An Experimental Study of the Rill Formation Process on a Bare Slope

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Abstract

A large number of small channels, or rills is formed on a bare slope about the same time as surface flow is generated, and the sediment yield rapidly increases as the pattern of rill grows.

In this paper we describe an experimental study of the process of growing rill which are formed on composite granite soil, or "MASA-DO", by supplying artificial rainfall. We photographed the changes in plane and cross sectional patterns of rills over time and also measured sediment yield.

The complexity of rill patterns was expressed numerically using the concept of fractal dimension. As a result of this analysis, the change in fractal dimension of rill patterns over time was closely related to the change in sediment yield and water discharge from the slope.

1 . Introduction

Rill generally develops on a bare slopes of reclaimed land, roadbanks, housing lots, construction sites and agricultural land. In these places, accelerated soil erosion often occurs and causes major damage to irrigation systems, agricultural products, etc. As the sediment run-off from rill erosion is considerably larger than that caused by surface erosion or sheet erosion, it is important to reveal the mechanism of rill generation and development and to identify an effective method of control. The problem of soil erosion, in particular splash erosion and rainflow erosion, has been studied by many researchers, however, the study of rill erosion is a field where research has lagged: to date solutions have not been identified because of the complexity of the problem and also the rapid change in rill patterns over time.

In this study, based on a series of experiments, we describe the characteristics of plane and sectional patterns of rill, sediment and water discharge over time. Secondly we apply an up-to-date geometrical concept to express numerically the degree of complication of the plane patterns which was formed in the experiment by applying the artificial rainfall to the slope. This concept is 'fractal dimension' which has been used recently to express numerically the complexity of patterns in the natural world. We compared the time variations of these values with the experimental data of sediment and water discharge and discussed.

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Experimental Apparatus and Procedure

1. *Experimental Apparatus*

Fig.1 shows a sketch of an experimental rainfall runoff facility in the field consisting of a container 2.4 meters in width, 5.4 meters in length, 1 meters in depth. The experimental slope which size is 0.95 meters in depth at upper side and 0.05 meters at lower side was formed in this container. Decomposed granite soil(”Masa-do”) was used as a sample soil having a mean particle diameter of 0.1 cm. A wooden container (3m × 0.9m) was placed along the lower side of slope to catch the soil that washed out by the rainfall, and a V-notched weir was located on the underside of this container to measure the water discharge. The artificial rainfall was generated by six sprinkling nozzle which were all suspended at 1.8 m in height from the ground. This height is not sufficient to gain terminal velocity, so the force of waterdrop impact can be ignored comparing with that of natural rainfall. The plane patterns of rill were photographed with a 35 mm still camera which was placed 8.5 m in height above the slope. The sectional patterns of rill were recorded using the simple device as shown in Fig.2. This device was designed in order to record directly the roughness of surface within a short and limited time. The wooden squared timber in which a number,88, of small holes are

