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Hydrological and geomorphological studies of debris slides on forested hillslopes in Japan

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ABSTRACT Debris slides are the predominant erosional process on forested hillslopes in Japan. The hillslopes in a basin are composed of slope units of three different types, i.e. convergent, divergent and plane types. More than 80% of debris slides occur on the convergent slopes, which collect and discharge storm water as well as weathered material most actively. The writers have called this spoon-shaped slope unit a 0-order basin, which is the most important slope unit from the hydrological and geomorphological viewpoint. Field investigations in 0-order basins indicate that pipes develop in shallow soil layers to discharge the converging subsurface storm water. Nearly 100% of the discharge from a trench profile in a 0-order basin was through pipes. Discharge through the soil matrix was negligible. The pipeflow is presumed to play an important role in debris yield in a mountain basin during extremely heavy storms.

OUTLINE OF EROSION ON HILLSLOPES IN JAPAN

Nearly 70% of the islands of Japan are mountainous. The remaining 30% consist of alluvial and diluvial deposits which are densely populated. Almost all the mountain slopes are covered with vegetation, generally with natural and artificial forest ranging from the subtropical to the subfrigid zones. These slopes generally have well developed forest soils, except for the steep slopes in high mountain regions. Because of the forest cover, surface erosion (sheet, rill and gully erosion) seldom takes place on the hillslopes. Mass slides predominate on the forested hillslopes. The writers have classified the mass slides on the hillslopes in geomorphological equilibrium into two types, i.e. debris slides and bedrock slides. The former involve the sliding of weathered material, mainly of forest soil itself, on the bedrock, and are generally shallow and small. The latter involve the sliding of rotted or fractured bedrock, and are deep and large. The former belongs to the "debris slide" and the latter to the "slump" categories in Sharpe's classification (Sharpe, 1968). The features of the two types of slide are listed in Table 1.

Slides of the above two types occur somewhere in Japan on average once or twice in several years, during the rainy or typhoon seasons. On these occasions, almost all slides are debris slides. Bedrock

TABLE 1 Classification and characteristics of mass slides

Characteristic	*Type of slide:* *Debris slide (shallow slide)*	 *Bedrock slide (deep slide)*
Depth of slide	*0.5-2.0 m, within the surface soil affected by organic matter*	*5.0 m, within the bedrock itself*
Formation of sliding mass	*Convergence of weathered surface material*	*Fracturing, rotting and weathering of bedrock*
Characteristics which affect the occurrence:		
Topography	*Affected by micro-slope forms and convergence of subsurface stormwater*	*No relation to slope form*
Rainfall	*Mainly rainfall intensity*	*Both intensity and total amount of storm rainfall*
Forest	*Deforestation accelerates occurrence, especially decay of root systems*	*No relation to deforestation*

slides are quite rare. Based on estimates of debris yield to downstream torrents, debris produced by heavy storms is listed in Table 2. The areas associated with these estimates are of the order of several km^2. The writers estimate that a storm of 1000 mm, the heaviest storm in Japan, yields debris with an average depth of nearly 100 mm from a mountain basin of several km^2.

TABLE 2 Debris yields in heavy storms during the period 1935-1965

*Average depth of debris (mm)**	*Number of events*	*District where disaster occurred (Year)*
100-150	*2*	*Ina (1961), Nishitani (Fukui-gifu) (1965)*
50-100	*8*	*Rokko (1938), Akagi (1947), Aso (1953), Minamiyamashiro (1953), Aritagawa (1953), Komarugawa (1954), Isahaya (1957), Neo (1965)*
30-50	*5*	*Moji (1953), Azumigawa (1953), Ootogawa (1953), Fujigawa (1959), Nagaoka (1961)*
10-30	*12*	

* *Volume of eroded mass divided by the area.*

These slides frequently develop into mudflow torrents, which cause serious disasters on downstream fans. In Japan, most small fans at the base of hillslopes are composed of the deposits of these mudflows or gravelflows. Torrents with no downstream fan sometimes raise their beds by up to 10 m with mudflow deposits after a heavy storm. In this paper, the writers investigate the geomorphological and hydrological characteristics of debris slides, which are the most important erosional processes for hillslope formation and also the most important disaster phenomena in Japan.

