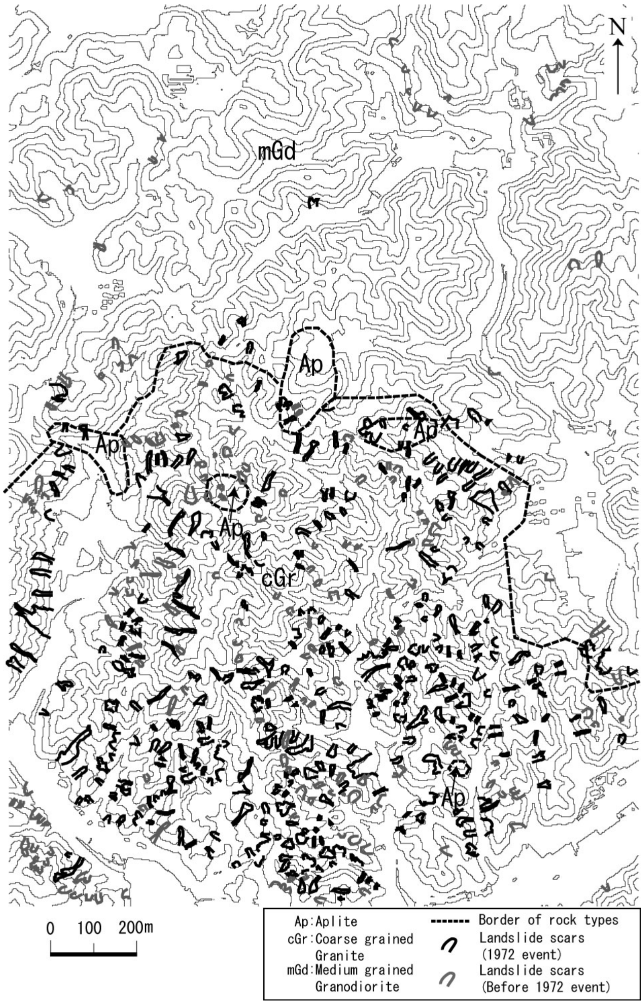

Fig. 3. Landslide distributions and rock types in airborne laser scanner area. Landslides concentrated in granite (cGr) area. Contour distance is 10 meters. This area is indicated in dotted box in Fig.1.

area used for the calculation of the cells contained areas with less than 20° gradient. The landslide densities that occurred before the 1972 event were $120/km^2$ in granite area and $28/km^2$ in granodiorite area: the density contrast was consistent to that by the 1972 event. Therefore, the landslide densities during the 1972 event showed the same trend of landslide densities in a long term.

Relationships among weathering, weathering profile, and strength of weathered products

The distributions of landslides were controlled by rock types as stated before, which were explained by the structure and properties of weathered materials near slope surface. From this viewpoint, we performed field observation of weathering profiles, in-situ share test, and cone penetration test.

The field observation showed different weathering grades between granite and granodiorite. According to the classification of weathering grade by Honshu-Shikoku Bridge Expressway Company, we classified highly weathered granitic rocks into D_H, D_M, and D_L, which correspond to IV, V, and VI grades of AFTES classification respectively (Japan Society of Engineering Geology work group, 1984). In granite area, weathered granite classified into D_H and/or D_M were widely distributed; on the other hand, in granodiorite area, rocks with D_H class were not observed and D_M and/or D_L class rocks were widely distributed. At the outcrop containing corestones, weathered products among corestones were observed for the classifications. Outcrops hardly containing weathered products were classified into C_L class.

Shear strengths of weathering products were determined by in-situ shear test and showed remarkable

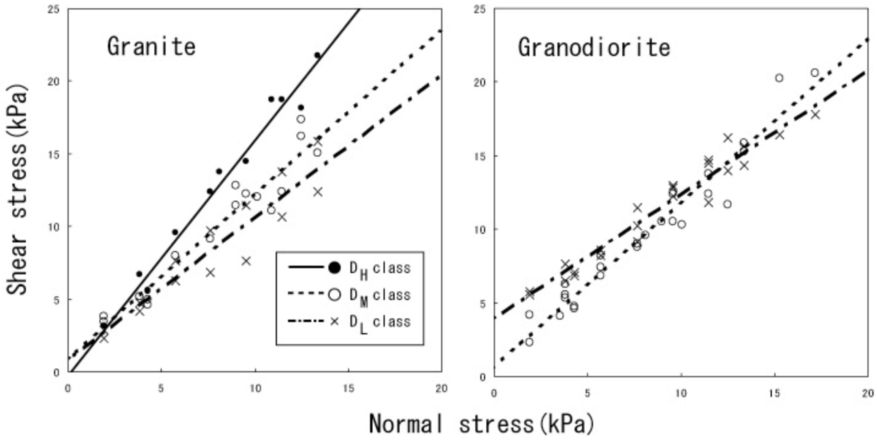

Fig. 4. Variations of shear strengths with weathering. In granite, internal friction angle decrease. On the other hand, in granodiorite, internal friction angles decreased but cohesions increased.

