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Slope failure in the rectilinear zone of hillsides

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傾斜変換帯における崩壊

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地形解析により斜面を傾斜変換帯とそれ以外の地域に分け，それぞれの地域における崩壊発生頻度，崩壊面積，上部変換線から崩壊発生位置までの距離について検討した。その結果，傾斜変換帯の上部地域に崩壊が多発していることが明らかになった。また土壌の深さについては，崩壊地の上部で厚く，下部で薄くなっているが，崩壊地に近接する未崩壊斜面では逆の傾向がみられた。これらを総合して，表層土壌の深さの不均一さが，傾斜変換帯上部における浸透水の集中と崩壊の発生に密接に関係していると考えられた。

従って，傾斜変換帯あるいは上部傾斜変換線は，山地における崩壊危険地帯予知の1つの有用な指標になりうると判断された。

The mountain slope was divided into two parts, the rectilinear zone and curvilinear zone (the convex or concave zone) by analyzing topographical maps. The frequency and size of slope failure and its position from the upper inflection contour line were studied in regard with the rectilinear or curvilinear zone of the mountain slope. It was then made clear that many slope failures were distributed in the upper part of the rectilinear zone of slope. The measurement of soil condition showed that the surface soil layer was generally deep at the upper part of slope failure and was shallow at the lower part. On the other hand, the depth of the surface soil on nearby nonfailed slopes was quite reverse to the above mentioned situation. From these analyses, it was concluded that the disproportion in the depth of the surface soil layer was closely related to the concentration of infiltrated water and the occurrence of slope failures at the upper part of the rectilinear zone of slope. The rectilinear zone of slope or the upper inflection contour line could probably be a very useful index for predicting the dangerous area of slope failure occurrence in the mountain.

Key words : Slope failure, Rectilinear zone of slope, Morphometry, Depth of surface soil layer

I. Introduction

The prediction of the dangerous area of slope failure occurrence is a very important problem to prevent mountain disaster. The rate of the total area of slope failure caused by heavy rainfall is almost less than several percent of mountainous area, and the slope failure occurs as the results of a combination of many factors such as heavy rainfall, topography, geology, ground cover, soil condition and so on. Therefore, the detailed investigation of the geological and topographical factors connected with the occurrence of slope failures and the definition of dangerous slopes are necessary for predicting the dangerous area of slope failure. In addition, the infiltration of water into soil and the flow of ground water brought by heavy rainfall should be analyzed accurately. However, it may be almost impossible to investigate many factors in detail in all mountainous regions.

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In this study, the rectilinear zone of slope and the depth of the surface soil layer were taken into account among many other factors which connected with the occurrence of slope failures, and discussion was made whether or not the rectilinear zone of slope would become a very useful index for predicting the dangerous area of slope failures in the mountain.

II. Study region and method of investigations

1. Study region

The study region for predicting the dangerous area of slope failures was Obara Village and Fujioka Town(about 30 km northeast from Nagoya City, Aichi Prefecture). There was more than 200 mm of rainfall for five consecutive hours in July 12～13, 1972 and the maximum rainfall intensity was recorded 60～80 mm per hour. Sediment discharge from slope failures attacked this region, and brought the serious sediment disaster with heavy casualties.

Geology in this region belongs to younger granitic rocks in Ryoke belt. The great part of this region is Medium-grained hornblende-biotite granodiorite and Coarse-grained biotite-granite, and some part is Fine-grained biotite-grainite.

Study area was 1,200 ha in the middle part of the Odaira river, which is a branch of the Inubuse river. Elevation of this area was 160～410 m above the sea level. The feature of mountains was hilly and complex. Most summits of mountains were globular, the continued slopes from each summit were relatively steep, and the lower parts of slopes were gentle. Namely, most of slope profiles formed S-shaped slope.

