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SEDIMENT YIELD IN BARE SLOPES

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SYNOPSIS

Sediment yield is characterized by various regional factors including geology, topography, weather and vegetation. Ashida and Sawada(1,2) suggested a method of surveying the process of sediment yield on a bare slope and evaluation of slope characteristics related to sediment yield. Based on the test slopes,the authors have clarified that sediment yield is governed by the gradient of any given bare slope, the compressive strength of soil of that slope, rainfall ,and frost-induced heaving and thawing.

INTRODUCTION

In order to predict the environmental change in a drainage basin and to establish the countermeasures to be taken, it is necessary to obtain precise information concerning the elements of the environment. Recently, land use near rivers has diversified extensively, and therefore, both qualitative and quantitative information of sediment runoff are essential.

For making precise qualitative and quantitative predictions of sediment yield in a drainage basin, it is necessary to clarify the mechanism of slope erosion and the factors involved in it based on the real situation of sediment yield. The sediment yield in any drainage basin can be roughly divided into two kinds, depending on occurrence, frequency, and scale. While the large-scale collapses leading to massive sediment yield occur at intervals of about 100 years, small-scale sediment yield due to rainfall or frost heaving constantly occurs at bare slopes, along with that from minor collapse or human activities. The sediment yield of the latter case is very small for each slope, but the total sediment yield within a drainage basin plays an important role. Therefore, in the present research, field survey and observation were carried out for clarifying the real situation of sediment yield on a bare slope. In this paper, the real situation of sediment yield obtained from the observational study conducted over several years for several experimental slopes under different conditions are discussed.

Sediment yield can be roughly divided into 1) erosion by over-land flow, 2) separation and fall, 3) collapse, and 4) debris flow.

The subject of this research will cover parts of 1) and 2), the test sites being bare slopes with surface gradients greater than 10 and slope lengths of about 10 m.

METHOD OF MEASURING SEDIMENT YIELD AND THE CHARACTERISTICS OF SLOPE

Scope of Research Subject

The form and the factors of sediment yield are diversified and complicated and depend on the characteristics of slope. The drainage basin selected to be tested was the Takahara River basin (Fig.1) of the Jinzu River System, where various bare slopes are distributed and the forms of sediment yield are greatly varied. Therefore, comparative studies of slopes with different conditions could be undertaken. However, it is necessary to clarify the items that were compared. In this paper, the characteristics of sediment yield is discussed by clarifying 1) sediment yield per unit area, 2) scale of sediment yield and its occurrence frequency, and 3) qualitative configuration of sediment yield.

1) Sediment yield per unit area:

This value is convenient for comparing the degree of sediment yield and is normally estimated per unit drainage area km^2 by using dam sedimentation data. These data can be used as annual mean value over a relatively long period of time and as an index for sediment yield. However, various forms of sediment yield are included in a basin of large scale, so that comparison of local characteristics of sediment yield is difficult to perform. Therefore, in the present research, it was decided to compare the sediment yield in m^2 unit on small-scale slopes.

2) Scale and occurrence frequency of sediment yield:

The scale of sediment yield greatly fluctuates, and the phenomenon having a larger fluctuation in sediment yield will have a lower occurrence frequency. The length of test slopes are 5 m to 20 m which may be regarded to be of relatively small scale. Thus, the sediment yield from the slopes governed by rainfall and frost heaving and thawing are small per single event, but the occurrence frequency tends to become relatively large. Therefore, the interval of measuring period was set from one week to one year.

3) Qualitative composition of the sediment yielded :

Particle size distribution of sediment yielded plays an important role as an factor governing the runoff process of sediment. Furthermore, the particle size distribution is governed by the forms of sediment yield, so that it becomes possible to estimate the forms of sediment yield from the measurement of particle size distribution.

Forms and Measuring Method of Sediment Yield

The forms of sediment yield are roughly divided into three types as explained below for convenience depending on the gradient of the slope.

a) Slopes less than the angle of repose:

Erosion depth is determined from the change in the length of exposure of stakes (steel rods). The slope being considered comprises unsolidified deposit of volcanic ejecta, and the stakes can be easily inserted into the ground. The exposed length of the stakes was measured in spring (June) and autumn (October).

