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Creep and Failure of Palaeozoic-Rock Slope

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Abstract

The process of a rockfall and slides which occured on the 22nd April, 1973 at a cut slope of a Prefectural Road in Kyoto consisting of alternation of sandstone and slate of the Chichibu Palaeozoic system is described. A retaining wall had been under construction at the site and the effect of the work on the stability of the slope is discussed. It is found out that the site has been at a marginal stability for some time exhibiting creeping and causing rockfalls from time to time. A loosening of rock mass due to the excavation at the slope end for construction of the retaining wall and a rainfall on the 21st to 22nd may probably have accelerated the creeping and caused the rockfall and slides. This case history indicates that even phenomena as rockfalls or rockslides are accompanied by a creep and the nature of these may be utilized for prediction or for estimating the extent of danger in this respect.

1. Introduction

A rockfall and slides happened on the 22nd of April 1973 at a cut slope of a Prefectural Road, Kyoto and a block of rock crashed against a car passing through the site killing a child and injuring five people in it. A retaining wall had been under construction at the site and the effect of the work on the rockfall was suspected. Further, the question of prediction of a rockfall in such a slope was raised for engineers and scientists who are concerned with techniques in this connection.

In the present paper the process of the rockfall and the slides and the results of investigations carried out after the accident including rock conditions, observed creep phenomena, etc. are described and the effect of the earthwork and the correlation between the creep and the rockfall as well as the slides is discussed.

2. Process of Slope Failure and Rainfall[1,2]

Two blocks of rock of $90\times70\times30$ cm^3 and $80\times50\times20$ cm^3 respectively fell from a cut slope on a Prefectural Road along the Tawara river, Kyoto at about 14 : 50 on the 22nd of April 1973 and the former block crashed against the roof of a car passing through the site and killed a child and injured five people. Small pieces of rock dropped down intermittently after the rockfall and subsequently two rockslides, amounting to 50 m^3 and 15 m^3 respectively followed during 16 : 10 to 16 : 40. The larger slide originated from a slope face about 30 m high above the road level and the smaller one from just above the lowest retaining wall 5.5 m high.

The rainfall in this district preceding the accident was as shown in Table 1.

Table 1a. Daily amount of rainfall in April 1973.

Observatory / Date	Kyoto Local Meteor. Observ.		Daily amount		
	Daily amount (mm)	Max. hourly amount (mm)	Kyoto (mm)	Aodani (mm)	Jibusan (mm)
4. 1	0	0	0		
2	0	0	0		
3	0	0	0		
4	2.5	1.0	2.5		
5	0	0	0		
6	0	0	0		
7	0	0	0		
8	0	0	0		
9	0	0	16		
10	43.5	7.0	28	opened on 11,	
11	0.5	0.5	9	2.0	
12	10.5	7.0	2	7.0	
13	0	0	0	0	
14	0	0	5	5.0	
15	51.0	7.0	47	33.0	
16	4.0	3.0	57	34.0	
17	61.0	10.5	8	12.0	opened on 18,
18	0	0	0	0	
19	0	0	4	3.0	1.0
20	3.5	2.5	0	0	1.0
21	33.5	8.0	44	64.0	61.0
22	10.5	4.5	0	0	2.0

The maximum amount in this month is 10 mm/hr or 33 to 60 mm/day both of which occurred on the 17th of April. There had been no remarkable rainfall since the 17th until the 21st when a rainfall of max. 7 mm/hr or 40 to 60 mm/day was recorded from the evening of the 21st through the morning of the unhappy 22nd.

3. Construction Work at the Site

A retaining wall as illustrated in Fig. 1 had been nearly completed when the rockfall occured, and some effect of the work on the accident was first suspected.

The construction work consists of

1) a wall 5.5 m high and 60 m long along the road,
2) stone guard (fence) 1.55 m high on the top of the wall 1),
3) a wall of 10 m high and 15 m long in the middle height of the slope, and
4) a rock net of 10 m wide and 20 m long on the right of the middle-height wall.