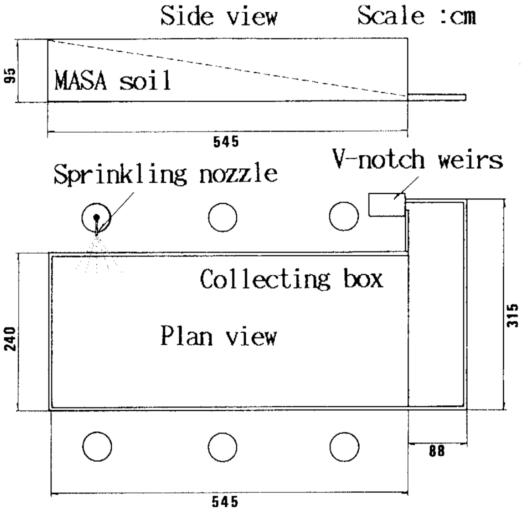

Fig. 1 Sketch of the experimetal slope

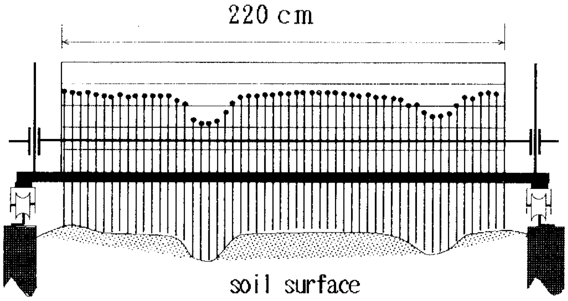

Fig. 2 Sketch of the device for measuring cross sectional patterns of rills

arranged at intervals of 2cm lies horizontally immediately above the surface and can be moved along the surface on rails, keeping a constant distance from the surface. Measurement was carried out by dropping the light bamboo bars that pass through the holes on the surface of slope. The line connecting the opposite end of these bars shows the approximate roughness of the surface of slope.

2. *Experimental Procedure*

The range of rainfall intensity applied to the slope was from about 20 to 100 mm/h. The flow discharge from the slope was recorded every 10 minutes with a V-notch weir, by measuring the elevation of the water surface above the bottom of the notch through a Point Gauge. The sediment discharge deposited in the container was also collected every 10 minutes. After leaving for a few hours and measuring the net mass of the collecting sample, part of the sample was dried in a drying oven in order to measure the moisture content. The total dried weight of the sample that washed out in a ten minutes period could be obtained by this method.

The plane patterns of rill were recorded photographically at specified time intervals of 10 minutes. After developing and producing enlargements from this film, we reproduced the plane patterns of rill by tracing the edge of rill drainage on the tracing paper, and input the plane co-ordinates along the rill boundary (x_i,y_i) to a personal computer using digitizer. The variation of sectional patterns over time was also measured by taking photographs of measuring bars. The fractal dimension of sectional patterns could not be obtained using this data because the interval of measuring bars was too long to obtain the detailed information of surface roughness.

Experimental Results

1. *Types of Erosion Observed on the Slope*

We will first describe, in outline, the generation and growing of the rills. In the early stages within ten minutes after applying the artificial rain until the seepage line begin to appear on the lower part of slope, the splash of soil particles by the raindrop impact was predominant on the slope. The surface flow began to generate at the lower part of slope as the seepage line gradually moved up the slope. This process may be considered as follows. As soil moisture content increases and infiltration capacity declined, the excess rainfall changes the surface flow because water did not soak directly into the soil, and runoff occurred. In this stage, which is commonly described as the sheet erosion or surface erosion, mainly sand and silty clay was transported by surface flow, so the composition of particles on the surface of slope, particularly on the lower part of slope, became more and more coarse.

2. *Changes in the Plane Patterns over Time*

As the sheet erosion continued, many small puddles appeared on the lower part of slope. Some of them increased in size, and grew into small channels, or the first stage of rill, by concentrating the surrounding surface flow into them. These channels generally spread upward up the slope through spreading their plane size, branching and meandering, however, the behavior of that growth was very unstable because a channel sometimes joined another one, or a channel which had been just formed was buried by the sediment yield, and the time at which rill generation began, depends on the rainfall intensity. In this stage, the change in the rill patterns over time is the most obvious of any stage in the life of rill. As an example, a series of the growth of plane pattern which was traced on printing paper is shown in Fig.3.

3. *Changes in the Sectional Patterns over Time*

Secondly, we will discuss the changes in cross sectional patterns of rill over time. Fig.4 shows an example which was obtained at a distance of 160 cm from the lower side of slope. The pattern of surface roughness can be considered to be a complex periodic wave in two dimensional space which is expressed mathematically by the