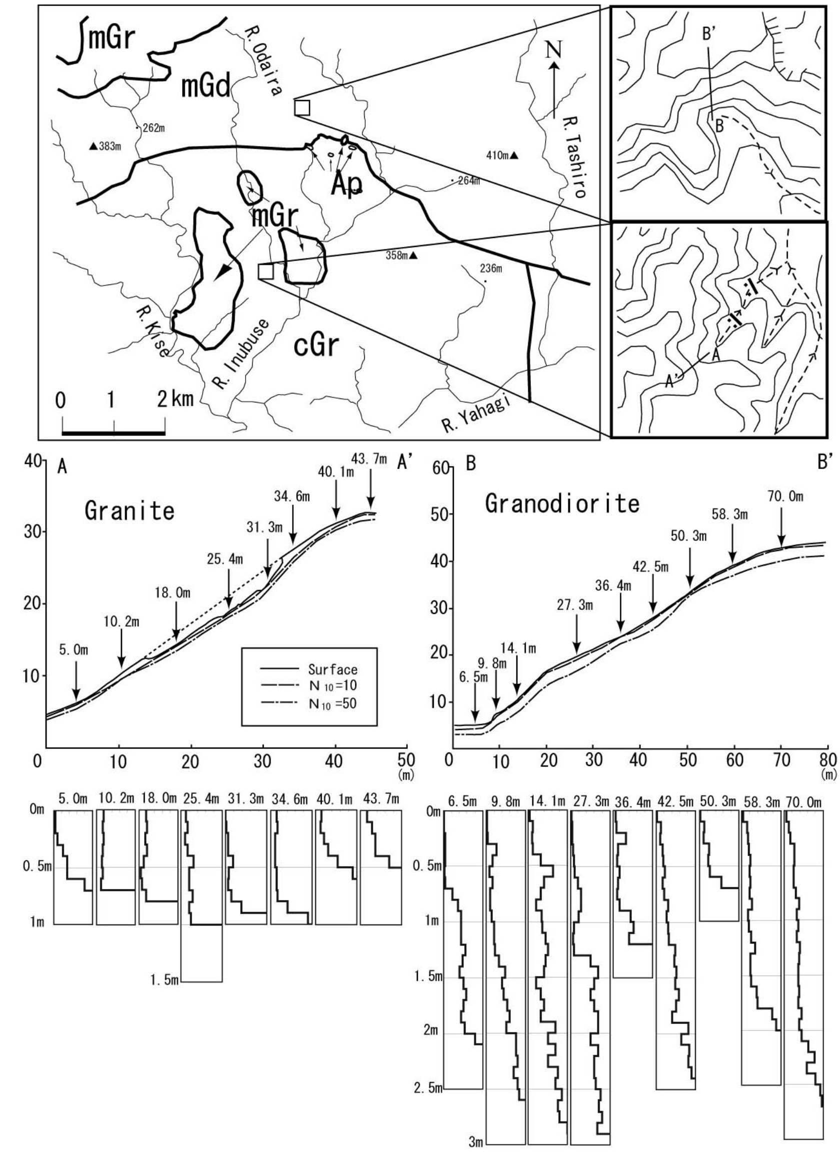

Fig. 5. Profiles of N_{10} values in slope surfaces. $N_{10} < 50$ layer is thin and profiles have sharp breaks in granite.

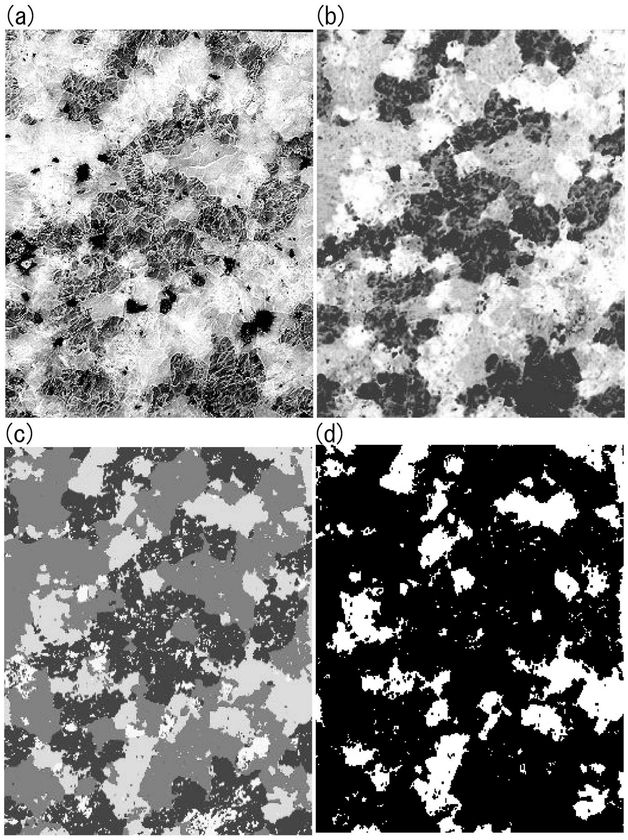

Fig. 6. Method of image processing (a) Cutting sample and polishing surface (b) Staining K-feldspar (c) Coloring each mineral (d) Extracting the mineral to analyze

