The Experimental Study on the Model of Soil Erosion by the Impact of Raindrops

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(Received July 15, 1986)

Abstract

Soil erosion is caused by the interaction between rainfall and soil factors. Despite the considerable complexity of interaction between these factors, there is a need to reveal their mechanisms, and to quantitatively predict the rate of soil loss. In this study, the relationship between the rate of soil loss and factors upon which this loss depends was investigated using dimensional analysis. Erosion processes caused by the effects of raindrop impact were represented by a simple mathematical model which has been used in bed–load studies in the open channel. This model contains two parameters ξ_h, η_F, the first represents the effect on the detachability of soil by raindrops, the second represents the effect on soil transport by surface flow. Regarding to the simulated laboratory experimental data, it was found that the raindrop impact causes the transportation of soil by surface flow even if the flow is below the critical tractive force and the value for ξ_h increased in the begining and then decreased with increasing depth of water flow. The value for η_F increased linearly with increasing the water depth.

Introduction

Soil erosion is generally caused by the detachment of soil from the ground followed by the transporting of the soil by the surface flow. This movement of soil particles can be classified into the following four processes as shown diagramatically in Fig. 1, (1) movement due to the repeteition of detachment of soil by raindrop impact, (2) transportation of soil particles by surface flow following the raindrop detachment, (3) movement of soil particles entrained in flow by the tractive force, namely, rolling, sliding, and saltating. Such means of transportation are commonly refered as the transport of bed–load. (4) movement in suspension when the motion of soil particles is such that they are surrounded by fluid. Among these processes, the amount of soil loss by raindrop detachment is negligible compared with that by the other three processes. Furthermore, in such cases in which the tractive force of the run–off flow does not exceed the critical force, transportation of soil particles does not occur. Even under the above mentioned condition, detachment followed by transportation does occur if raindrop impact is exerted to the flow surface. In this case, interaction between raindrop impact and the tractive force of the run–off flow are often highly complex.

The objectives of this study are to experimentally investigate the effect of raindrop impact on soil detachment and transportation when run–off water is present. In order to confirm experimentally the effect of the raindrop on the soil movement, the surface flow was restricted under the critical flow. Namely, the effect of detachment by the surface flow and

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the effect of bed slope on soil loss are out of consideration. Laboratory experiments were performed varying the factors on which erosion depends, that is, the depth of surface water, the diameter of soil particles and the raindrop impact (rainfall intensity, raindrop energy).