Besides, there had been an old retaining wall above the middle-height wall and further the northern part of the slope had been protected by sprayed-concrete covering. The items 3) and 4) had been supplemented to the original plan after a

Table 1b. Hourly and total amount of rainfall on the 21st to 22nd of April 1973.

Date	Time hr.	Kyoto (mm)	Aodani (mm)	Jibusan (mm)
Apr. 21	14	0	—	—
	15	0	0.5	—
	16	2.0	3.5	—
	17	4.5	7.0	8.0
	18	2.5	5.0	8.0
	19	5.0	7.0	7.0
	20	1.5	1.0	4.0
	21	2.0	0.5	1.0
	22	7.0	2.0	2.0
	23	4.0	2.0	3.0
	24	5.0	6.0	6.0
Apr. 22	1	2.0	2.0	4.0
	2	2.0	2.0	—
	3	0.5	1.0	3.0
	4	0.5	—	—
	5	2.5	12.0	5.0
	6	1.0	0.5	2.0
	7	2.0	6.0	3.0
	8	0	4.5	4.0
	9	0	1.1	1.0
	10	0	—	1.0
Total		44.0	64.0	62.0

small slide had occurred in January, which will be described later. On the day of the accident only the fence net, which is to be spanned between steel posts 1.55 m high and is for preventing falling stones from bounding over, had not yet been finished.

4. Rock Conditions

The rock at the site consists of an alternation of sandstone and slate belonging to the Chichibu Palaeozoic system. The sandstone is penetrated by several systems of joint, one of which coincides with the bedding plane to which very often a thin layer of slate with well-developed Slickensides adheres. The matrix of unweathered sandstone exhibits dark bluish color.

The slate exists in a form of either a stick to the sandstone or a thick layer in which case it exhibits black to dark-grey color, looking like wooden coal, and also includes several system of Slickensides.

The unweathered part of sandstone is very hard and it is rather difficult to break by hammering, while weathered part is very weak and can easily be broken into pieces. Fracture often occurs along one of the Slickensides. The slate is, on the whole, much weaker than the sandstone and can easily be broken into small

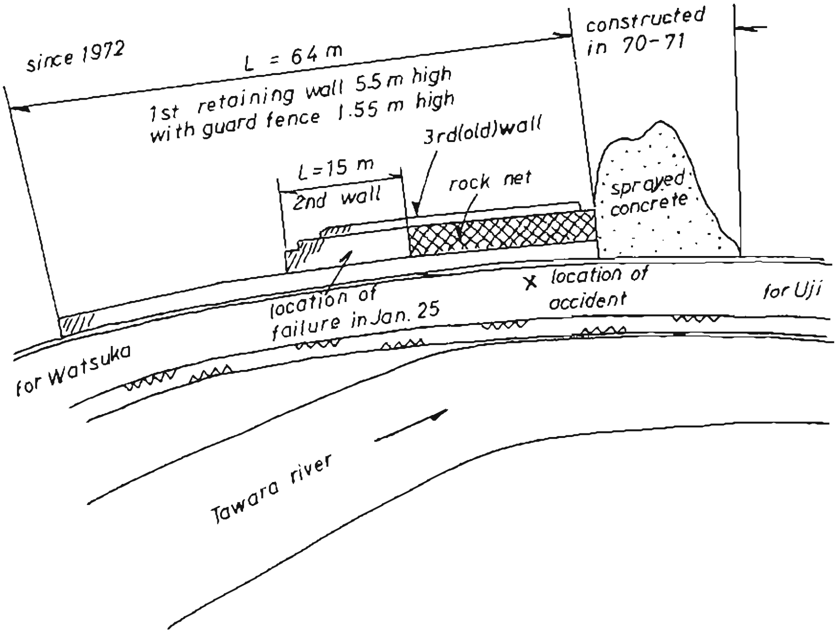

Fig. 1. Schematic representation of preventive works against rockfalls and slope failures at the site.

pieces by hammering.

