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Influence of Slope Gradient on Interrill Erosion of Shirasu Soil

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Abstract

A simulated rainfall study was conducted to evaluate the effects of slope gradient on interrill erosion of Shirasu, a volcanic ash soil. A simulated 30-min., 62 mm/h rainfall was applied to the slopes of 6°, 9°, 12°, 15° and 20° to measure interrill erosion and runoff. Whether runoff or soil loss rates all showed rapid increase in first ten minutes from the start of experiment except for slope 6° and 9°. Runoff became almost constant for slopes of 12°, 15° and 20°, but soil loss rates showed a different variance according to slope gradient at the latter half of 30 min run. A third -degree polynomial for the relation of gradient with runoff and soil loss rates can be established based on the result of regression analysis of data. But variance in gradient for runoff differed from that for soil loss. For runoff, under the conditions of the experiment, the maximum was 15°, and there was a decrease beyond this slope gradient. Soil loss rates increased with slope gradient within the range of steepness in the experimental conditions. But increment rates differed according to the slope gradient, rapid increase was noted for slopes from 9° to 15°, and soil loss rates flattened beyond 15°.

Key words : Shirasu, Interrill erosion, Slope gradient

1. Introduction

Soil erosion and its causes have been studied extensively. As an important factor affecting the magnitude of soil erosion, slope gradient have been studied deeply. Previous studies conclude that the relation between slope gradient and soil loss is curvilinear. Investigation by Zingg (1940) showed the relationship between slope steepness and soil erosion to be expressed by $y=ax^b$ where b is 1.48, a is 0.065, x is the present of slope gradient and y is the eroded weight of soil loss in pounds. Meyer and Monke (1965) used a variable sloping bed filled with grass beads to derive a modified power equation with a slope factor exponent b, ranging from 2.0 to 2.5. Smith and Wischmeier (1958) developed a polynomial equation to define the relationship between soil loss and gradient that used in Universal Soil Loss Equation (USLE) (Wischmeier and Simith 1978). Singer and Blackard (1982) studied the interrill erosion of two soils on slopes from 3 to 50%, interaction between slope gradient and soil properties was suggested by the results, a second-degree polynomial of the form $Dw=0.22+9.37\sin Q-8.43\sin^2 Q$ for silty clay loam soil and a third-degree polynomial, $Dw=-0.10+7.66\sin Q+59.49\sin^2 Q-101.65\sin^3 Q$ for loam soil used in their study, where Dw is interrill soil loss, Q is slope angle.

Yair and Klein (1973) who, in an investigation on natural runoff from three ebris-covered hillslopes with slope gradient of 15°, 19° and 25°, found an inverse relation between sediment yield and slope gradient. Additional research dealing with slope gradient factor in the

Universal Soil Loss Equation has indicated that the effect of slope gradient on interrill erosion depend on the soil (Quansah 1981, Singer and Blackard 1982, and Meyer and Harmon 1989).

Soil erosion is divided into interrill, rill, and gully types. Interrill erosion soil particle detachment by raindrop impact and particle transport by splash and shallow overland flow. Models such as the Water Erosion Prediction Project (WEPP) have distinguished interrill and rill processes in the study of soil detachment and transport.

This study was conducted to determine the effect of slope gradient on interrill erosion of Shirasu soil in southern Kyushu of Japan and to show how interrill erosion is related to slope gradient.

2. Method and Materials

The soil used in this study was taken from Miyazaki, a prefecture in southern Japan. Shirasu is volcanic ash soil which is susceptible to erosion owing to its low in organic matter content, loam contents, aggregate percent and small density. Its physical properties and texture are shown in Table 1. Soil particle size was determined according to Japanese unified soil classification system.