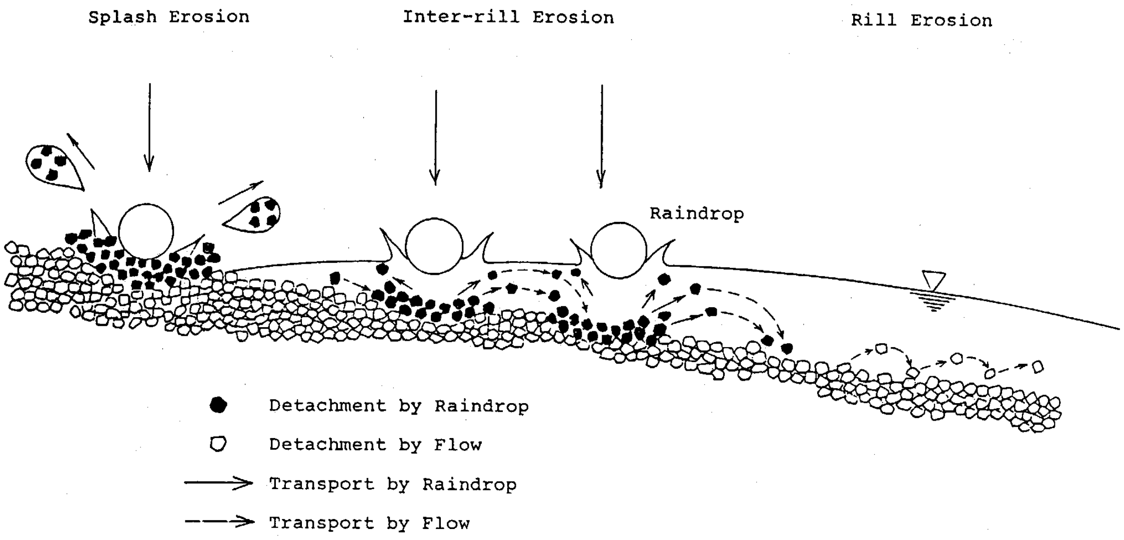


Fig. 1 Schematic diagram of erosion process

Analysis Model

In this study we consider the movement processes of soil particles (1), (2), as mentioned in the Introduction ; namely that soil detachment does not occur by the tractive force of surface flow, and that soil particles do not start to move until the raindrops splash to the surface of the flow. As it seems that the mass of soil transport by process (1) is negligibly small compared with that of the other process (2), it is then sufficient to further consider process (2). This process has been classified into (1) the process of detachment by raindrop impact, and (2) the transport process of soil particles that were detached by rainflow impact. These processes are represented by the following mathematical models.

It is satisfactory to consider soil erosion in nature as a mathematical model in the following Eqs. (1).

$$\phi = \phi_D + \phi_F \qquad (1)$$

where ϕ is dimensionless soil eroded by rainflow, ϕ_D is dimensionless soil eroded by rainfall impact, and ϕ_F is dimensionless soil eroded by surface flow. In this study the surface flow was kept below the critical flow, consequently ϕ_F is zero and is equal to ϕ_D.

The process of detachment may be expressed by Park[1)] as :

$$f_1(D, \rho_d, \varepsilon, V_D, d, V_*, \sigma, \rho_s, u, \rho, \mu, h, t, i, g, T, a) = 0 \qquad (2)$$

where :
D : raindrop diameter
ρ_d : fluid density of the raindrop

ε : deviation of drop size
V_D: terminal velocity of raindrop
d : diameter of soil particles
V_*: critical scouring velocity of soil particle
σ : standard deviation of particles size distribution
ρ_s : density of soil particle
u : flow velocity
ρ : density of water
μ : viscosity of water
h : water depth
t : time
i : slope gradient
g : gravitational acceleration
T : surface tension
a : characteristic lenght describing the geometry of the system

After dimensionless analysis, Eqs. (2) may be reduce to:

$$M_s/M_D = f_2(\mathrm{Re}, \mathrm{Fr}, \mathrm{We}, h/D, tV_D/D, \varepsilon/D, \sigma/d, \mathrm{Sf}, \sigma, V_D/V_*) \tag{3}$$

where :
M_s: weight of detachment soil
M_D: weight of drop
Re : the Reynolds number
Fr : the Froude number
We: the Weber number
Sf : the shape factor

Since splash erosion is limited to interrill areas where surface flow is not well developed, terms describing the flow characteristics, such as Re, Fr, and We, may be dropped out. For specific soil and rainfall intensity, where the terms ε /Dand σ /d becomes constant, Eqs. (3) can be further simplified to:

$$M_s/M_D = f_3(V_D/V_*, h/D, i, tV_D/D) \tag{4}$$

Eqs. (4) becomes a steady–state equation if the effect of time is negligible:

$$M_s/M_D = f_4(V_D/V_*, h/D, i) \tag{5}$$

In considering soil particles detached into the surface flow, the number of detached soil particles, N $[1/cm^2/sec]$, is:

$$N = M_s f_D/\rho_s A d^3 \tag{6}$$

where f_D is frequency of rainfall drops $[1/cm^2]$, and A is the shape factor of the soil particle. By substituting Eqs. (5) into Eqs. (6)

$$N = M_D f_4(V_D/V_*, h/D, i)\, f_D/Ad^3 \tag{7}$$

In the process of transportation, the volume of eroded soil per unit width and unit time, q_D, is :

$$q_D = Ad^3N(\beta u_*) \tag{8}$$

where u_* is friction velocity, β is a constant ratio. In ordeer to express the rate of eroded soil as demensionless, transform Eqs. (8) into Eqs. (9).