GEOMORPHOLOGICAL CHARACTERISTICS OF THE SITES OF DEBRIS SLIDE OCCURRENCE ON HILLSLOPES

Mountains in Japan are composed of various geological structures and rocks with variable relief. According to Strahler's hypsometric index, most mountains are in the mature stage, having no flat ridges. The curvature of the hillslopes in both the contour-line and stream-line directions is gentle when compared to the steepness of the hillslopes, except in high alpine regions. The writers suggest that this results from the forest cover which reduces physical weathering and promotes the accumulation of weathered material on the slopes.

The writers (Tsukamoto *et al.*, 1978) have investigated debris slides both in the field and on 1:2000 topographic maps in four districts. The four areas comprise mountains of comparatively low relief. As shown in Fig.1, hillslopes may be divided into three units according to their topographic shape. The three types are termed convergent slope units, divergent slope units and plane slope units. Convergent slope units are associated with spoon-shaped small basins on the hillslope where streamlines converge on the hollow line. Divergent slope units comprise the pointed ends of ridges where streamlines diverge. Plane slope units are those slopes with no curvature where streamlines run parallel down the slope. The slopes in a basin are composed of a combination of the above three units and the writers have found that these are the

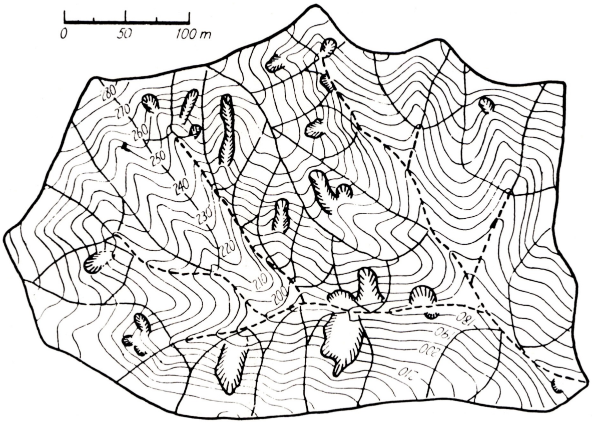

FIG.1 Hillslope topography and debris slides.

three basic slope components in a basin from the hydrological and geomorphological viewpoint. The three slope units were found to have excellent correspondence with the occurrence of debris slides. A summary of the results of the analysis is as follows.

(a) The area of convergent slope units occupies on average 60% of the whole basin area.

(b) n/N in Table 3 is regarded as an index of the probability of occurrence of debris slides on respective slope types. Under the same storm conditions, more slides are liable to occur on convergent slopes than on divergent slopes or plane slopes. In Nishimikawa, the occurrence rate on convergent slopes is three times that of other slopes and in Seirenji it is ten times.

TABLE 3 Relationship between slope unit type and the occurrence of debris slides

District	*Slope type*	*N*	*n*	*m*	*n/N (%)*	*n/ΣN (%)*	*m/M (%)*
Amakusa	*C*	*705*	*211*	*232*	*31.5*	*18.6*	*82.3*
	P	*191*	*15*	*19*	*7.9*	*1.3*	*6.7*
	D	*289*	*21*	*22*	*7.3*	*1.9*	*7.8*
Seirenji	*C*	*893*	*263*	*276*	*29.5*	*17.1*	*87.6*
	P	*209*	*6*	*6*	*2.9*	*0.4*	*1.9*
	D	*432*	*10*	*10*	*2.3*	*0.7*	*3.2*
Nishimikawa	*C*	*505*	*309*	*387*	*61.2*	*34.5*	*77.0*
	P	*106*	*24*	*28*	*22.6*	*2.7*	*5.7*
	D	*283*	*37*	*40*	*13.1*	*4.1*	*8.1*

EXPLANATION OF ABBREVIATED LETTERS: C = Convergent type slope unit, P = plane type slope unit, D = divergent type slope unit, N = number of slope units, n = number of the slope units on which debris slides occur, m = total number of debris slides in the given type of slope unit, M(=Σm) = total number of debris slides in the given basin.

(c) n/Σn, which is the product of N/ΣN (% area of the respective slope types) and n/N (occurrence rate of debris slides on respective slope types), expresses the probability of occurrence over the whole area of a given slope type. The values of n/ΣN in Table 3 indicate overwhelmingly high rates of occurrence of debris slides on convergent slope units.

(d) Most slope units, regardless of the slope type, have one debris slide as shown in Table 4. These slope units can be regarded as the unit area of occurrence of debris slides.