The drop-former type rainfall simulator selected in the study was designed by Hosoyamada in 1986, It consists of a raindrop-former, two pressure water reservoirs and a timer. The features of rainfall simulator in this study have been reported by Hosoyamada (1986). The raindrop-former is consisted of 21 pipes with 13 nozzles, and raindrops are formed at 260 cm from the surface of test plot. Rainfall intensity was controlled by adjusting time for the valve left open or shut. In this study, 0.1 second for open and 0.3 second for close were selected to control raindrop-forming, and to give a 62 mm/h rainfall (a little weaker than that indicated in Tables on the same combination of open and close time, because of the senility of raindrop-former). Raindrop size distribution and terminal velocity as two important parameters in rainfall simulation are listed in Tables 2 and 3. Table 3 shows raindrop velocity to be essentially same with the terminal velocity of natural rainfall.

The soil was packed into 150 cm long, 40 cm wide and 20 cm deep wooden-boxes with holes on the bottom, and adjusted to reach a bulk density of 0.83 g cm^{-3} (Fig. 1). Splashed particles were collected using three tin plate of 50 cm height mounted vertically on the plot box sides (see photo. 1). The lower splash collector was rested on the sides of the front runoff spout,

Table 1 Physical properties of soil used in the experiment

Soil density	Aggregate percent	Infiltration parameter	Soil grade		
			Sand	Silt	Clay
2.529 (g/cm^3)	4.4%	1.42×10^{-2} cm/sec.	76.7%	14.8%	8.5%

Table 2 Raindrop distribution of the rainfall simulator

Pressure (kg/cm^2)	Electromagnetic valve		Rain intensity (mm/hr)	Raindrop size (mm)	
	Open (sec.)	Close (sec.)		Mean	Range
0.20	0.10	0.30	83	1.79	1.2~3.3
	0.15		107	1.88	1.2~4.4
	0.20		142	1.80	1.2~4.4
	0.25		202	1.75	1.2~2.2

Table 3 Raindrop velocity of the rainfall simulator

Pressure (kg/cm^2)	Electromagnetic valve		Rain intensity (mm/hr)	Raindrop velocity (m/s)	
	Open (sec.)	Close (sec.)		Mean	Range
0.20	0.10	0.30	83	8.7	8.0~10.5
	0.15		107	8.0	6.9~ 9.6
	0.20		142	7.8	6.4~10.8
	0.25		202	7.5	6.1~ 9.5

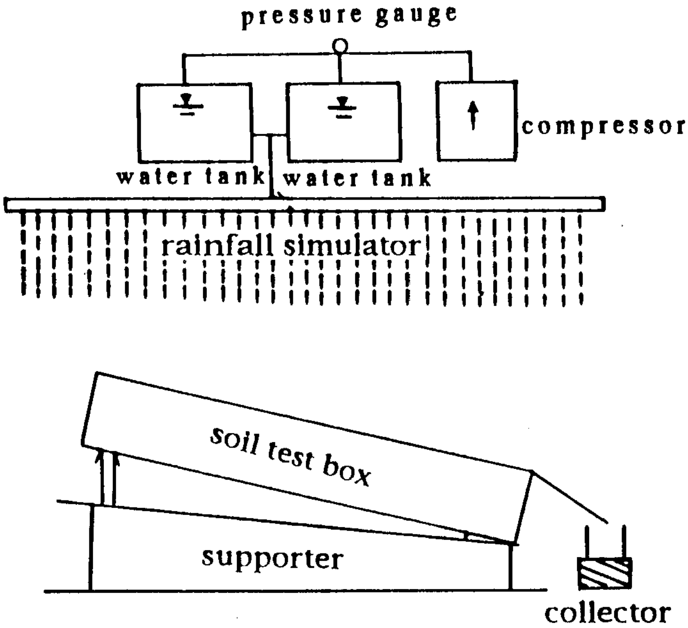

Fig. 1 The illustration of rainfall simulated test.

leaving 5-mm-wide gap between the splash collector and the top of the lower side in order to let runoff and soil pass through. Splash samples were collected at four different sites at a two minutes interval for washed- and splashed-off material throughout each 30 minutes run. All sampled were washed off each splash board into a lower channel and then into four separate containers. Surface flow erosion samples were collected simultaneously. The soil was saturated as fully as possible with a sprinkler before the beginning of tests in order to keep a same surface situation.