$$q_D/\sqrt{sgd^3} = Ad^2N\beta u_*/\sqrt{sgd} \tag{9}$$

where S is the specific gravity of soil particles in water. From the theory of sediment transport

$$\phi_{DF} = q_D/\sqrt{sgd^3} \tag{10}$$

$$\psi = u_*{}^2/sgd \tag{11}$$

where ϕ_{DF} is dimensionless eroded soil which is detached by rainfall impact, and ψ is dimensionless tractive force and then transported by surface flow.
By substituting Eqs. (10) and Eqs. (11) into Eqs. (9):

$$\phi_{DF} = Ad^2N\beta\psi^{1/2} \tag{12}$$

By substituting Eqs. (12) into Eqs. (7):

$$\phi_{DF} = M_D f_4(V_D/V_*, h/D, i) f_D \beta \psi^{1/2}/\rho_s d \tag{13}$$

Dimensionless detached soil by rainfall impact, ϕ_{DD}, is:

$$\phi_{DD} = M_D f_4(V_D/V_*, h/D, i) f_D/\rho_s d \tag{14}$$

The relationship between ϕ_{DF} and ϕ_{DD} becomes:

$$\phi_{DF} = \phi_{DD}\beta\psi^{1/2} \tag{15}$$

Dimensionless detached soil by rainfall impact where h and i are equal to zero can be expressed as:

$$\phi_{DDO} = M_D f_5(V_D/V_*) f_D/\rho_s d \tag{16}$$

where ϕ_{DD} is basic dimensionless detached soil caused by rainfall impact. Introducing a parameter which represents the effect on detachability of soil by rainflow, ξ_h, and changes according to water depth:

$$\phi_{DD} = \xi_h \phi_{DDO} \tag{17}$$

where if h is zero ξ_h is equal to 1.
And introducing a parameter which represents the effect on soil transport by surface flow, η_F:

$$\phi_{DF} = \eta_F \phi_{DD} \tag{18}$$

ϕ_{DF} is in proportion to $\psi^{1/2}$ as shown in Eqs. (12), and assumes that ψ becomes a dimensionless critical tractive force, ψ_C. Every detached soil particle is transported and reduces to a eroded soil particle, that is, ϕ_{DF} is equal to ϕ_{DD}.

$$\eta_F = \phi_{DF}/\phi_{DD} = (\psi/\psi_c)^{1/2} \tag{19}$$

On interrill erosion when surface flow is below critical flow :

$$\phi = \phi_D = \phi_{DF} \tag{20}$$

$$\phi = \eta_F \phi_{DD} \tag{21}$$

$$= \xi_h \eta_F \phi_{DDO} \tag{22}$$

It is the purpose of this study to understand the two parameters ξ_h, η_F quantitatively and to ascertain the significance of ξ_h, η_F experimentally.

Experimental Apparatus and Procedure

In order to investigate only the effect of raindrops on the detachability of soil when the surface flow is present, and that this flow does not exceed the critical force, two kind of experiments were performed and are described in detail in the following.