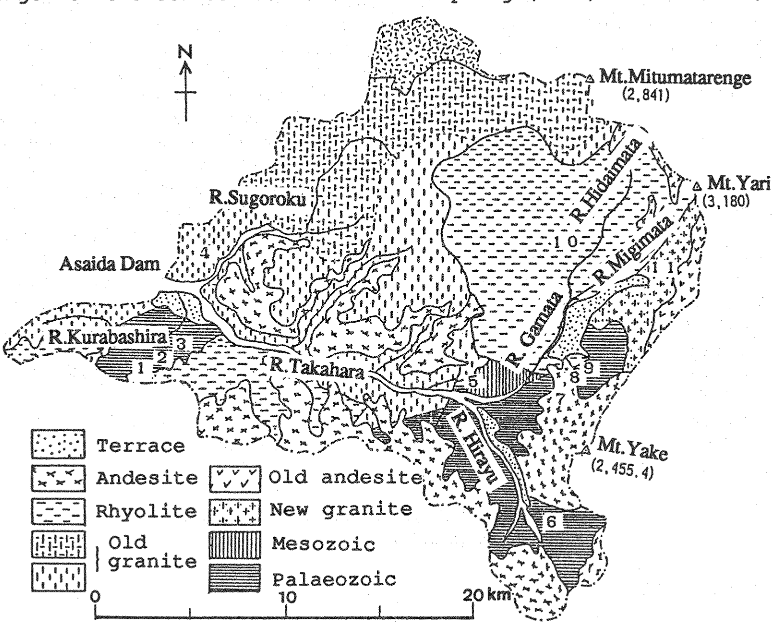

Fig.1 Geology of test basin and location of test sites (The number in the figure)

Stakes were driven at intervals of one meter along the slope length. The surface layer portion of about 2 cm deep of the slope was not dense in spring because of the effect of frost columns, but this portion was not evident in autumn thereby indicating a seasonal fluctuation in the surface layer portion. The particle size distribution of the deposit on the slopes contains even boulders but consists mostly of fine particles.

Table 1 Characteristics of each test site (No. is shown in Fig.1) based on sediment sampling boxes

No.	Geology	Compressive strength kg/cm^2	Slope gradient	Sediment yield (kg/m^2) '85 14weeks	'86 34weeks	'87 34weeks	'88 35weeks	'89 35weeks
1	Rhyolite	5.0	52	3.80	8.67	12.48	10.78	2.86
2	Rhyolite	10.5	54	2.25	8.43	16.69	8.99	3.86
3	Rhyolite	3.3	50	4.25	9.54	11.73	13.01	5.83
4	Granite	1.2	43	15.60	41.03	35.56	-	-
5	Palaeozoic	4.3	50	1.15	4.96	7.04	5.28	-
6	Palaeozoic	3.8	60	10.50	20.17	32.61	19.41	-
7	Pyroclastic	0.9	55	8.10	13.51	16.49	22.27	48.65
8	Rhyolite	0.6	42	2.20	6.68	13.43	9.77	6.05
9	Rhyolite	0.5	35	2.65	4.16	6.90	6.47	3.96
10	Rhyolite	2.0	50	2.05	6.38	-	5.11	-
11	Rhyolite	2.8	48	2.65	11.02	-	10.07	-

b) Slopes steeper than the angle of repose:

Most of the slopes of this kind have only thin deposit layers so that their surfaces comprise bedrock and weathered substances, making it difficult to drive stakes into the slopes. Therefore, the measurement of erosion is not possible by using stakes. As an alternate method, sediment sampling boxes were set at the lower portions of the slopes. The weight and particle size distribution of the collected sediment were measured every week. Sediment was collected and measured at 11 points. Table 1 shows the gradient of slope, geology and the compressive strength of the surface layer of the slope.

c) Slope close to the vertical:

It is difficult to directly measure the amount of erosion at the wall surface of gully or a cliff with a steep gradient. Therefore the sediment yield is indirectly determined from the amount of deposited sediment at the foot of such a slope. On the other hand, at the slope of a torrent bank where the silted deposit is frequently eroded, direct measurement is necessary by using the light wave range finder. This method had required a reflector on the slope to be measured, but recently a new type has been developed, which requires no reflector if the measuring distance is less than 300 m, so that, measurement can be now performed more safely and easily. The slope surveyed was a wall surface of a gully formed by erosion of the deposit surface of volcanic ejecta. Its height ranged from 5 m to 30 m. The wall surface was composed of andesitic volcanic ashes and sand gravel,and also contained cobble stones with diameters of up to 1 meter; obviously particle size distribution varied widely .