3. Results and Discussion

Slope gradient is a factor affecting raindrop detachment, infiltration and energy of runoff. Thus, not only the magnitude of soil loss, models of runoff and soil erosion is also affected by slope gradient. The influence of slope gradient on interrill erosion was thus examined by analysis of variance of the soil loss process, runoff, and soil loss amount.

1) Soil loss process

Fig. 2 shows soil loss process on different slopes. Soil loss rate was small and slight fluctuation with time on the slopes of 6° and 9°, but was considerable for slopes of 12° and 15°.

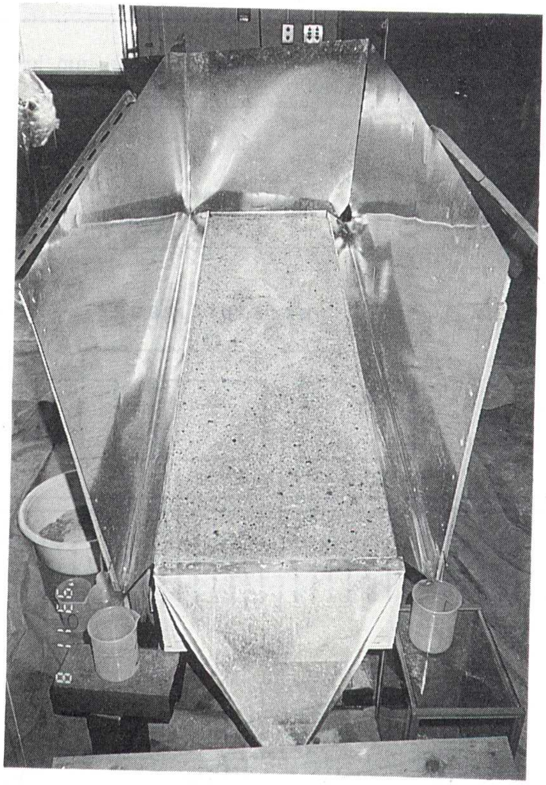

Photo. 1 Soil test box, upslope, downslope, and side splash collectors.

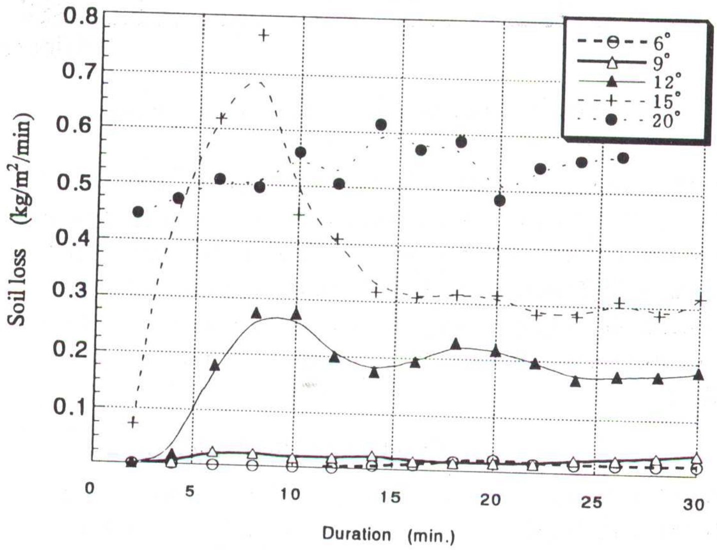

Fig. 2 Variance of soil loss rate with test time.

In such cases, soil loss rate increased quickly during the first ten minutes, and then decreased slightly becoming almost constant. On the slope of 20°, soil loss rate was always much and tend to increase slightly.

Runoff rate increased quickly in the first ten minutes, and then hardly changed for slopes of 12° and 15° (Fig. 3). On the slope of 20°, trend of runoff was greater throughout experiment and similar with soil loss. Runoff rates, on slope of 12° and 15° exceeded that of the 20° slope during the last fifteen minutes. Runoff rates on slopes of 6° and 9° increased throughout the study. These results show that runoff rates is affected strongly by slope steepness.