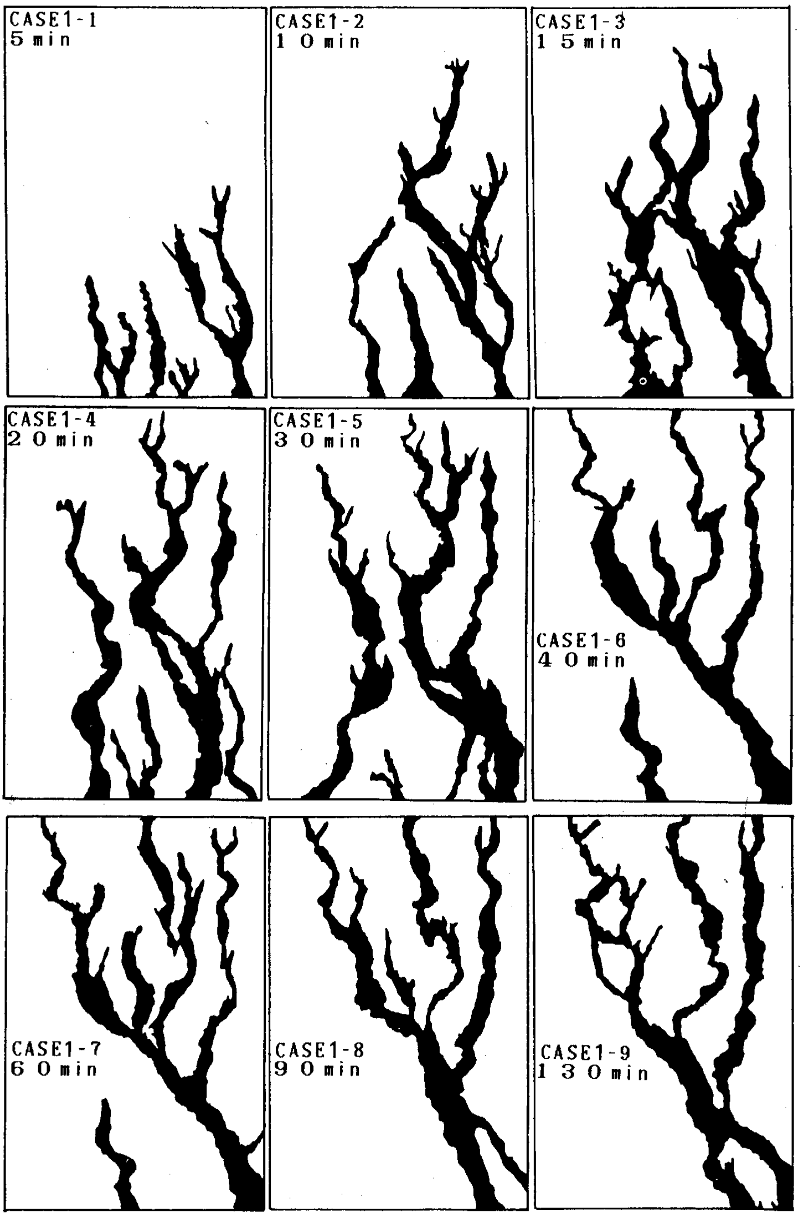

Fig. 3 A series of the growth of plane patterns in CASE-1

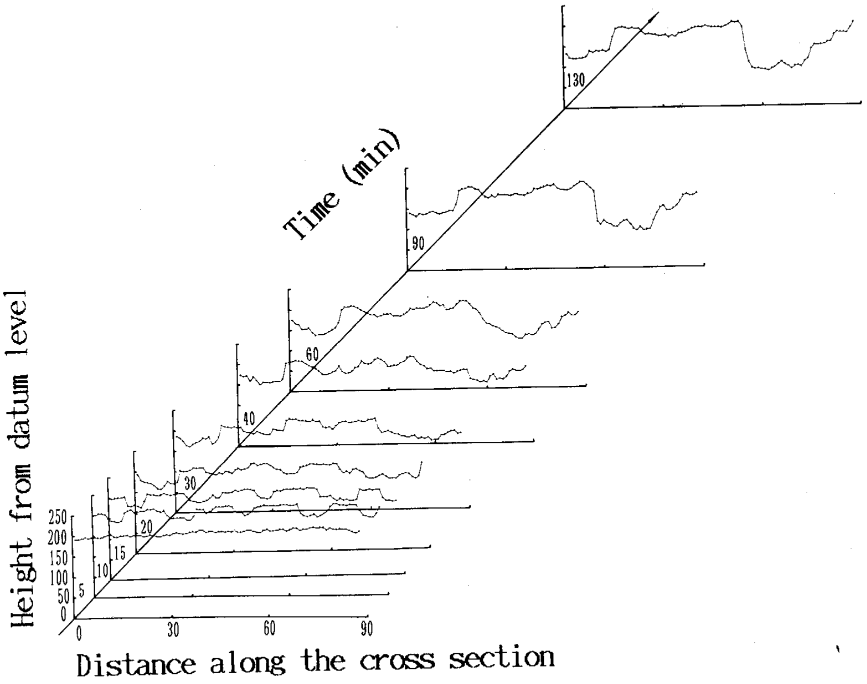

Fig. 4 Changes in the cross-sectional patterns over time

overlapping of many sinusoidal waves with different periodic and amplitudes. Observing the cross-sectional patterns from such a viewpoint, the amplitude of roughness of the cross section increased gradually, on the other hand the frequency of wave decrease with time goes on. As is obvious from the series of figures, the sectional patterns changed significantly in the same manner as the plane patterns during the first few ten minutes of application of artificial rainfall. After about 30-40 minutes had elapsed, some of channels were restricted to develop in the vertical direction because the position of watercourse fixed on the slope,

4. *Changes in the Water and the Sediment Discharge over Time*

Fig.5 and Fig.6 show the water discharge and the sediment discharge from the slope as a function of time respectively. Both increased rapidly with the growth of rill, but after several tens of minutes, the water discharge changed at a constant rate; while, the latter became the highest value within a few minutes and decreased gradually over time.

Fig.7 shows an example of the changes in total area of rill as a function of time. As is evident from Fig.5 and Fig.6, this shows a similar tendency to the water and the sediment discharge, that is, the change in the area of rill over time becomes gentle and constant after the first ten minutes. This time matches well with the time which shows the peak of the sediment yield. This result indicates that rill grows faster in plane than in vertical during the first ten minutes of the generation of the rill, and the plane patterns of rill does not change after the first ten minutes, or reaches 'equilibrium' stage of development.