difference between the two rock type. In granite, internal friction angles decreased with weathering (D_H: 57°; D_M: 50°; and D_L: 49°) while cohesions almost 0°. On the other hand, in granodiorite, internal friction angles decreased (D_M: 48°, D_L: 40°) but cohesions increased with weathering (D_M: 0, D_L: 4 kPa)(Fig.4). In-situ shear test is a simple method developed by us for measuring the properties of weathered products. Due to simple method and device, it is suitable for measuring fragile samples, which cannot be brought to laboratory. The device is approximately 15 kg in weight; shearing surface has an area of 51 cm^2; and the height of a sample to be sheared is 3 cm. Firstly we make a stub of weathered rock cut out from the ground; secondly a frame was set around the stub and weight was set on the stub; thirdly spring scale connected to the frame was pulled at an constant rate to shear the sample; and finally we recorded the maximum force of the spring scale. We used several weights to measure several shear stresses under different normal stresses. The normal stresses and the shear stresses were plotted in a chart to obtain the internal friction angles and the cohesions. The tests were performed 7 and 8 times in granite and granodiorite area respectively. We referred Yamamoto et al. (1999) to develop the system. The effect of water content was not significant, which we confirmed by shearing saturated samples and samples under natural water content.

We performed cone penetration test to obtain profiles in representative slopes in granite and granodiorite. The results are shown as profiles of N_{10} values, which is a blow number necessary to penetrate the cone for 10 cm by free-fall hitting of 5 kg weight for 30 cm. In weathered granite slopes, N_{10} values near surface were less than a few or 10 and increased abruptly at several tens of cm or 1 m depths, while N_{10} values increased gradually without sharp breaks in weathered granodiorite slopes. The sharp breaks are due to the loosening of weathered granite near slope surface.

Relationship between petrologic textures and weathering styles

To examine the cause of the differences in the strength of weathering products and the weathering profiles, we compared the petrologic textures between granite and granodiorite. We analyzed the petrologic textures by cutting rock samples, polishing the surface with #600 powder of carborundum, staining K-feldspar

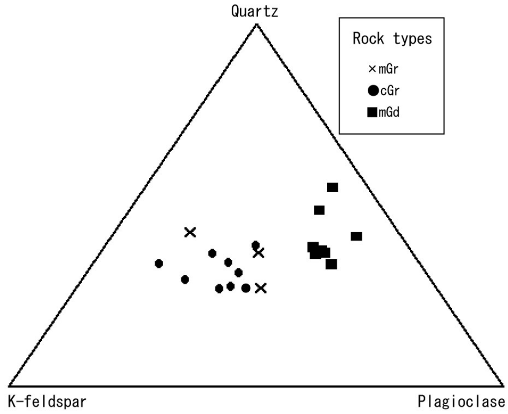

Fig. 7. Diagram of quartz, K-feldspar, and plagioclasede in granite and granodiorite

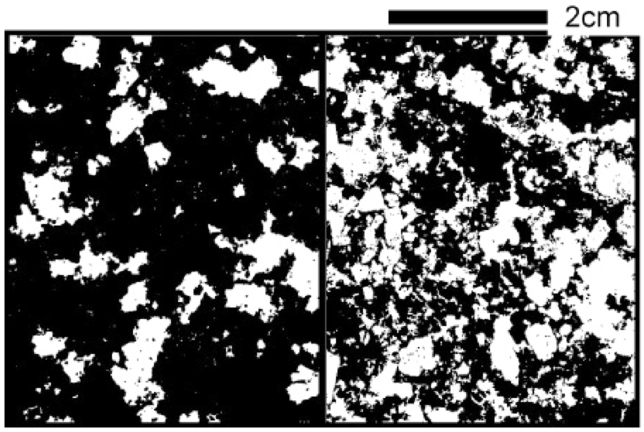

Fig. 8. Connectivity of plagioclase in granite (left) and granodiorite (right).

with hydrofluoric acid and sodium cobalt nitrite, and processing texture images by computer (Fig.6). Each mineral was stained by different colors on an image to calculate mineral modes. For the connectivity analysis of a certain mineral, that mineral was extracted as white pixels in black background. Adobe Photoshop ver.6.0 made by Adobe Systems Incorporated was used for the image analyses. This method is based on Nishimoto (1996).