To determine soil loss and runoff with time simultaneously, sediment concentration was calculated as shown in Fig. 4. Fig. 4 shows that the steeper the slope, the more quickly sediment concentration becomes maximum. Sediment decreased slightly in the last twenty

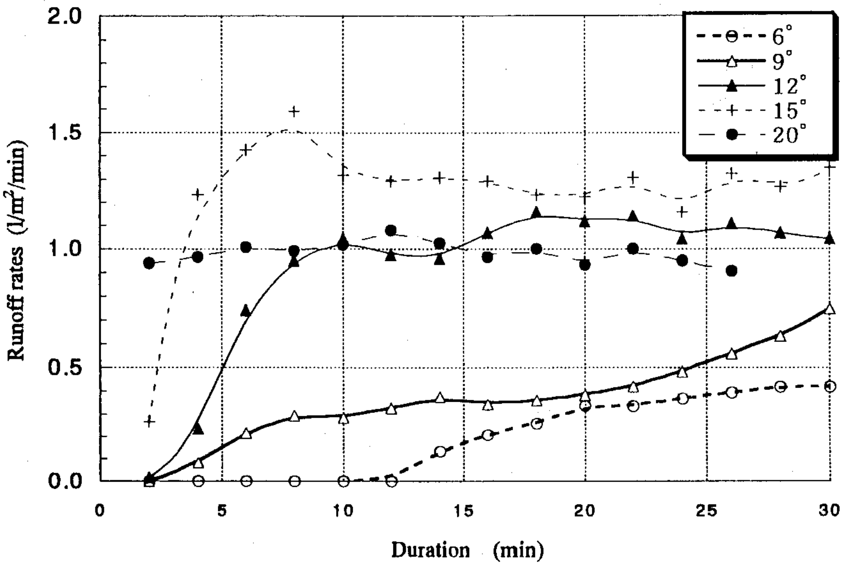

Fig. 3 Variance of runoff rates with experiment duration.

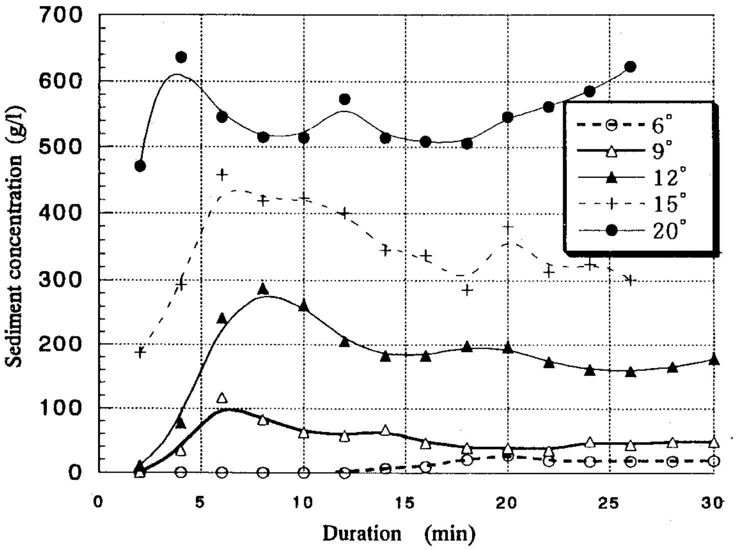

Fig. 4 Variance of sediment concentration with experiment duration.

minutes on all except the slopes of 6° and 20°, where it increased slightly in the last half of the test since runoff erosivity was greater.

2) Runoff

The effects of slope on runoff have been studied in detail. Yair and Klein (1973) found no clear relationship between slope angle and runoff on arid soils. Duley and Hays (1932) report runoff under a 25 mm/h rainfall runoff increased from 69% of rainfall at a 5% slope to 86% of rainfall at a 20% slope on silt loam. Parsons and Abrahams (1992) found a gradual increase of runoff as slope gradient increases to 12° and rapid decrease in runoff beyond 12°. Grosh and Jarrett (1993) noted that for slopes except the 5% slope, runoff increase gradually to nearly a constant rate in 10 min. As reasons for the above, (1) soil used for test was different, and (2) slope ranges and test scale were not same, should be considered.