2. Method of investigations

The trace of slope failures and the topography were measured on the aerial photographs (scale ; about 1 : 6,000) taken after the disaster and some topographical maps (scale ; 1 : 2,500, contour line ; 2 m) illustrated from its aerial photographs. The position and the size of all slope failures of more than 50 m^2 were plotted on the topographical maps. The rectilinear zone of slope was defined from the interval of contour lines on the topographical maps as follows.

Most slope profiles are generally known to consist of a summital convexity, a rectilinear section and a basal concavity as shown in Figure 1 (3). The varied point between a summital convexity and a rectilinear section is termed an upper inflection point of slope, and the varied point between a rectilinear section and a basal concavity is termed a lower inflection point of slope, respectively.

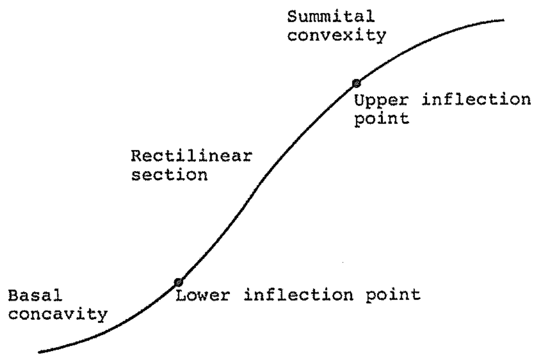


Fig. 1. Composite slope form

Two kinds of the line connecting each upper inflection points and each lower ones to the direction of contour lines are called an upper inflection contour line and a lower one, respectively. The zone covered between an upper and a lower inflection contour line is assumed a rectilinear zone of slope, and the zone excepting a rectilinear zone is called a curvilinear zone of slope.

Judging from the contour lines of the topographical maps, the upper part of slope is usually gentle, the continued slope from the upper part is relatively steep and the lower part of slope is gentle again. When the slope changes from being gentle to steep or steep to gentle, the upper and lower inflection contour lines were determined on the map as the lines where the inclination angle between the upward and downward made a difference of more than 10° over the horizontal distance of 40 m.

The rectilinear zone was the area surrounded by the upper inflection contour line, the lower one and the side lines. Each side line was connected the end points of upper and lower inflection contour lines to the inclined direction. The number of the rectilinear zone of slope was 690, the total area was 398 ha, with its mean area of 0.58 ha. In this investigation, the flat ground such as residential sites, crop fields and so on were eliminated from the study area, and the hillside was only measured.

The areas and the inclination angles were measured on all the slope failures plotted on the topographical maps. The original position of a given failed slope was defined provisionally as the point of one-thirds along the center line drawn downward from the top of the slope failure. The horizontal length from the upper inflection contour line to this point was finally measured on the map.

An example of the rectilinear zone of slope and the distribution of slope failures is shown in Figure 2.

In order to measure the inclination angle of slopes, 2 cm mesh grids were placed on the map, and were counted the number of contour lines contained in the lines of 1 cm (real distance ; 25 m) at right angles to the contour lines from all grid points. The inclination angle was then calculated by using the number of these contour lines, which indicated every 2 m difference in elevation, at 25 m of horizontal distance in the grid. Data were collected on 3,886 grid points. In addition, the inclination angle of slope failures