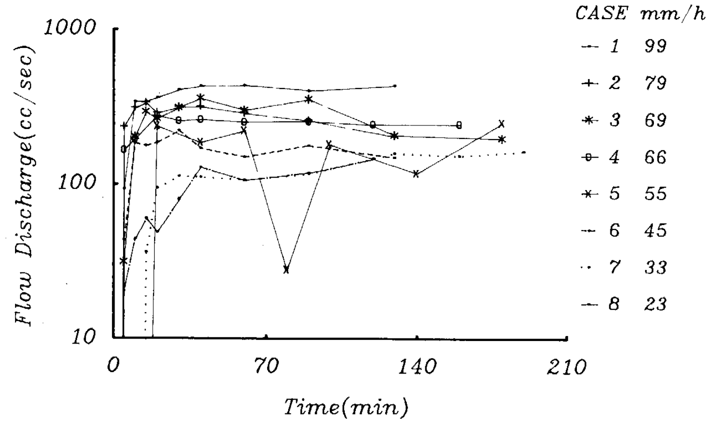

Fig. 5 Changes in the water discharge out of slope over time

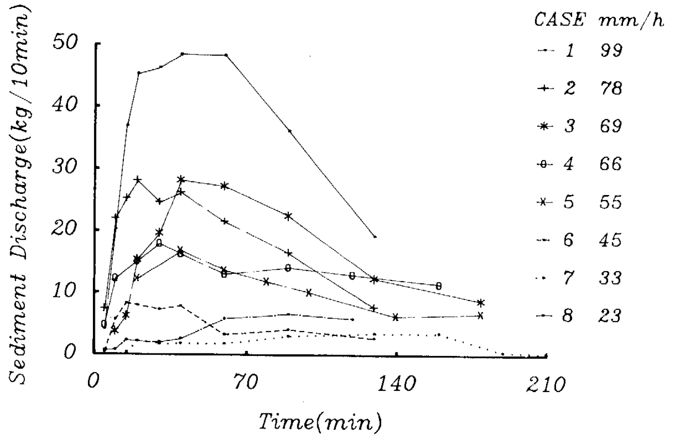

Fig. 6 Changes in the sediment discharge out of slope over time

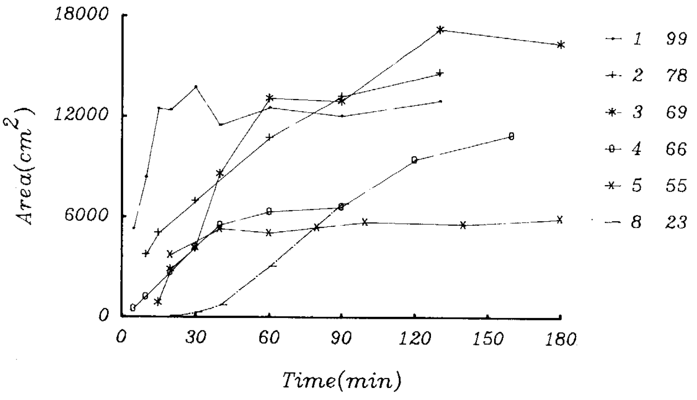

Fig. 7 Changes in the area of rill over time

Quantification of the Plane Patterns of Rill

As is well known, the complex patterns in the natural world can be characterized by a fractal dimension which is a non-integer value. In this paragraph, we do not explain this general concept in detail. The method of evaluating the fractal dimensions of rill patterns is discussed in detail in our report(1). Here we would like to only briefly outline two methods of fractal dimension, the square method and the length-area method.

1. *Fractal Dimension by the Square Method*

In Fig.8 the procedure of obtaining the fractal dimension by the square method is outlined. It is quite easy to reproduce the plane patterns of rill on the monitor because the coordinates of the circumference of the rill were input to a personal computer. The reproduced picture of the rill on the monitor can be divided into square pieces by imposing a lattice taking the length of one side r which varies from one dot, minimum, to 50 dots maximum. The number of the squares in the picture are automatically input to a personal computer, even if only tiny element bounded by circumference of rill is contained in a lattice. Fig.9 shows an example of a method of computing the fractal dimension at the time of 130 minutes in case of CASE-1. As is obvious from this figure, after plotting r_i and $N(r_i)(i=1,2,....n)$ on double logarithmic graph paper and drawing a approximate straight line through the values, the fractal dimension can be easily described by the slope of this line.

2. *Fractal Dimension by the Length-Area Method*

In classical geometry, the ratio of the circumferential length of a planar shape to the