At the present site three main joint systems are remarkable, which correspond either to bedding planes, planes parallel to the slope surface and those intersecting with the both at greater angles. The latter two joint systems will be called hereafter as sheeting joint and cross joint, respectively. The bedding planes dip into the slope at an angle of about 15 to 20 degrees in the higher part of the slope and 40 to 60 degrees at the river bed of the Tawara river.

A polar representation of the distribution of joints at an old slide scarp in the uppermost part of the slope and at the river bed is given in Fig. 2. In the figure the poles for the slope surface (N30W/55N) as well as for the old slide scarp (N55W/80N) are also given.

Materials accumulating on the slope surface consist mainly of unweathered debris of rock and weathered soils interbedding small fragments of rock. The size distribution of debris estimated from rock pieces sampled at random in the higher part of the slope are as follows:

in case of sandstone, 50 to 200,000 cm^3 and

in case of slate, 90 to 4,000 cm^3 (see Fig. 3).

The most frequent sizes correspond to the class 300 to 1,000 cm^3 for both types of rock.

The volumes of the rock blocks having fallen prior to the slides are 310,000 and 225,000 cm^3, which belong to the class of the biggest size. The debris are in general angular and the angle of friction of the aggregate is estimated to be higher than

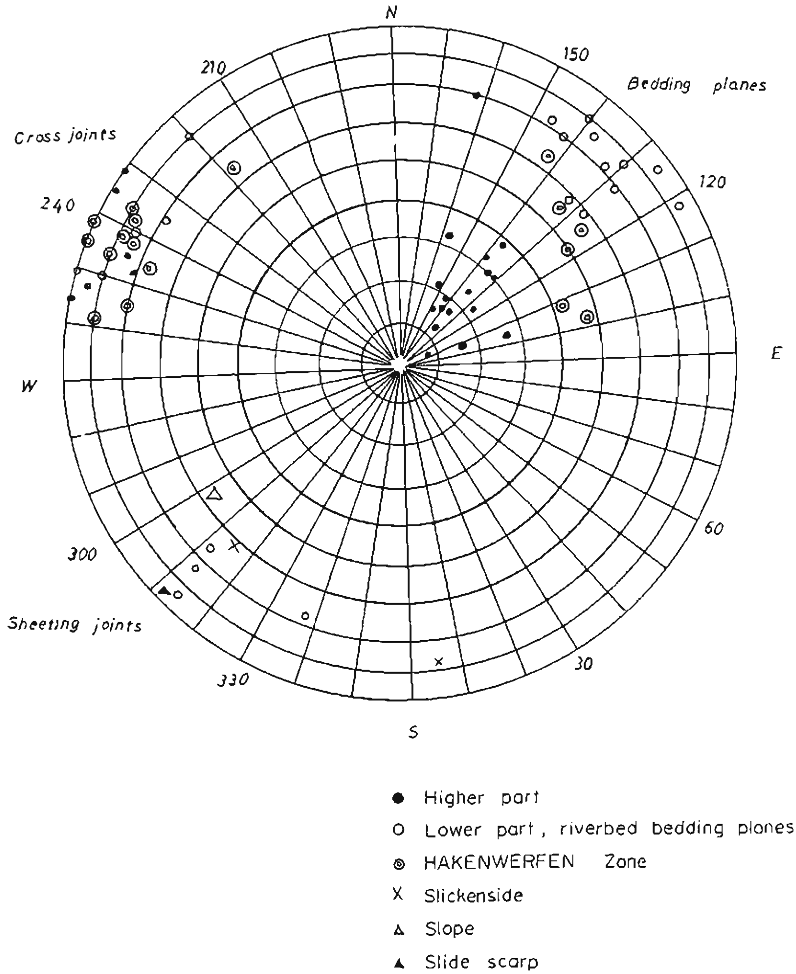

Fig. 2. Distribution of joint orientations in a higher and lower part of the slope.

45 degrees. That of the soils is estimated to be about 45 degrees through their unstable behavior, moving easily with only a very slight provocation.

It is noted in the higher part of the slope that the orientation of the slide scarp is nearly coincident with the average of those of sheeting joint. The angle between the average orientations of sheeting joint and of the slope as a whole is about 20 degrees. The gaps between joint surface in the upper part are 5 to 15 cm for bedding joint, 1 to 25 cm for cross joint and 5 to 10 cm for sheeting joint.