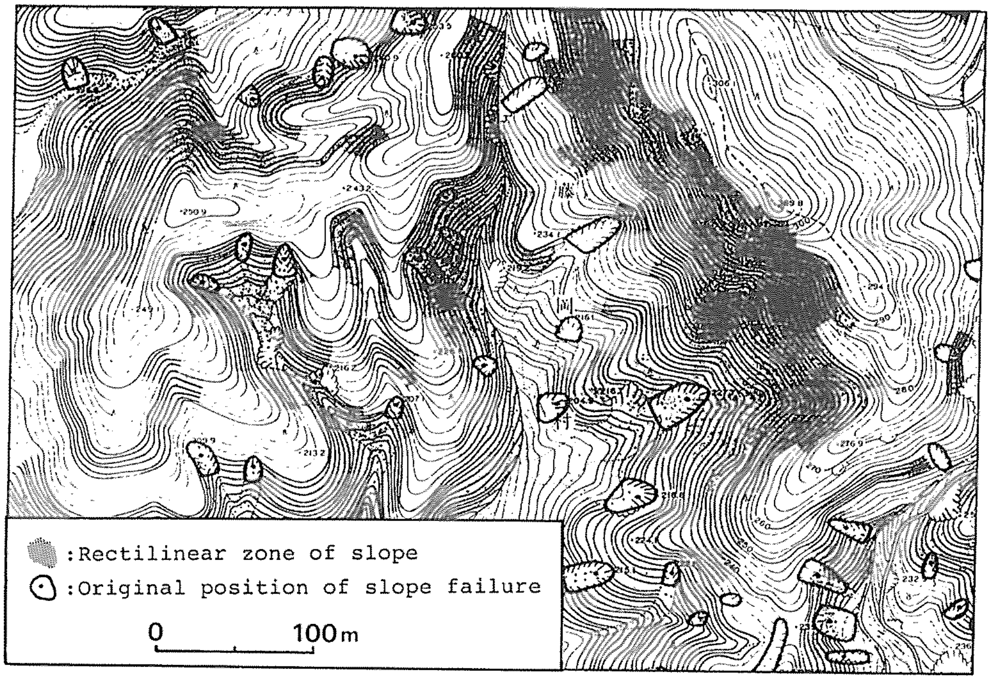


Fig. 2. Rectilinear zone of slope and distribution of slope failure

was calculated by using the value of the height difference and the horizontal distance between the highest and lowest points of slope failures.

From the articles obtained by above treatment, the data of slope failures were arranged in each geology. The depth of the surface soil layer was also measured by the field investigation in each failed and nonfailed slope of the study area where the morphometry had been carried out.

Ⅲ. Results through morphometry

1. Occurrence of slope failures

Table 1 shows the situation of occurrence of slope failures in the rectilinear and the curvilinear zone of slope. About the occurrence of slope failures, the number and the area of slope failures per unit area in the rectilinear zone of slope was about four times as high as that in the curvilinear zone. It was clear that the occurrence of slope failures was apt to concentrate to the rectilinear zone of slope.

The frequency of the occurrence of slope failures was high in Coarse- and Fine-grained biotite-granite, and was low in Medium-grained hornblende-biotite granodiorite. Comparing the occurrence of slope failures in different geologies, the frequency of the occurrence of slope failures in the rectilinear zone of slope is three to five time as high as that in the curvilinear zone of slope in each geology. This difference in the occurrence of slope failures is large. K. Yairi et al. (2) explained the causes of this difference as follows. Coarse-grained biotite-granite is easy to change to sandy particles by the mechanical weathering, and the water brought by heavy rainfall infiltrates easily into soil. Therefore, the slope failures due to piping phenomenon has a tendency to occur in this geology. Otherwise, Medium-grained hornblende-biotite granodiorite is apt to take more chemical weathering, and the weathered soil layer is usually deep. The infiltration of water by heavy rainfall is inferior because of containing much clay mineral in this geology. Accordingly, the occurrence of slope failures in this geology is less than that in the other geologies.

Figure 3 shows the frequency curves of the angle distribution of slopes and slope failures. Mean angle of slopes at all intersection points was 27.8° and that of slope failures was 33.0°. The difference in the two is 5.2°. The maximum frequency of the angle distribution of slope failures appeared at the angle of 30～40°. Figure 4 (a) and (b) show the frequency curves of the angle distribution of slopes and slope failures in the rectilinear and the curvilinear zone of slope, re-