(e) In the case of convergent slope units, nearly 85% of debris slides takes place on the central hollow line and at the approximate shifting point of streamlines from convex to concave form.

(f) Regarding the head of a debris slide as the upper end of a stream in a convergent slope unit (basin), Horton's laws of stream length and gradient are valid. This means that convergent slope units maintain harmony with downstream reaches. Therefore, the

TABLE 4 Number of debris slides on individual slope units

District	*Slope type*	*Number of debris slides on one slope unit*			
		1	*2*	*3*	*4*
Amakusa	*C**	*211(95.5)*[+]	*9(4.0)*	*1(0.5)*	
	P	*12(80.0)*	*2(13.3)*	*1(6.7)*	
	D	*20(95.2)*	*1(4.8)*		
Seirenji	*C*	*251(95.4)*	*11(4.2)*	*1(0.4)*	
	P	*10(100.0)*			
	D	*6(100.0)*			
Nishimikawa	*C*	*258(83.5)*	*37(12.0)*	*1(3.2)*	*4(1.3)*
	P	*20(83.3)*	*4(16.7)*		
	D	*34(91.9)*	*3(8.1)*		

** C, P and D are defined in Table 3.*

[+] *Number (%).*

writers regarded convergent slope units as basins which have ephemeral streams functioning during heavy storms.

The above results led the writers to the following conclusions. Mountain slopes are not uniform, but consist of three different slope units. Among these three types, convergent slope units are the most active from the erosional viewpoint. The writers have termed the convergent slope unit a 0-order basin and this is the basic unit of convergence and discharge of weathered material. From this viewpoint, debris slides can be regarded as a development phenomenon of the 0-order basins.

HYDROLOGICAL CHARACTERISTICS OF 0-ORDER BASINS

In Japan, typical debris slides occur in granite regions where the slope surfaces are mantled with thin soil layers, usually less than 1-2 m deep. Tanaka (1961) explained the mechanism of debris slides as follows. When saturated subsurface flow appears at the ground surface, the piping phenomenon develops. In addition, a bulging phenomenon occurs on the lower slope of the piping point as a result of hydrodynamic pressure due to the outflow of seepage water. Once these phenomena occur, the wedge shaped soil mass between the slope surface and the free water surface slides down, and a succession of such slides may occur. The writers presume that the stream head of a 0-order basin in a heavy storm is this piping point. In order to clarify the hydrological characteristics of 0-order basins, the following investigation was carried out.

Pipe networks in 0-order basins

The hillslope edge above the slide or the outer edge of the debris slide scar in a 0-order basin offers evidence of the existence of natural pipes developing in the soil. According to the investigation on the granite hillslopes, these exhibit the following features.

(a) Out of 64 debris slides scars, only four had no pipes. The remaining 60 had at least one pipe and there was on average 3.6 pipes in a slide scar.

(b) The average diameter of the pipes was 14 cm and the average cross sectional area was 200 cm^2.

(c) The depth of the pipes at the outer edges of the slide scars was 30-60 cm beneath the soil surface, and they occurred towards the bottom of the B horizon.

(d) Several pipes were traced over 5 m.

Observation of pipeflow in a 0-order basin

The above investigation indicated the importance of pipes in 0-order basins. The writers tried to measure pipeflow in a 0-order basin and a trench was dug at the foot of a 0-order basin as shown in Fig.2. Simple gauging apparatus was installed to measure the

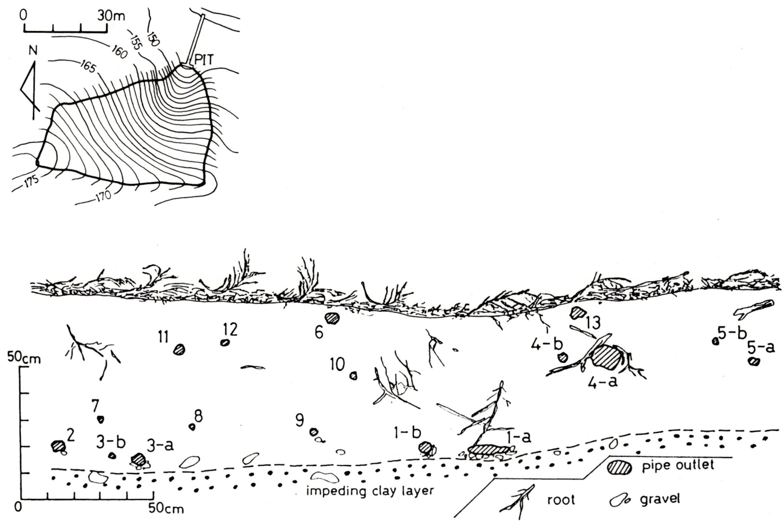

FIG.2 Topographic map of the 0-order basin and the soil profile in the trench.