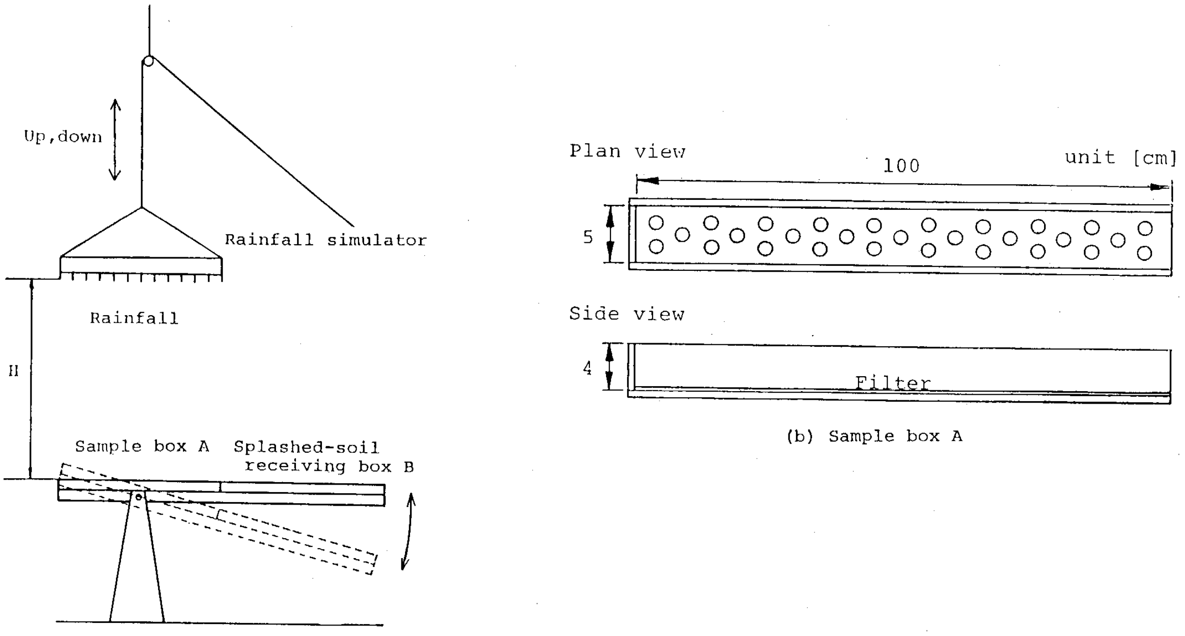
Two sand grains were used as a sample having a mean diameter of 0.048 cm and 0.069 cm respectively. Rainfall was simulated by rainfall modules (135 cm×35 cm) suspended from a framework above the sample box, from which capillary tubes protruded downward as shown in Fig. 2. Each capillary tube used generated a raindrop with a 0.57 cm average diameter. The height of the module above the sample box could be adjusted by a suspended rope. The inflow rate to the module was controlled by a valve.

—Experiment 1—

The objective of this experiment is to investigate the rate of soil detachment from a sample box when raindrops splash to the surface of dried sand. A sketch of the apparatus used is shown in Fig. 2. The sample box has a cross section of 5cm×4cm and is 100 cm long. A number of holes were made in the bottom to drain off any seepage from the rainfall, and a filter made of cloth was placed along the bottom to prevent sand from flowing out. When applying the rainfall to the surface of the sample box, the mass of detached soil was measured seperately for each raindrop intensity, and seperately for each raindrop energy.