The degree of hardening of these deposits is low, they have no cohesion, and their erosion resistance against water current is small.

CHARACTERISTICS OF SEDIMENT YIELD

Slope milder than Angle of Repose

Where the gradient of slope is milder than the angle of repose, the movement of sediment on the slope is caused by the surface flow, rain drops, frost columns and wind. There should be no water paths on the slope where observation and survey are being conducted. Since the observation of erosion depth was performed at reach of 1 m below from the top of slope, the occurrence of surface flow during rainfall is not considered at this point. Particle size distribution of the sediment forming this slope ranged widely from volcanic ash to cobbles 30 to 50 cm in diameter, but most were fine -grained components less than 1 cm.

The results of measurements on this slope are shown in Fig.2. In this Figure, the ordinate is erosion depth (cm/year) of slope while the abscissa is the gradient of slope in sinθ. This Figure shows the data since 1982, and the tendency for erosion depth E to increase in proportion to the gradient of slope can be recognized. This can be expressed by the following general form:

$$E = a \sin^3 \theta \quad (\text{cm / year}) \tag{1}$$

where, the value of "a" is assumed to be determined by a regional factor or external force ; and thus the erosion depth can be estimated if the value of "a" is known. As stated above, the erosion depth is determined by the gradient of slope at the place where the occurrence of surface flow is not considered. This means that if frost heaving and thawing occurs in winter when there is no snow on the slope, then small stones about 1 cm in diameter will be lifted by frost columns and then moved down the slope by the melting and breaking of the frost columns. The moving distance of sediment by such phenomenon at any time can be expressed by tan θ h if the frost columns completely melt, or expressed by h if the frost columns collapse without breaking, where h is the height of frost columns. Therefore, erosion by the above will be determined by the cycles of frost heaving and thawing.

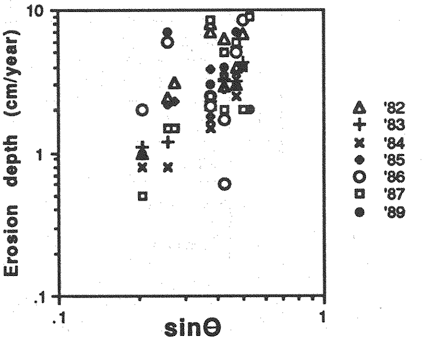

Fig.2 Relation between the gradient of slope and amount of erosion

Slope Steeper than the Angle of Repose

The present survey has been carried out continuously since 1985. A part of the results is shown in Table 1. The sediment yield is shown as gm/m^2/wk. First, the relation between sediment yield and the gradient of slope is shown in Fig.3. As apparent from the Figure, the sediment yield generally increases with the slope gradient. However, some plots deviate from this trend, probably because of differences in cohesion of materials on the slope, as well as in the occurrence of frost heaving and thawing. Next, the relation between the sediment yield and compressive strength of soil by simplified tests are indicated in Fig.4. The trend of increase in sediment yield in response to the increase in compressive strength as well as its upper limit value are recognized in Fig.4.

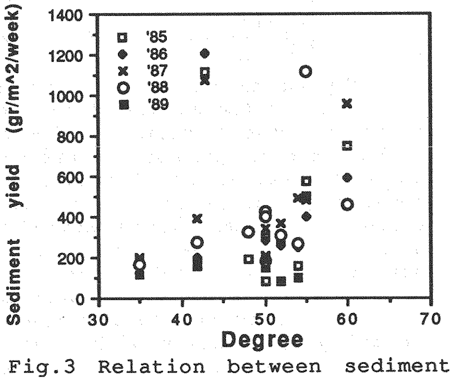

Fig.3 Relation between sediment yield and the gradient of slope

Now the relation between sediment yield and external forces will be reviewed. In this region, rainfall and frost heaving and thawing play important roles as the cause of sediment yield. Firstly, with respect to the frost heaving and thawing, sediment yield is large in March and April when air temperature change a overs around 0 °C , but the effect of rainfall is not apparent in this season.