The result of comparing petrologic textures showed that the granite and granodiorite had different mineral modes: K-feldspar had modes of 29–50% and 5–17% in granite and granodiorite respectively; plagioclase had modes of 13–34% and 30–45% in granite and granodiorite respectively (Fig.7). In addition, plagioclase connectivity was quite different between these two rocks: it is relatively isolated in granite while well connected to each other to form a framework in granodiorite (Fig.8). The other minerals hardly showed the differences in mode and connectivity.

The causes of the contrast in landslide density between granite and granodiorite areas

The difference in landslide density and the relation between landslide densities and precipitations result from the difference in weathering profiles, which reflect the difference of petrologic texture in two rock types. Important difference of the petrologic textures between granite and granodiorite is that plagioclase grains in granodiorite are well connected to each other to form a framework and that in granite was relatively isolated in granite. The connectivity of plagioclase becomes more important when the rock is weathered and plagioclase is transformed into clay minerals, such as halloysite and kaolinite.

Table 1 is the result of mineral analysis by X ray diffraction, showing that plagioclase is weathered to form kaolinite in accordance with the result of Kimiya (1975) and Shimizu (1972). Each sample was from

Table 1. Mineral composition in each weathering grade.

rock type	weathering grade	sample	Qz	Kf	PL	Bi	Ho	Vm	Mc	Ka
Granite	C_L	Gr-1	++	++	++	++				
	D_H	Gr-2	++	++	++	+				
	D_M	Gr-3	++	++	++			+		+
	D_L	Gr-4	++	++	+			++	++	++
		Gr-5	++	+	+			++	++	++
Granodiorite	C_L	Gd-1	++	++	++	++	++			
	D_M	Gd-2	++	++	++	+	+			
		Gd-3	++	++	++			++	++	
	D_L	Gd-4	++	++				++	++	++
		Gd-5	++	++				++	++	++
		Gd-6	++	+					++	++

++:much +:little
Qz:Quartz Kf:K-feldspar PL:Plagioclase Bi:Biotite Ho:Holnblende
Vm:Vermiculite Mc:Mica clay minerals Ka:Kaolin minerals

representative outcrops of rock types and weathering grades. The conditions of measuring were 40kV in voltage, 20mA in current, 1kcps in range, 1 degree in divergence slit, 0.15mm in receiving slit, 1 degree in scattering slit, $2\theta = 4$ degree per minute in scanning speed, and CuKα was used. Geigerflex made by Rigaku-Denki Corporation was used for the measurement.

Clay minerals from plagioclase is well connected in granodiorite, forming a network and binding weathering resistant quartz and K-feldspar grains effectively, but not in granite because of its less connectivity of plagioclase. In addition, a certain type of granite is micro-sheeted in the surveyed area, which accelerates disaggregating of particles. Consequently, weathered granite easily loosens and slides near surface in the slopes, but weathered granodiorite does not. The binding effect of weathered plagioclase was supported by in-situ shear experiments, and loosening patterns of weathered granite were confirmed in the N_{10} profiles obtained by cone penetration tests.

The layer of weathered products in granodiorite has no sharp break of soil hardness and is thicker than that in granite. Therefore the rainwater can infiltrate deeper into weathered granodiorite than into weathered granite. Onda (1989) mentioned that granodiorite has large storage capacity than granite and thus does not fail easily. Durgin (1977) mentioned that it is the empirical fact that saprolite does not fail easily. Those agree with the consideration of this study.

Conclusions

We analyzed the relationships among the distribution and density of landslides, precipitation, and petrologic types of granitic rocks in Obara village, Aichi prefecture, Japan, where numerous shallow landslides were induced by heavy rainstorm in July 1972.

Following results were obtained.

1) The landslide density in granite area was 293 /km^2 in maximum and was more than ten times larger than that in granodiorite area (13 /km^2 in maximum), even though both the areas had the same precipitation. And landslide densities increased with the amounts of precipitation in the granite area.

2) Airborne laser scanner, which detected old landslides before the 1972 event, indicated that the above contrast of landslide densities already existed before the event. The landslide density before the 1972 event in granite and granodiorite area was 120, 28 /km^2 respectively. Thus landslide densities had a consistent trend in a long term.

3) The difference of landslide density between the two type of rocks result from the difference in weathering profiles; whether surface loosened layer is formed or not.

4) Whether surface loosening occurs or not is dependent on the connectivity of plagioclase. Plagioclase, which is weathers fast and changes into clay minerals, had lower connectivity in granite than in granodiorite, hence clay minerals from plagioclase effectively combine the surrounding minerals in weathered granodiorite but not in weathered granite. Therefore, weathered granite easily loosens and slides at its surface part.

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