outflow through individual pipes and the seepage outflow through the soil matrix of the trench profile. Examples of observed pipeflow hydrographs measured during a typhoon storm (total 197.5 mm in 2 days) are shown in Fig.3. Table 5 gives the total outflow through respective pipes during the storm. The following findings were obtained:

(a) Discharge through a pipe commences when saturated conditions reach the level of the pipe. Outflow through the pipes occurs suddenly. The shallower a pipe is in the soil, the steeper the rising and falling limbs of the hydrograph become.

(b) More than 95% of the outflow from the entire trench profile was through the pipes. Seepage through the soil matrix was negligible.

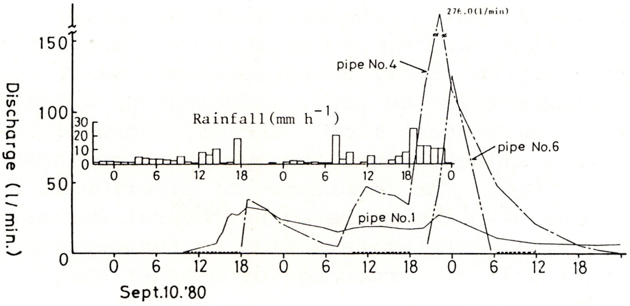

FIG.3 Observed pipeflow hydrographs during a typhoon storm.

TABLE 5 Pipeflow discharges during the storm

*Pipe number**	*Diameter of pipe (cm)*	*Peak discharge (l min^{-1})*	*Total discharge (m^3)*	*Proportion (%)*
1	*3.5*	*33.12*	*64.5*	*30.9*
2	*0.5*	*0.01*	*9.3*	*4.5*
3	*5.0*	*8.34*	*-*	*-*
4	*10.0*	*267.54*	*123.4*	*59.1*
5	*3.2*	*0.43*	*-*	*-*
6	*3.0*	*125.53*	*10.7*	*5.1*
Seepage		*0.35*	*1.0+*	*0.5*
Surface runoff		*0.74*	*0.01*	*0*
Total			*208.9*	

** See trench profile in Fig.2.*
+ Rough estimate.

(c) During the period of observation, No. 6 pipe was enlarged in diameter and produced an extremely high discharge. The writers presume that creation of new pipes and their extinction by blockage occur frequently in the surface soil.

The importance of pipeflow in debris slide occurrence

Forest soil well covered by humus and litter has a very high infiltration capacity as shown by Sato *et al.* (1955). All storm rainfall falling on forested slopes will infiltrate except on trails or other bare areas with no litter cover. In an O-order basin, storm water converges into the comparatively narrow hollow along the centre of the basin, when an impeding layer exists in the soil. The writers' presumption is that, under the above condition, an O-order basin has to have an efficient system for discharging the concentrated water, related to the surface infiltration capacity and the convergence of this infiltrated water. This drainage system would be a pipe network. As to the mechanism of occurrence of debris slides in 0-order basins, the writers' explanation is that this efficient pipe system experiences blockages, which cause sudden increases in the pressure in the pipe, inducing the upwelling and appearance of saturated surface flow. The blockages could be brought about by tiny slides around the outlet or collapse of the inner walls of the pipes. The importance of pipeflow in hillslope hydrology has already been demonstrated by several workers (Kirkby, 1978; Jones 1978, 1979). The writers wish to further emphasize the importance of pipeflow in the hydrology of 0-order basins and in the occurrence of debris slides.

PREDICTION FORMULA FOR MAXIMUM DEBRIS YIELDS IN A MOUNTAIN BASIN

The writers have assumed the following in order to estimate the total debris yield from a comparatively small mountain basin exhibiting equilibrium characteristics.

(a) All debris slides occur in 0-order basins.

(b) In a given basin, the average area of the debris slides varies linearly with that of the 0-order basins.