Table 1. Occurrence of slope failures

Articles	Entire area			RZ/CZ	CB		RZ/CZ	FB		RZ/CZ	MH		RZ/CZ
	RZ	CZ	Total		RZ	CZ		RZ	CZ		RZ	CZ	
Study area (ha)	398.0	643.7	1041.7		225.3	320.8		40.3	64.5		132.4	258.4	
Number of slope failures (n)	714	270	984		566	215		112	41		36	14	
Total area of slope failures (ha)	18.38	7.69	26.07		14.80	6.28		2.48	1.11		1.10	0.30	
Number of slope failures per unit area (n/ha)	1.79	0.42	0.94	4.3	2.51	0.67	3.7	2.78	0.64	4.3	0.27	0.05	5.4
Area of slope failures per unit area (%)	4.62	1.19	2.50	3.9	6.57	1.96	3.4	6.15	1.72	3.6	0.83	0.12	6.9
Mean area of slope failures (×100m²)	2.57	2.85	2.65		2.61	2.92		2.21	2.71		3.06	2.14	

Note, RZ : Rectilinear zone of slope
CZ : Curvilinear zone of slope
CB : Coarse-grained biotite-granite
FB : Fine-grained biotite-granite
MH : Medium-grained hornblende-biotite granodiorite

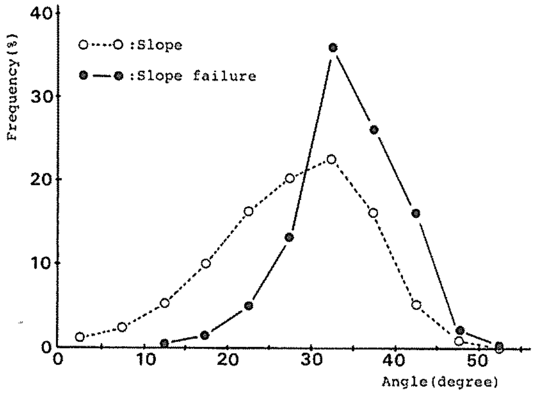


Fig. 3. Frequency distribution of angle of slopes and slope failures(study area)

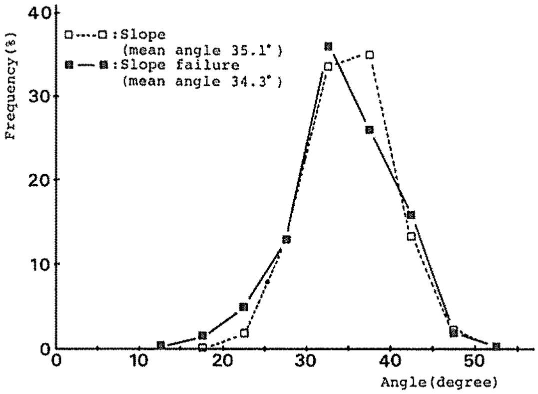


Fig. 4 (a) Frequency distribution of angle of slopes and slope failures (rectilinear zone of slope)

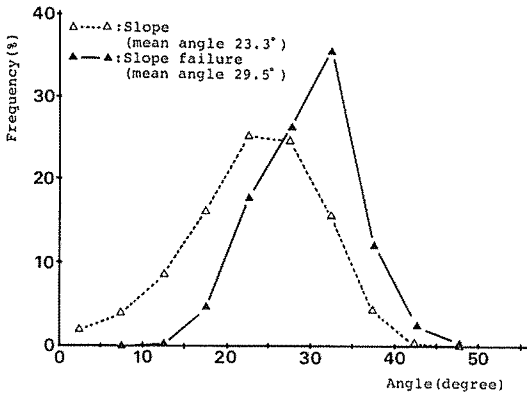


Fig. 4 (b) Frequency distribution of angle of slopes and slope failures (curvilinear zone of slope)

spectively.

Two curves in Figure 4 (a) were of almost similar shape, while two curves in Figure 4 (b) were different. Namely, in the rectilinear zone the difference in two curves is not almost found, but the peak of frequency curve of slope failures in the curvilinear zone was biased in the right side(steep side)as compared with that of slopes. From these results, it is reasonable to conclude that the slope failures in the rectilinear zone were apt to occur at almost the same probability on every slope, but in the curvilinear zone of slope the occurrence of slope failures were apt to concentrate on steeper slope in this zone. These relationships were also found in other geology.