—Experiment 2—

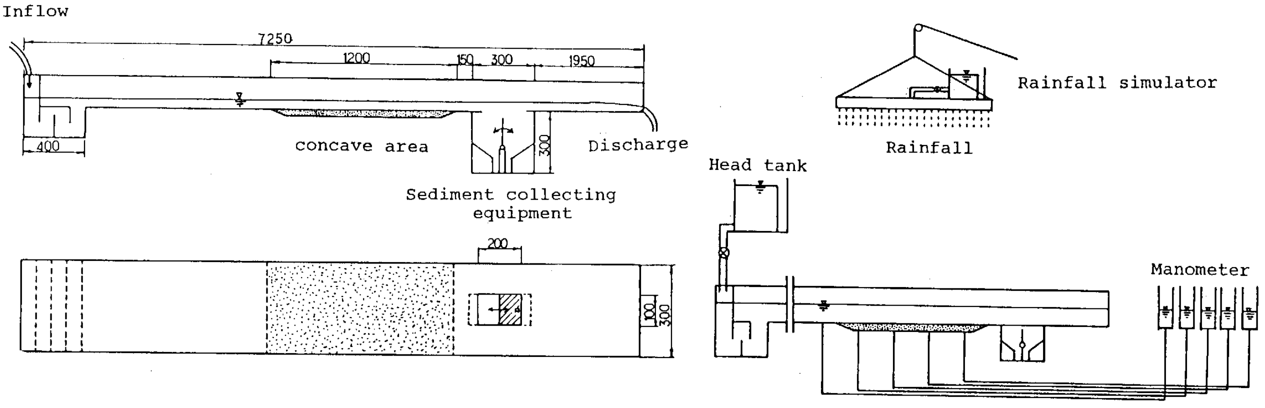
This experiment was performed in an attempt to investigate the effect of raindrops on the transportation of soil particles when surface flow is present, and the mean flow velocity does not exceed critical value. As shown in Fig. 3, the experiment was performed in a 30 cm wide, by 727 cm long flume made of acrylic plate, the bottom of which had a concave area (30 cm wide, by 100 cm long, 2 cm in depth). This area was filled with sand grains so that the top sand would be the same as that of the flume bottom. A sampling device was mounted downstream from the test area. The sand grains used as samples are the same as those used in experiment 1. The range of the rainfall intensity and raindrop energy applied to the test area was almost the same as that of experiment 1. The water was applied from the head tank to the upper end of the flume so that the flow could be uniform and maintained below the critical flow condition. The water depth along the sand bed was obtained by measuring the water level in manometers with a point gauge having 0.01 cm graduations. Mean velocity of flow was calculated by dividing the flow volume by the mean cross—sectional area of the surface flow. Upon applying rainfall to the test section, the mass of bed–load in a sampler was measured.



(b) Sample box A

(a) Diagram of apparatus used for detachment soil quantitative distribution

Fig. 2 Experiment 1



(a) Experimental channel

(b) Diagram for rainflow erosion experiment

Fig. 3 Experiment 2

Results and Considerations

1. Effect of raindrop impact on soil detachment

On the basis of the results of experiment 1, shown in Fig. 4–(1), Fig. 5–(1), the relation between the specific mass of splashed sand (M_s/M_D) and falling velocity was obtained. These results suggest that there exists a critical value for falling velocity V_* under which detachment dose not occur. The values of for $V_* = 180$ (cm/sec), 170 (cm/sec) for a sand of 0.069 cm, 0.048 cm in diameter respectively, was obtained from the results shown in Fig. 4–(1), Fig. 5–(1). Fig. 4–(2) and Fig. 5–(2) show the functional relationship between M_s/M_D ($= \phi_{DD}$) and V_D/V_* which seem to describe the following quadratic from,

$$\phi_{DD0} = M_{S0}/M_D = C\,(V_D/V_*)(V_D/V_* - 1) \tag{23}$$

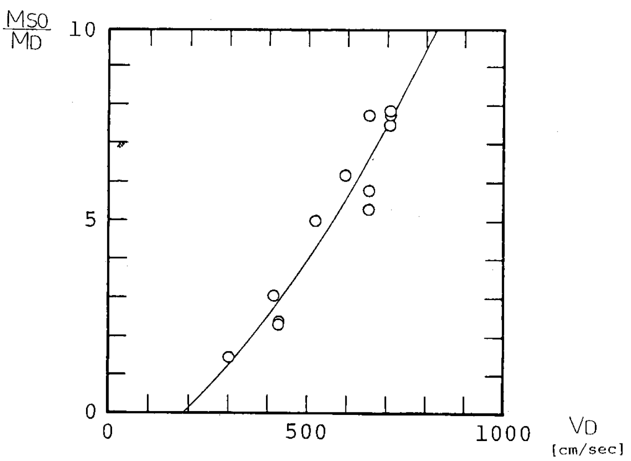


Fig. 4 -(1) Relationship between a standard detachment soil quantity M_{S0}/M_D and falling raindrop velocity V_D (d=0.069cm)