In this study on the effects of gradient on runoff on a slope of volcanic ash soil, findings are the same as those of Parsons and Abrahams (1992) on the relationship of slope steepness to runoff, as shown in Fig. 5. The runoff rates increased gradually on slopes from 6° to 9°, and then rapidly with slope gradient increase to 15°, followed by decrease with slope gradient increase beyond 15° under the conditions of this study (length of soil-box, constant, but slope length only decease 6% with slope gradient from 0 to 20°. Effects of slope length on runoff not shown here). The gradient at which runoff reached maximum was greater (about 15°) than that found by Parsons and Abrahams (12°).

Results from regression analysis suggested that relationship of runoff rate and slope gradient is best fitted with the following a third-degree polynomial :

$$R_r = a + b\sin Q + c\sin^2 Q + d\sin^3 Q \qquad (1)$$

R_r = runoff rate

Q = slope angle

a, b, c, and d = fitted constants, and given the best fit ($r = 0.9936$)

3) Soil loss

Zingg (1940) and Smith and Wischmeier (1957) conclude that overall soil loss increases with

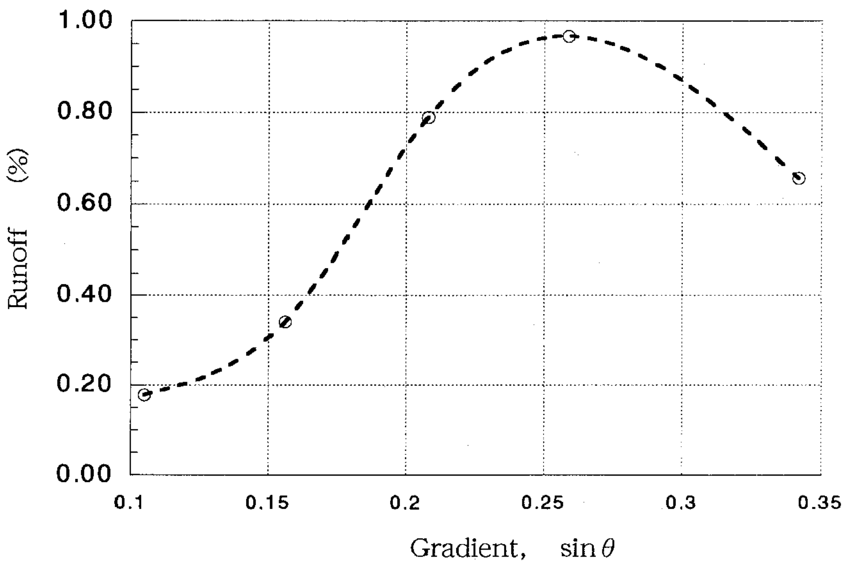

Fig. 5 Runoff rates with slope steepness.

slope gradient. Parsons and Abrahams (1992) found increased sediment yield with gradient for hillslopes gradients of as much as 12°, but for gradients steeper than this, sediment yield decreased with gradient, thus demonstrating a convex-upward relation with a vertex at 12°. Foster *et al.* (1977) and Grosh and Jarrett (1993) suggest linear relationship of interrill erosion to slope steepness. The best known relation is that of slope steepness in the Universal Soil Loss Equation (USLE). However, the relation is based in data for soil-covered hillslopes gradients≤25% (Smith and Wischmeier, 1957).

The present data show that soil loss increase with slope gradient, and fluctuation according to slope gradient was shown in Fig. 6. Soil loss increase slightly on slopes from 6° to 9°. Then there is rapid increase with slope gradient to 15°, beyond which soil loss with slope gradient becomes flat. These results was different with Parsons and Abrahams (1992) who found erosion rates to be maximum on a slope of 12°.