2. Size distribution of slope failures in the rectilinear zone of slope

The number of slope failures smaller than 850 m^2 in the rectilinear zone of slope was plotted on semilog graph paper in connection with each size of slope failures and each geology, and was shown in Figure 5. These slope failures were to correspond to about 98 percent of the total number of slope failures.

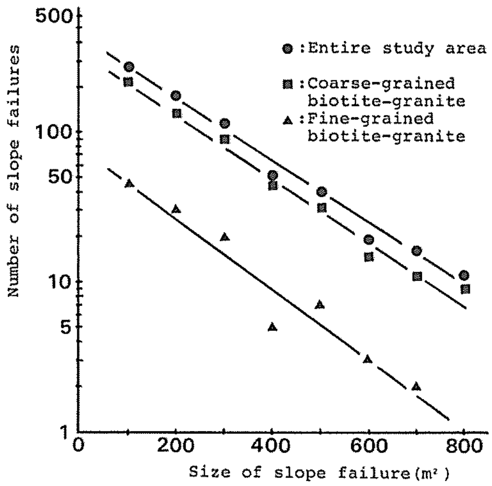


Fig. 5. Distribution of number and size of slope failures on semilog graph paper (rectilinear zone of slope)

From Figure 5, the relationship between the number of slope failures and its size was essentially a straight line in semilog graph. This shows that the number of slope failures decreased exponencially as the size of slope failures.

3. Relationship between number and size of slope failures, and the distance from the upper inflection contour line to the original position of slope failure in the rectilinear zone of slope

About 73 percent of the total number of slope failures were found in the rectilinear zone of slope (about 38 percent of the study area). Because the distribution of the inclination angle of slope failures nearly coincides with that of slopes in the rectilinear zone of slope, possibility of the occurrence of slope failures seemed to be equal in any rectilinear zone of slope.

The number of slope failures where the size of slope failures was smaller than 850 m² and where the distance from the upper inflection contour line to the original position of slope failure was shorter than 70 m was shown in Figure 6. These slope failures were about 96 percent of the total number of slope failures. As shown in Figure 6, about one half of slope failures were distributed within the distance of 10 m from the upper inflection contour line, and the size of slope failure was within the area of 300 m². And about 75 percent of the total number of slope failures were distributed within the distance of 20 m from the upper inflection contour line. As the distance from the upper inflection contour line increased, the number of slope failures and the rate of small slope failures decreased. Because the shape of each rectilinear zone of slope was complex as seen in Figure 2, and because the area of the rectilinear zone decreased as the distance from the upper inflection contour line becomes large, the number of slope failures at each distance did not show the real frequency of slope failures there. However, these results were to be a very useful information.