It the river bed the bedding plane is more steeply inclined than in the higher part of the slope, and gaps between joints are 5 to 20 cm for bedding, 15 to 20 cm for cross joints and 10 to 20 cm for sheeting joints, respectively, which values are appreciably greater than those in the higher part.

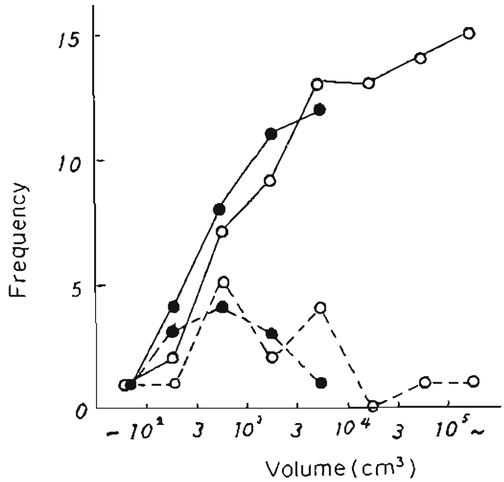

Fig. 3. Size distributions of debris; ○ sandstone, ● slate; ...... size frequency curve, —— size accumulation curve.

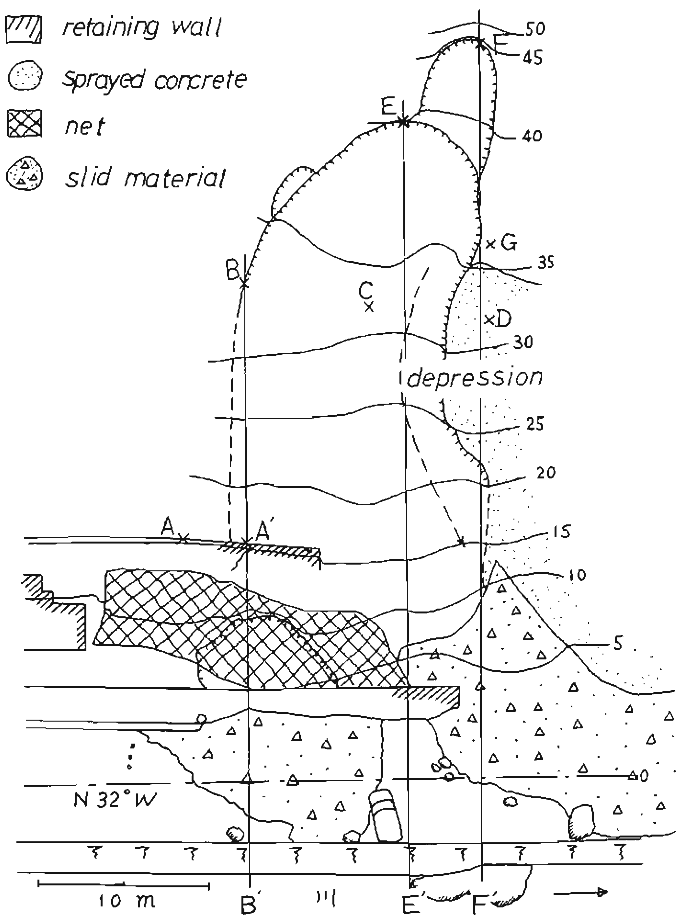

Fig. 4. Plan of the site.