Regression analysis indicated the same equation with runoff-gradient for the relationship of soil loss and gradient, and is best fitted by the following a third-degree polynomial :

$$S = 1.211 - 21.98 \sin Q + 119.6 \sin^2 Q - 178.9 \sin^3 Q \quad (2)$$

where S = soil loss rate

Q = slope angle

r = 0.999

This is supported by the findings of Singer and Blackard (1982) , but the fitted constants differ. The regression curves are not very fitted with measured soil loss on flatten slopes in the condition of this experiment.

4. Summary and Conclusions

Interrill erosion and runoff of volcanic ash soil under a simulated 30-min., 62 mm/h rainfall, were measured for slopes of 6°, 9°, 12°, 15°, and 20°. Splashment loss, runoff, and wash loss were determined every 2 min. Runoff and soil loss rates all increased rapidly in the first ten

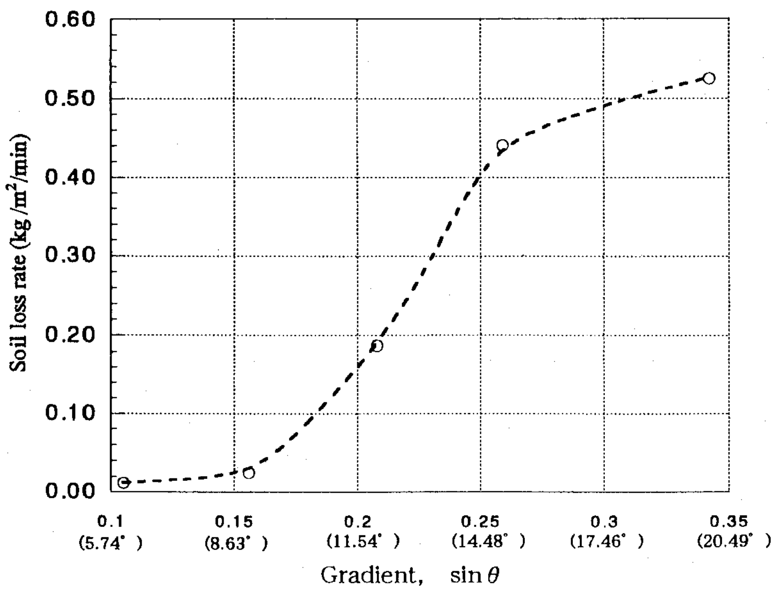

Fig. 6 Soil loss rates with slope steepness.

minutes for all except the 6° and 9° slope, and then runoff became constant for slopes of 12°, 15° and 20° gradients. Decrease in soil loss rates for all except the 20° slope was noted.

Regression analysis suggested a third-degree polynomial for the relationship between slope gradient and runoff rates and soil loss. Runoff showed a maximum at a 15° gradient, and decrease was noted beyond this. However, soil loss increased with slope gradient, rapid increase for slopes of 9° to 15° was observed, and flattened beyond 15°.

Analysis of soil loss and runoff rates indicated that on slopes with gradients beyond 15°, slope gradient affects erosion much more than runoff. For example, runoff rates was on the 20° less than 15° slope, but soil loss was greater.

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要　　約

本研究では，人工模擬降雨の実験のもとに，傾斜度がシラス土におけるリル間侵食に及ぼす影響が検討された。リル間侵食の変動および表面流出の発生を評価するために，強度が 62 mm/hr である降雨を実験槽に 30 分間与え。斜面傾斜度は 6°，9°，12°，15°，20° の 5 種類の実験を行った。結果として，6° の斜面の他は，いずれの斜面においても，流亡土，流出水ともに降雨実験の最初の 10 分間に急に増加し，実験経過時間の後半では，12°，15°，20° の傾斜度において，流出水が実験の経過にほぼ無関係に一様に発生するが，流亡土の方は傾斜度によって異なることが認められた。流亡土および流出水と傾斜度の関係を見ると，いずれも三次元の関係式が導かれ，変動の傾向が異なることが指摘された。ここで行った実験条件の場合では，流出水は 15° 付近でピークに達して，更に増加すると，減少することがみられた。しかし，流亡土が傾斜度の増大に伴って増加し，特に 9° から 15° までの間に顕著な増加の傾向があり，15° を越えると，流亡土の増加は減衰する傾向が現れた。

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