4. Relationship between the number, size and angle of slope failures

The number of slope failures of less than 850

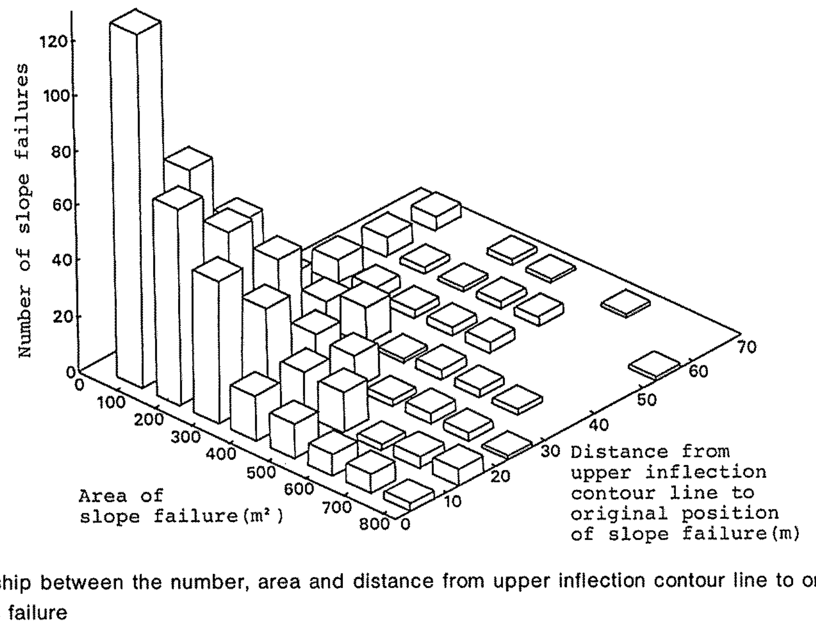


Fig. 6. Relationship between the number, area and distance from upper inflection contour line to original position of slope failure

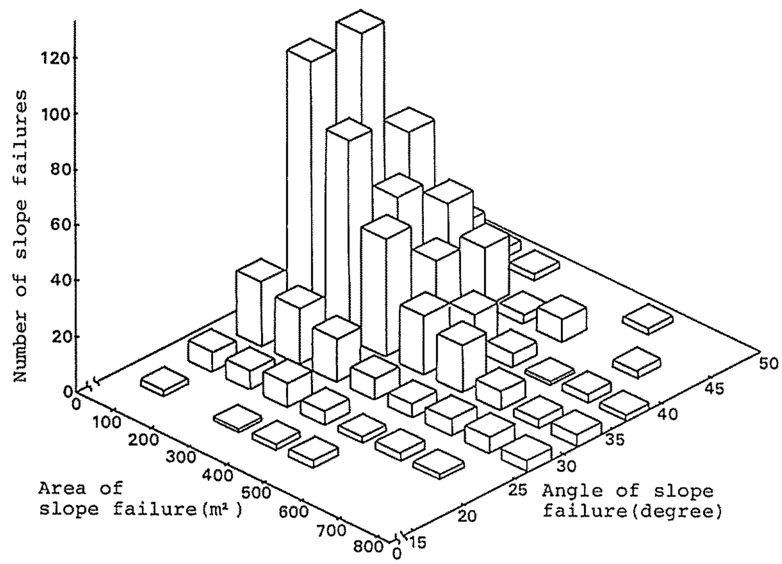


Fig. 7. Relationship between the number, area and angle of slope failures (rectilinear zone of slope)

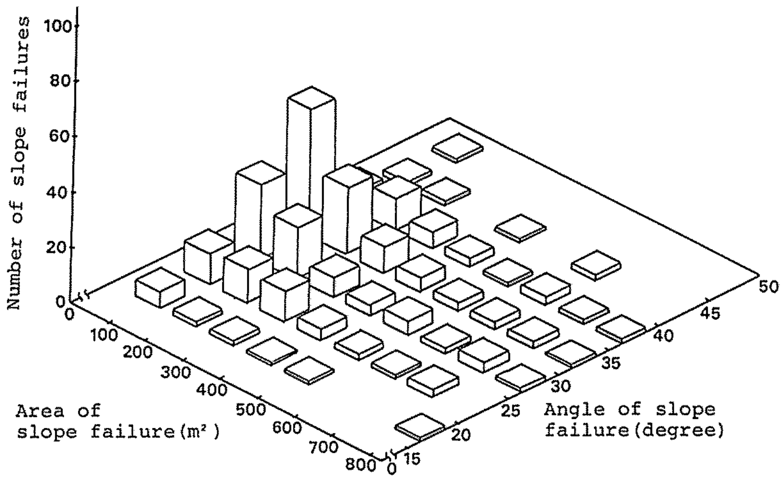


Fig. 8. Relationship between the number, area and angle of slope failures (curvilinear zone of slope)

m^2 was illustrated in connection with the size and the inclination angle of slope failures in the rectilinear zone of slope, and was shown in Figure 7. These slope failures were about 97 percent of the total number of slope failures. As shown in Figure 7, there were many slope failures with the angle of 30～45°, and a great part of them was within the area of 300 m^2. Especially, there were a large number of slope failures with the angle of 30～40° and with the area of about 100 m^2. This tendency shows a special feature that the size of slope failures in granite area was small. Among the slope failures with the angle of 20 ~ 30°, the rate of slope failures with the area less than 200 m^2 was about 41 percent. On the contrary, among the slope failures with the angle of 30 ~ 40°, the above mentioned rate was about 57 percent. The small slope failures of less than 200 m^2 in gentle slope were not so many as in steep one. This shows that the small slope failures were apt to occur in steep slope.