(c) It is possible to assume a average depth for the debris slides in a given basin.

The total area of debris slides in a mountain basin is given by a simple formula as follows:

$$S = \Sigma s = (f\ N)\ \bar{s} = (f\ N)\ k\ \bar{a} = f\ k\ p\ A \qquad (1)$$

$$V = (f\ k\ p\ A)\ \bar{h} \qquad (2)$$

$$N\ \bar{a} = p\ a \qquad (3)$$

where: S is the sum of the horizontal areas of the debris slides in the given basin; s is area of an individual debris slide; N is the number of 0-order basins in the basin; n is the number of 0-order basins in which debris slides occurred; f is n/N, i.e. the occurrence rate of debris slides in 0-order basins; a is the area of an 0-order basin; k is s/a; p is $\Sigma a/A$, the area ratio of 0-order basins to the whole basin area, and $\bar{}$ is the symbol for the mean value.

The values of k, p and f were obtained as follows (Tsukamoto, 1981). Inspection of various aerial photographs of debris slides revealed a positive relationship between the area of an 0-order basin and the area of the debris slide. Data collected from basins with a wide variety of drainage density were used to construct Fig.4, which demonstrates a clear relationship between the mean values of both 0-order basin area and debris slide area. To construct Fig.4, streams and 0-order basins were delineated on the maps, which provide the numbers of 0-order basins and the areas of debris slides. Then, A/N(= a/p) is estimated and s/(a/p)(= p s/a = p k) obtained for respective basins. Fig.4 shows that the average value of p k is approximately 0.1.

As to the value of f, it is presumed that f is a function of both the erosional susceptibility or instability of a slope and the storm characteristics. The writers analysed the spatial distribution

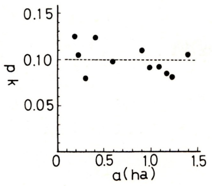

FIG.4 The relationship between O-order basin area (a) and the value of p k.

of the values of f in two different districts, Ina (143 km^2) and Fukui-gifu (154 km^2). These two districts are well known for their debris slide and mudflow disasters. The 1:10 000 maps were covered with a 0.25 km^2 grid and the number of O-order basins (N) and the number of debris slides (n) were counted in each grid square. The maps showing occurrence rates depicted the values of n/N. The maps indicated a definite tendency for the occurrence rates of debris slides to be concentrated. The writers concluded that this spatial concentration of the occurrence rate is due mainly to the mesoscale distribution of the storm, since the occurrence rate distribution took no account of geological, geomorphological and vegetational differences. Occurrence rates decline exponentially with distance from the centre as shown in Fig.5. The general form of the equation can be expressed as follows,

$$f = f_0 \exp(-c\ r) \tag{4}$$

where: f is the occurrence rate at r km from the centre; f_0 is the occurrence rate at the centre and c is a constant. According to 10 data sets, f_0 and c ranged from 0.7 to 0.9 and from 0.2 to 0.6 respectively. With f_0 and c, the following relationship, in which the value of f is at maximum, was obtained:

$$f_0 = 0.8\ c + 0.7 \tag{5}$$

Substituting equation (5) in equation (4) yields

$$f = f_0 \exp\left[(0.7 - f_0)\ r/0.8\right] \tag{6}$$

This equation gives the largest value of f at the time of an extremely heavy storm.

Under the assumption of the heaviest storm, the following are valid.

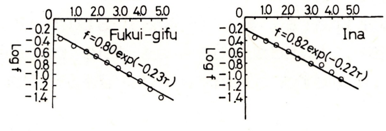

FIG.5 Examples of the spatial concentration of debris slide occurrence rates.

$$k\,p = 0.1$$

$$f \fallingdotseq 1.0$$

Substituting the above in equation (2),

$$V \fallingdotseq 0.1\,A\,\bar{h}$$

According to the field measurements, average values of $\bar{h}$ were 0.5~1.0 m. Then, the value of V becomes,

$$V \fallingdotseq \left[0.1\ (500\text{~}1000\ \text{mm})\right]\ A$$

$$\fallingdotseq (50\text{~}100\ \text{mm})\ A$$

This gives approximately the same values as Table 2. In the case of Ina and Nishitani, the values of V in Table 2 are larger than the above. This is attributable to the occurrence of several large deep slides (slump type).

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