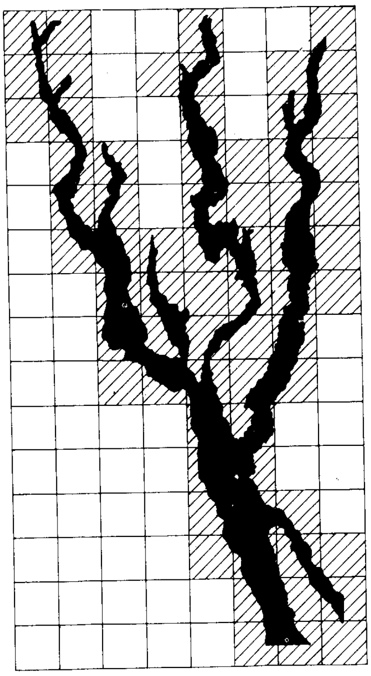

Fig. 8 Procedure for obtaining the fractal dimension by square method

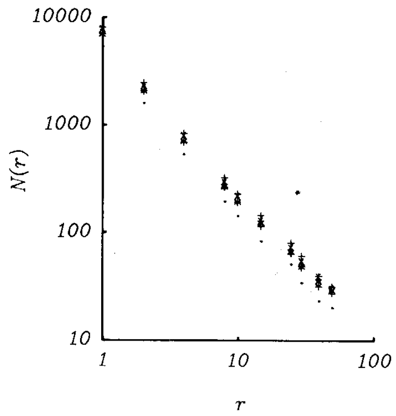

Fig. 9 Method of computing the fractal dimension

area bounded by the circumference is generally equal to a constant value determined by their common shape. In the simple example of a circle, it is obvious that the relation (length)$=2\pi^{1/2}$ (area)$^{1/2}$ can be established. In fractal geometry, the generalized relationship asserts that the ratio (length)$^{1/D}$/(area)$^{1/2}$ takes the same value for all mutually similar shapes, where D is a fractal dimension. For further details the reader should refer to the literature(2). In this method of computing the fractal dimension, the length and area of rill is obtained using the above mentioned square method that is, by adopting the values which were obtained by the computer graphics taking the length of lattice as dots on the monitor. The difference of two methods is that the square method is useful in determining the variation of fractal dimension as a function of time, while the length-area method is useful only when the fractal dimension is assumed to be constant with respect to time. The relationship between the length of circumference and the area of rills was shown in Fig.10. In this case, the coefficient of correlation of data is $R=0.877$, and the average fractal dimension is $d=1.20$.

3. *Changes in the Fractal Dimension with Time*

Fig.11 shows the changes in fractal dimension as a function of time when obtained by the square method. The fractal dimension generally changes over time in the initial stages, and increases slightly, but all values are almost constant after about 20-30 minutes. This indicates that the planar shapes of rill do not change after about 20-30 minutes has passed. The relationship between the area, the length of circumference of rill and the fractal dimension is shown in Fig.12, and in Fig.13, respectively. In both figures, the fractal dimensions have a tendency to increase as the area, and the length of circumference of rill increase. We conclude that the number of bifurcations is inclined to increase as the rill grows. The changes in the fractal dimensions of rill over time is similar to that of the sediment run-off, that is, both increased rapidly during a few ten minutes after generating the surface flow on the slope. The curve of sediment run-off began to decrease after peaking at its highest value at 30-40 minutes, and this maximum value is inclined to increase as the intensity of artificial rain increases.