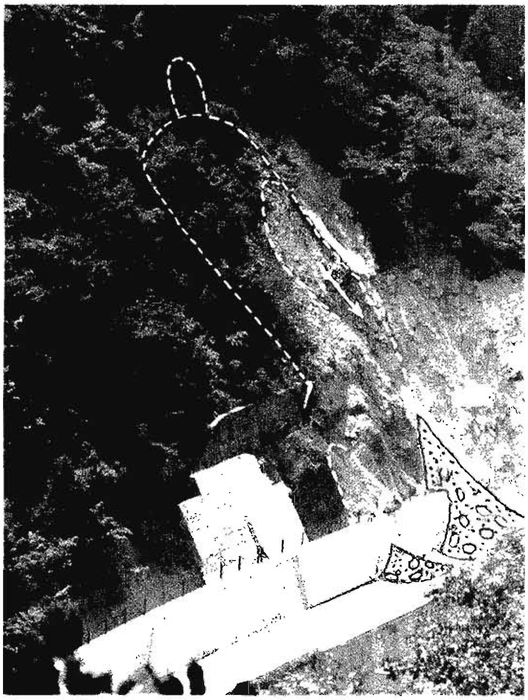

Fig. 5. View of the site.

Fig. 6. A trace of slip amounting to about 25 cm.

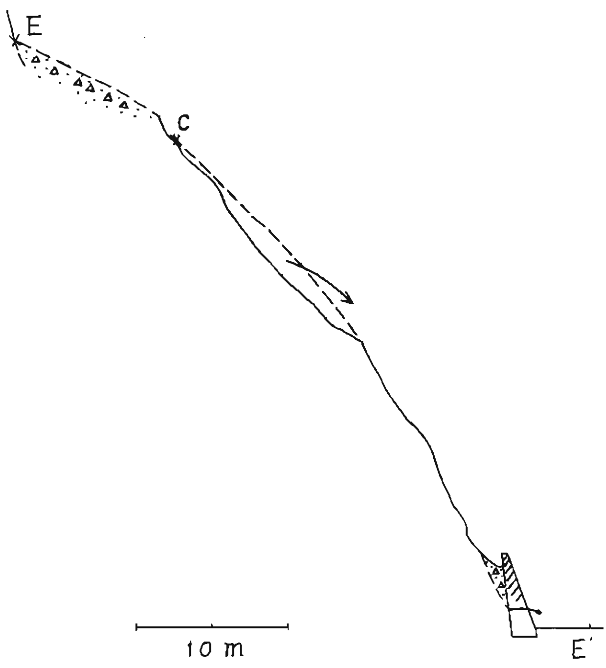

Fig. 7. Longitudinal section of the slope.

5. Evidence of Integrated Slide

As a result of site investigation it was found out that a larger area including the two present slides is moving downhill. Its upper end is bounded by an old slide scarp, the northern side by a boundary of sprayed concrete, and the southern side by a line which coincides with a fresh crack found in the existing old retaining wall (Fig. 4, 5). The scarp exhibits a height difference of 2 to 3 m across it and is accompanied in the northern half by another smaller slide of 5 m long, which also is bounded by a scarp of 5 m high. Also the southern periphery of the main slide is accompained by a small slide of about 1 m width. After the accident a new

Table 2. Daily amount of rainfall in January 1973.

Observatory	Kyoto Local Meteor. Observ.		Daily amount			
Date	Daily amount (mm)	Max. hourly amount (mm)	Kyoto (mm)	Kizu (mm)	Tanabe (mm)	Watsuka (mm)
1. 1	18.5	4.5	21.0	18.0	23.0	×
2	5.5	2.0	4.0	3.0	2.0	×
3	—	—	—	—	—	—
4	—	—	—	—	—	—
5	—	—	0	—	—	—
6	0	0	6.0	7.0	7.0	8.0
7	23.5	5.0	18.0	12.0	18.0	19.0
8	0	0.5	1.0	3.0	—	—
9	0.5	0.5	—	—	—	—
10	0.5	0.5	2.0	—	—	—
11	5.0	1.5	5.0	—	0	2.0
12	4.0	3.0	4.0	—	—	0
13	—	—	—	—	—	—
14	—	—	0	3.0	2.0	1.0
15	5.5	1.5	6.0	9.0	6.0	5.0
16	—	—	5.0	6.0	4.0	4.0
17	15.5	2.0	36.0	37.0	38.0	37.0
18	29.5	6.5	5.0	4.0	5.0	7.0
19	0	0	0	—	0	0
20	0	0	0	—	—	—
21	—	—	—	—	—	—
22	0.5	0.5	1.0	4.0	4.0	4.0
23	0	0	0	—	—	—
24	21.0	6.5	21.0	23.0	20.0	11.0
25	0	0	0	—	—	—
26	0.5	0.5	2.0	—	1.0	1.0
27	2.0	1.0	3.0	—	—	3.0
28	2.0	1.0	0	1.0	—	—
29	—	—	0	—	—	2.0
30	0	0	—	—	—	5.0
31	—	—	—	—	—	—

trace of slip amounting to about 25 cm was observed along the boundary of the integrated sliding mass (Fig. 6).