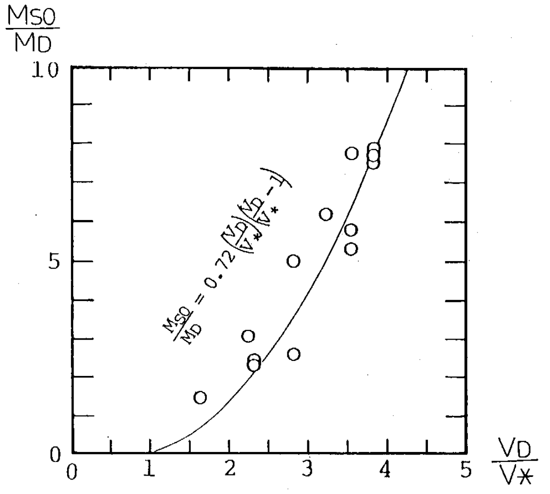


Fig. 4 -(2) Relationship between a standard detachment soil quantity M_{S0}/M_D and dimensionless falling raindrop velocity V_D/V_* (d=0.069cm)

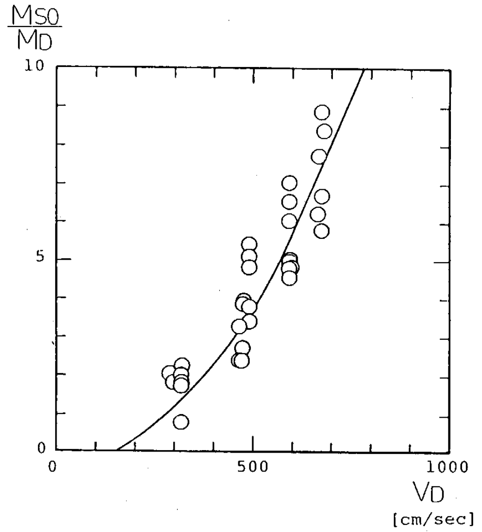


Fig. 5 -(1) Relationship between a standard detachment soil quantity M_{S0}/M_D and falling raindrop velocity V_D (d=0.048cm)

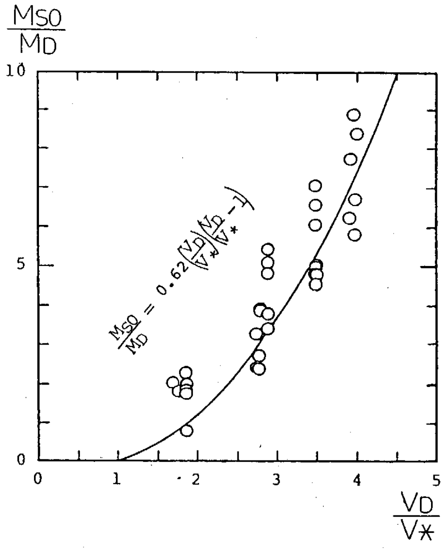


Fig. 5 -(2) Relationship between a standard detachment soil quantity M_{S0}/M_D and dimensionless falling raindrop velocity V_D/V_* (d=0.048cm)

in which C is an empirical constant. Values for C taken from the curve in this figure were 0.62 with d = 0.048 cm and 0.72 with d = 0.069 cm respectively. Soil loss function ϕ_D can be expressed as:

$$\phi_D = \beta \psi_c^{1/2} \phi_{DD} \tag{24}$$

where ψ_C is critical tractive force, ϕ_{DD} is dimensionless mass of detachment, and β is an empirical constant. Using Eqs. (17), (23), (24) ξ_h can be calculated. The calculated values for ξ_h, which represent the effect on detachability of soil to rainfall, versus h/D (the ratio of water depth h to raindrop diamerter D) are shown in Fig.6. As can be seen in these figures the values for ξ_h increase with increasing nondimensional depth h/D to a maximun which occurs at h/D = 1.5 for d = 0.069 cm, and at h/D = 2.0 for d = 0.048 cm respectively, and thereafter decrease with increasing h/D. A similar tendency is also shown in the investigations of Rose[2] (1983b), and Iwagaki[3] (1956). As mentioned above, there are two characteristic water depths h/D. The one is a point the maximum value for ξ_h occurs, the other is a point at which minimum value for ξ_h occurs. It seems that the location at which ξ_h has maximum value increases as sample size decreases. This kind of behavier can be explained simply as follows. As water depth increases, the effect of raindrop impact on soil surface become smaller because of the absorption of energy by a fluid, and the larger particles are not more subject to detach than particles of smaller size. As a physical explanation of the minimum value of detachment, it seems that the shear stress of flow generated restoring the water level after raindrop splashing causes the detached particles to backfill. Explanation of the growth mechanism of this stress is the subject for a future study.