Similarly, Figure 8 shows the number of failures in connection with the size and the inclination angle of slope failures in the curvilinear zone of slope.

Because the inclination of the curvilinear zone was gentle in comparison with that of the rectilinear one, many slope failures were naturally distributed in gentle part of this zone. The rate of the number of slope failures of larger than 300 m^2 to all ones was relatively higher than that of smaller than 300 m^2 in comparison with the case in the rectilinear zone of slope. In addition, it was seen in Table 1 that the mean size of slope failures in the curvilinear zone of slope was larger than that in the rectilinear zone of slope. From these facts, it was surmised that the occurrence of slope failures was affected with the inclination angle of slope and the depth of the surface soil layer.

Ⅳ. Depth of the surface soil layer

Judging from the results of morphometry on the topographical maps, it became clear that the slope failures were distributed at the upper part of the rectilinear zone of slope.

The depth of the surface soil layer on the periphery of slope failure and the nonfailed slope in the neighborhood of slope failure was measured by field observations at the same area as the morphometry had been carried out. The first part of measurement on the depth of the surface soil layer was done on the failed slope which was interpreted through aerial photographs, secondly on the nonfailed slope in the neighborhood of the failed slope with similar topography. Ten pairs of the failed and nonfailed slopes were respectively measured at the geology of Coarse-grained biotite-granite and Medium-grained hornblende-biotite granodiorite.

The depth of the surface soil layer in the upper, middle and lower parts of slopes and the spot of slope failures was measured by using a soil auger (1 m in length). On failed slope, the depth of the surface soil layer on the periphery of slope failure was measured, supposing that the depth of the surface soil layer on the periphery of the failed slope was nearly equal to that on the center line of the assumed slope after its slope had collapsed. On nonfailed slope, with an assumption that the upper inflection contour line would become the highest point of failed slope if the slope would collapsed, the depth of the surface soil layer of the center line was measured in concave slope. On the occasion of measurement, it was assumed that the distance which the inserted auger could reach at right angles to the slope was the depth of the surface soil layer there. Insertion was repeated five times per area of 1 m^2, and the five values were averaged. When these values varied widely, the maximum and minimum values were neglected. These results are shown in Table 2 (1). When it was too deep to measure, the depth of the surface soil layer was shown as > 105 cm in Table 2.

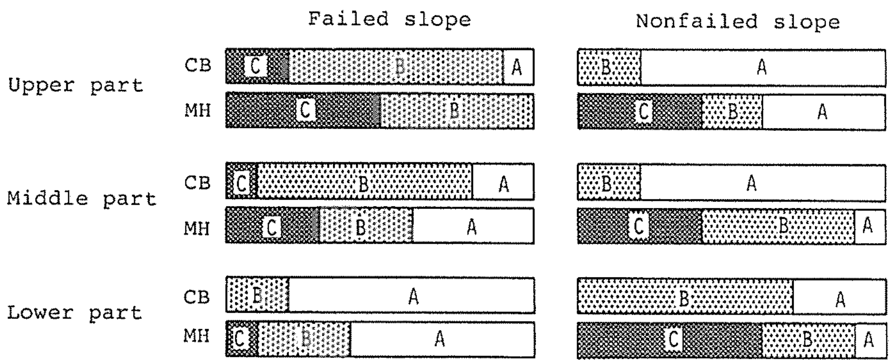
The depth of the surface soil layer in Table 2 was grouped into three classes for each geology such as A (less than 50 cm), B (55 ~ 100 cm) and C (more than 105 cm). The rate of each class was shown in Figure 9.