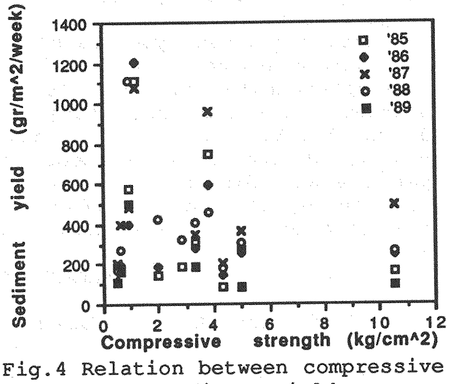

Fig.4 Relation between compressive strength and sediment yield

Large sediment yield in this season is believed to be caused by the separation and falling of sediment from the slope due to frost-induced heaving and thawing. On the other hand, particle size is larger in the frost heaving and thawing season, while relatively small in the rainy season. The reason for this tendency is probably because large sediment particles when dislodged can hardly be stopped in the process of downhill motion; on the other hand, sediment of particle size less than several mm is easily stopped, until moved again by rain drops or flows on the slope. Therefore, the variation of sediment yield and rainfall with time shown in Fig.5 reveals some hysteretic characteristics. In this Figure, the overall trend indicates that the sediment yield gradually decreases from May with some increases in response to rainfall. This trend shows annual periodicity. The characteristics stated above are believed to be caused by the decrease in that sediment which movement is easily induced by frost heaving and thawing. As stated above, the correlation between the total rainfall and the sediment yield is general positive except during the frost heaving and thawing period. There are, however, anomalies because of variable conditions of the slope. Although the action of rain water on steep slopes during rainfall is not apparent, the formation of water paths or rills on these slopes is not recognized. The relation between particle size distribution of sediment yield and rainfall will be discussed next. Fig.6 shows the particle size distribution of the portion with much sediment yield in Fig.5. The yield obtained on April 5 and May 2 had much sediment although the rainfall was light, and their particle size was also large. This is one of the characteristics of sediment yield due to frost heaving and thawing. On the other hand, the yield obtained on September 6 and 20 was low with small particle size although the rainfall was heavy. This seems to indicate a thin over land flow during rainfall which can wash out fine-grained components on a steep slope. Even if such a thin flow does not occur because of light rainfall, the bonding forces between particles are reduced due to the penetration of rain water, and particles may move down the slope. At that time, the particles larger than the irregularities on slope surface tend to move down continuously without being arrested.

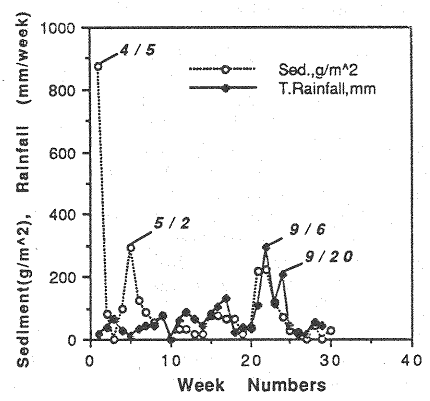

Fig.5 Hysteresis characteristics of sediment yield (Test site No.1)