The longitudinal section of the slope through the point E is shown in Fig. 7, from which the average inclination of the slope is revealed to be about 40 degrees in the upper half and 60 degrees in the lower half. On the main sliding mass there is a channel-like depression, which begins at about 35 m height and comes down curving gradually to left as shown schematically in Fig. 4. The depression seems to be the space from which the main larger slide originated.

6. Rocord of Past Slides[1)]

The slide scarps of several meters high suggest past slides along a surface which is possibly coincident with that of the present integrated slide. Besides, there are several reports of rockfall and rock slides in the recent past near the site;

1) a slide of 100 m^3 on June 6, 1971,
2) a slide with width of 10 m on July 12, 1972,
3) a slide on Sept. 16, 1972, and
4) a slide of 30 tons on Jan. 25, 1973.

It must be noted, however, that the positions for the cases of 1) to 3) cannot be determined deffnitely as indentical with that of the present case, while case 4) can evidently be correlated with the present sliding mass, and the description of that process follows:

The slide of about 30 tons happended at about 3 p.m. on the 25th of January 1973 from the foot of the existing retaining wall 15 m above the road level, while excavation of the slope end for the foundation of the new retaining wall was being executed. The rainfall in the preceding period given in Table 2 suggests a certain effect of rainfall amounting to 20 mm on the preceding day, however the essential cause of the failure should be loosening of rocks caused by undercutting. This case gives information on the extent of effects of human activity as well as rainfall on the stability of the slope.

7. Creep Phenomena

Within the sliding area there are very few plants growing, especially in the lower half. In the upper half and in the southern side, there is bush, however its height and density are apparently inferior than those in the surrounding area. The area above the upper end of the sliding mass, where cedars grow, seems to be very stable.

No significant difference in ages of trees, which ranged from 5 to 16 years, within and outside of the sliding area could be found, however the diameters of trunks differ evidently in both areas, i.e. those within the area are smaller than several cm, while those outside often exceed 10 cm. This fact suggest an instability of the area.

Proceeding creep can be presumed also by curving tree trunks (Fig. 8). Vines which extend from the bedrock over slide scarp to the sliding mass are in tension,

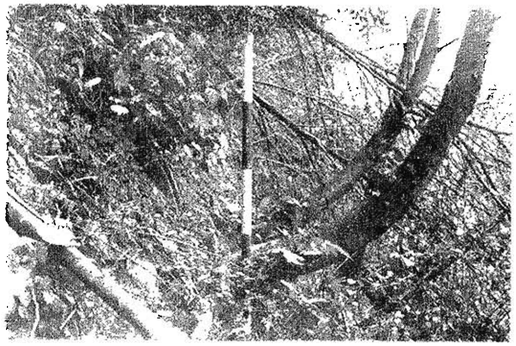
Fig. 8. Curving tree trunks.

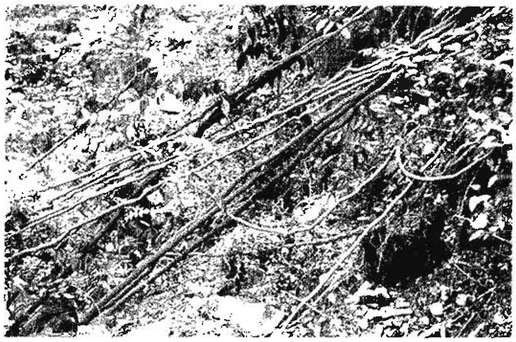
Fig. 9. Vines in tension due to differential displacement of ground.