In failed slope in each geology, the deeper classes of soil layer such as B, C were mostly located at the upper and the middle parts of slope,

Table 2. Depth of surface soil layer

No.	CB Failed slope (cm) U	M	L	CB Nonfailed slope (cm) U	M	L	MH Failed slope (cm) U	M	L	MH Nonfailed slope (cm) U	M	L
1	55	75	35	20	45	90	>105	>105	80	>105	>105	>105
2	75	40	35	80	70	60	60	55	40	95	>105	>105
3	30	55	25	20	30	40	90	45	60	35	60	>105
4	80	75	40	70	85	>105	85	60	25	30	90	>105
5	85	80	55	30	35	60	>105	45	20	15	30	20
6	85	80	40	45	40	70	>105	65	50	>105	90	100
7	90	60	50	45	50	65	>105	>105	>105	20	55	95
8	>105	>105	40	40	45	65	60	20	25	>105	>105	>105
9	85	45	35	20	20	20	>105	>105	60	>105	>105	>105
10	>105	55	80	25	35	15	85	45	10	60	70	65

Note. CB : Coarse-grained biotite-granite
MH : Medium-grained hornblende-biotite granodiorite
U : Upper part
M : Middle part
L : Lower part



Note, CB:Coarse-grained biotite-granite
MH:Medium-grained hornblende-biotite granodiorite
A:Depth of surface soil layer(~50cm)
B:Depth of surface soil layer(55~100cm)
C:Depth of surface soil layer(105cm~)

Fig. 9. Rate of each class on the depth of surface soil layer

and the shallower class of the soil such as A was abundant at the lower part. In nonfailed slope, on the other hand, the deeper class of the soil layer was distributed at the lower part, and the shallower classes were generally at the upper and the middle parts of slope. Namely, the depth of the surface soil layer in failed slope was related inversely to that in nonfailed slope.

V. Discussion and conclusion

Supposing that the weathering speed of slope is to be uniform, it is reasonable to assume that the residual soil accumulates thickly at the upper gentle hillside on account of weak erosional force caused by flowing water, and that the depth of the surface soil layer at the middle steep hillside becomes shallow on account of strong erosional force by flowing water. Furthermore, the sediment which has been eroded at the middle hillside will accumulate thickly at the lower hillside. According to these assumptions, the depth of the surface soil layer must be deep at the upper gentle part, and is shallow at the steep slope. Therefore, it may be considered that the neighborhood of the upper inflection contour line would correspond to the zone where the depth of the surface soil layer is gradually transiting from deep to shallow part.

As for the movement of water during heavy rainfall, some of infiltrated water is stored in soil at the upper gentle part, the excessive water moves down and reaches to the impermeable layer. It is supposed that if the water flows to the slope direction along the impermeable layer and reaches to the part of the shallow depth of the surface soil layer, the slope failure may take place by the outflow of seepage water.

From the reason why many slope failures were distributed in the upper part of the rectilinear zone of slope, it was considered most likely that the slope failure was caused by the difference in the depth of the surface soil layer of slope and the movement of infiltrated water. It is finally concluded that the rectilinear zone of slope, especially the upper inflection contour line, give the usuful information for predicting the dangerous places of the occurrence of slope failures in granite area.

Literature cited

(1) KATAOKA, J., TAKEDA, Y., and IIDA, O. : (A study on slope failures in concave slope), J. Jpn. For. Soc. 58 : 222～224, 1976*

(2) YAIRI, K., SUWA, K., and MASUOKA, Y. : (Slope failure due to heavy rainfall in July, 1972, -Disaster at Obara Villege and Fujioka Town-, The survey report for prevention of disaster due to heavy rainfall in July, 1972), 92～101, 1973*

(3) SMALL, R.J. : The study of landforms, Cambridge University Press, 204, 1970

*Only in Japanese

The titles in parentheses are tentative translation by the autors of this paper