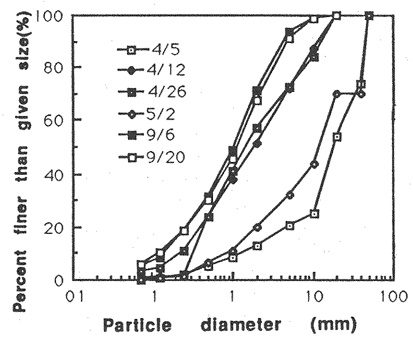

Fig.6 Seasonal change in particle size distribution of sediment yield

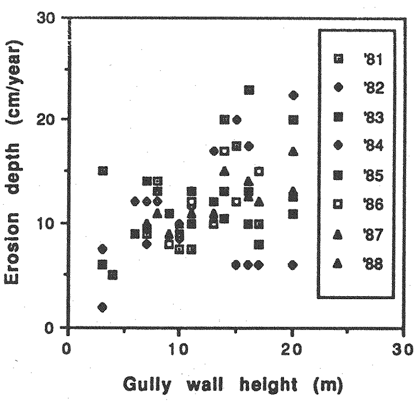

Fig.7 Relation between gully erosion depth and wall height

Erosion of Gully Wall close to the Vertical

Many gullys are well developed in the areas where volcanic accumulation layers are distributed, and they play an important role as a source of sediment in such drainage basins. In the surveyed area, there are gullys formed by erosion of the accumulation layer of the Yakedake Volcano, and, in fact, this sediment from the gully wall is the main source of the material of debris flows,and greatly governs the occurrence of debris flow. The gully wall surface is almost vertical and the foot of gully wall have a deposit surface with the angle of repose. Where the deposit of sediment is not eroded, the height of gully wall decreases as the height of the deposit surface increases, until finally, a stable deposit equal to the angle of repose remains. However, the deposit is frequently washed out by water or debris flow, and only the vertical gully wall surface remains. The observed relation between gully wall height and erosion depth of gully wall surface from 1981 to 1988 is indicated in Fig.7. This figure shows erosion depth (cm/year) on the ordinate and gully wall height (m) on the abscissa. As a general tendency, a proportional relation can be recognized between them though the relation slightly varies by year. On this slope, the erosion of fine particles due to frost heaving and thawing in winter and due to wind is significant, while erosion by rainfall is minor.

The reason why the erosion depth is proportional to the height of gully wall is considered as follows. The fine particles on gully wall surface are repeatedly dislodged by frost heaving and thawing and wind, resulting in large cobbles being exposed. When the exposure of the cobble becomes large, it finally falls, with resulting collision with the wall surface in the course of falling, inducing new erosion, so that the chances of collisions increase the higher the wall is. This characteristic phenomenon occurs because the particle size distribution of a gully wall has a wide range.

Prediction and Prevention of Erosion

So many elements are involved in the prediction of sediment yield in drainage basin, and thus the prediction of sediment yield specially by a new collapse is difficult to make. Here, the real situation of bare slope formed by collapses, etc. was clarified. As a result, the bare slope plays an important role as a source of sediment yield, and the approximate value of sediment yield can be estimated from the area, gradient and material of the slope. If a more detailed prediction is needed, then the results of observation over 2 to 3 years on the test slope in the object drainage basin will provide reliable information.

On the other hand, various methods have already been proposed for the erosion prevention for bare slopes milder than the angle of repose, and therefore the method should be selected depending on the characteristics of slope and the purpose of the erosion prevention. In the case of vertical and unsolidified deposit such as gully wall, the measures for erosion prevention are not easy. At present, one method has been preliminarily tested, in which the occurrence of frost heaving and thawing on the gully wall surface is restricted. Another method was also applied by dividing the gully wall and reducing gully height, and this method was evaluated to be effective.

CONCLUSION

In the prediction of sediment yield, there are so many factors to be considered that prediction is difficult. The present research has been carried out considering that sediment yield depends on the gradient of slopes, and the real situation of sediment yield was clarified through observation and survey of actual slopes in the field. The conclusions reached with respect to the gradient of slope classification are as follows:

(1) Gradient of slope less than the angle of repose: The erosion depth E (cm/year) can be expressed by using the gradient of slope θ, $E = a \sin^3 \theta$. The value of "a" is assumed to be governed by local geological and meteorological conditions.

(2) Gradient of slope steeper than the angle of repose: The factors governing the extent of erosion are frost heaving and thawing, rainfall penetration and the gradient of slope.

(3) Gradient of slope close to the vertical: The erosion depth is proportional to the height of slope at the gully wall formed by incohesive sediment having a wide range of particle size distribution.

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