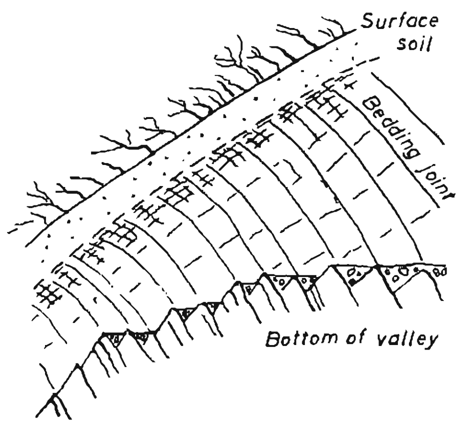

Fig. 10. Hakenwerfen or gravitational deformation of rock mass near slope surface.

suggesting a recent downhill displacement of the mass (Fig. 9).

A Hakenwerfen (gravitational deformation)[3,4] phenomenon is observed at a valley cutting normally into the slope at some tens of meters north from the site (Fig. 10). This phenomenon also indicates a proceeding downhill creep under the effect of gravity. Warping of the discontinuity develops as deep as 5 m into the rock mass, and above this depth the rock is appreciably loose because of toppling blocks[5] and opening joins. The rock condition is similar at this point and in the slide site so the phenomenon may probably be assumed also to have existed in the slope concerned.

The steeper dip of bedding at the river bed than at the scarp may be attributable to this phenomenon, being assumed that a loosened portion has been taken off by flowing water in the river bed, while that portion remains still in the scarp.

8. Discussion

The rocks at the site are alternation of sandstone and slate of the Chichibu Palaeozoic system, which is characterized by many joints and very unstable nature. This character is even more accentuated at the site by proceeding creep of surface soils as well as rock mass, which is revealed from the curved tree trunks, vines in tension, Hakenwerfen, etc. The creep is essentially caused by under-cutting by the Tawara river and the Prefectural Road along the foot of the slope. As a result there is a steeper inclination of the slope compared to the average value of inclination from the foot to the top of the mountain.

Thus, slides had occurred several times, resulting in scarps of a considerable height difference and an integrated sliding mass which is composed of several partial slides, to which the slide in January also belong. In the head of the sliding mass an amount of debris of sandstone and slate are accumulated being supplied from the scarps and higher part of the mountain. The fallen block in the present case is also a part of the debris thus accumulated.

The period from the rockfall until the initiation of slides is 1 hr 20 min. and the slides continued as long as 30 min. The original position of the fallen blocks is estimated to be at the northern part in the middle height of the sliding mass, which coincides with that of the present larger slide. The smaller slide originated from the southern boundary of the integrated sliding mass, just below the fresh crack in the old retaining wall.

The fact that the rockfall and the slides occurred almost at the same time and from correlated positions as described above suggests with high probability that they are not independent but correlated to each other.

The mechanism of the slope failure, accordingly, is supposed as follows: The slope had been at a marginal stability since long exhibiting proceeding creep. The effect of excavation at the slope end has been transmitted as high as the level of the middle of the creeping mass until April 1973 and the creep was accelerated changing the landform correspondingly. A rainfall amounting to 60 mm on the 21st to 22nd was enough to elevate the water table in the loosended part causing the increase of weight and the decrease of the strength of the rock mass at the same time. A slide along a surface of presumably 5 m deep occurred and yielded a displacement of about 25 cm. As a result the two blocks of rock which had been situated at an unstable position lost their support and fell down. The remaining masses slid down in a similar way and a provisory stability was attained.

This case history indicates that an apparently sudden phenomenon as rockfall or rockslide may be accompanied by a gradual creep phenomena. It is also noted that even in a brittle material as Palaeozoic sandstone a creeping in a macroscopic scale can be realized through "Bruchfliessen"[6] which is connected with the increase of bulk of the rock mass or "Dilatancy". By noting these phenomena of long duration a rockfall or rockslide prediction may be feasible or at least it would be possible to point out relatively dangerous sites in this respect.

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