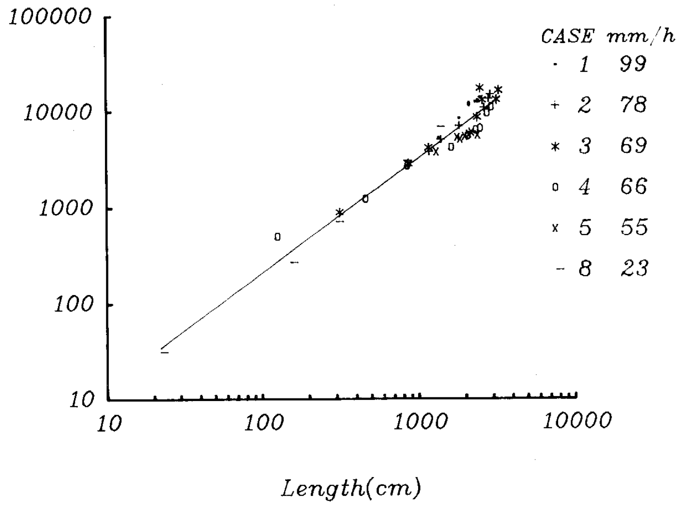

Fig.10 Relationship between the area and the length of circumference of rills

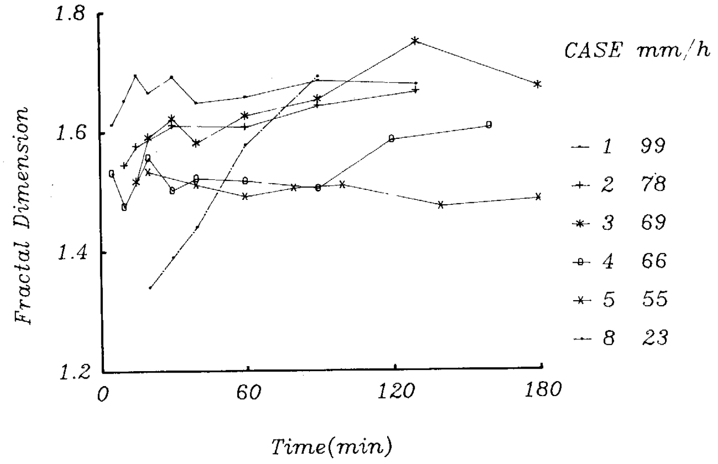

Fig.11 Changes in the fractal dimension as a function of time

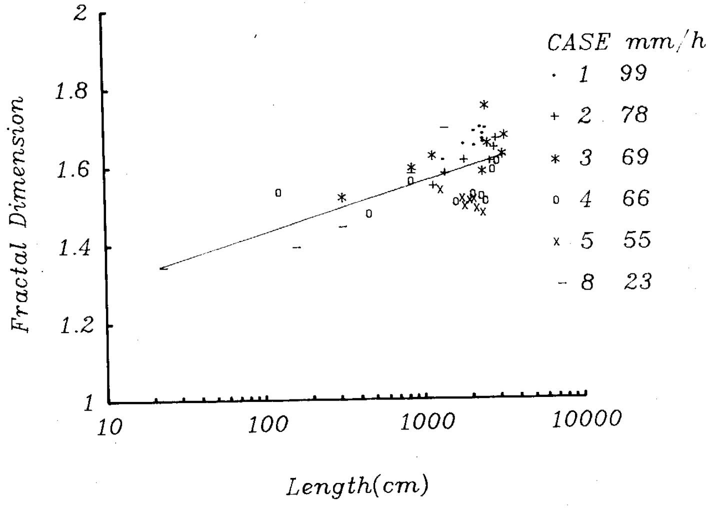

Fig.12 Relationship between the area and fractal dimension

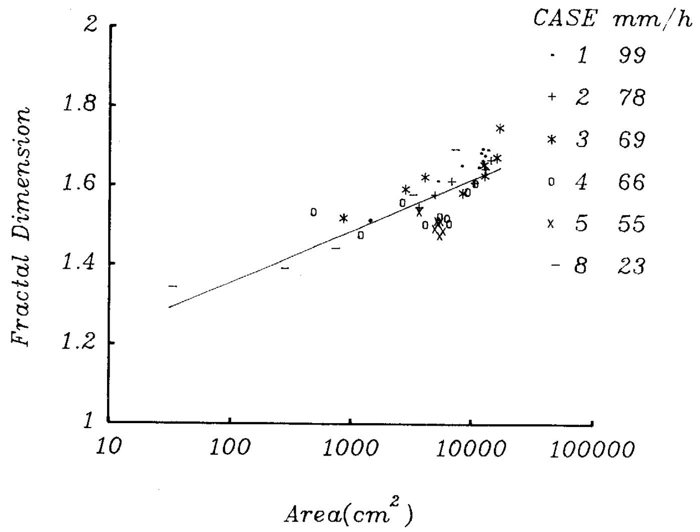

Fig.13 Relationship between the length of circumference and fractal dimension

Conclusion

This study may be summarized as follows. An experimental study of rill erosion on bare slope has shown that the plane and cross sectional patterns of rill may change rapidly during the first few ten minutes and thereafter they may change slowly. The sediment discharge was characterized by a rapid increase during the first few ten minutes of application of the artificial rain, and a decrease after taking a maximum value at about 30-40 minutes. The maximum value was inclined to increase as the intensity of artificial rain increased, while the time at which the sediment reached its maximum value is not so different in any of the experiments. Though the curve of water discharge with time was generally similar to that of sediment yield, it did not change after 30-40 minutes had passed.

Observation has shown that the plane and cross sectional patterns were more complex and the watercourse was unstable during the first few minutes of the generation of rill on the slope after the first ten minutes had passed, the position of the watercourse was settled and erosion proceeded in the vertical direction.

Analysis of the plane patterns of rill by fractal dimension has shown that the curve of fractal dimension with time increased while fluctuating during the first few ten minutes, and thereafter it changed little with time. Such behavior was very similar to that of water and sediment discharge out of slope.

In the above, the general features of the changes in the plane and cross sectional patterns of rill, the water discharge and the sediment discharge has been outlined. There are many points which must be solved, for example we must take up the mechanism of generation of rill in a future study.

Reference

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