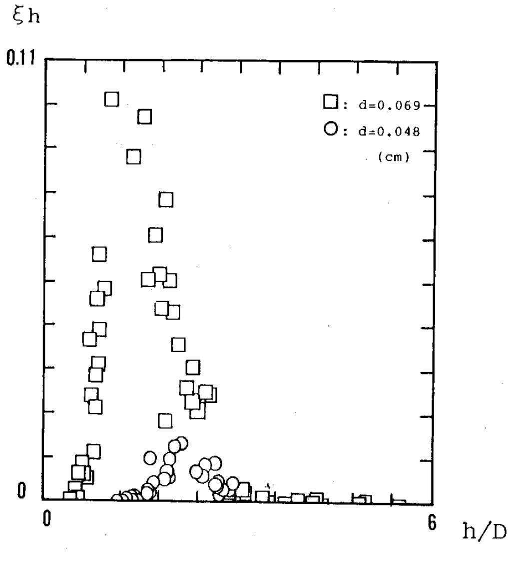


Fig. 6 Relationship between detachment effect ξ_n and dimensionless water depth h/D

2. Transported force by surface flow

The relationship between parameter η_F, Which represents the effect on transportaion of grains, and h/D is shown in Fig. 7–(1), Fig. 7–(2). The value for η_F increased in an approximately linear manner with the increasing of the non–dimensional depth h/D.

3. The tractive force of surface flow and the mass of soil loss

The empirical values for dimensionless eroded soil ϕ by rainflow were plotted in Fig. 8 versus the dimensionless tractive force ψ, with sand diameter as a parameter. Two solid curves are drawn in this figure, the one is Meyer–Peter Müller's semi–empirical bed–load function with $\psi_c = 0.047$, the other is the same function with $\psi_c = 0$, this means that all the entrained soil particles flow out even though shear stress does not exert on the bed. The physical meaning of this curve is considered to be the upper limitation of soil transport. Empirical data measured under the condition of various rainfall intensities are almost all located in the enclosed area between the two curves, this means that rainfall impact causes the transportation of sand grains, despite the flow having no tractive force. The assumption of a curve with $\psi_c = 0.047$ made by Meyer–Peter Müller is not reasonable, but indicates that this equation, with $\psi_c =$ an empirical value for each sand diameter, is capable of predicting the soil loss more accurately.

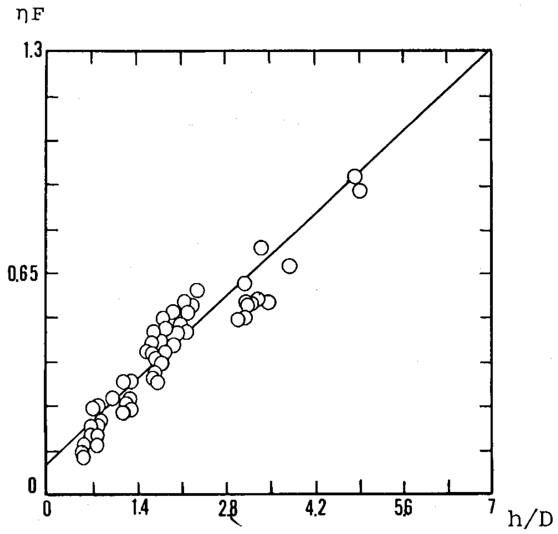


Fig. 7 - (1) Relationship between transport effect η_F and dimensionless water depth h/D (d=0.069cm)

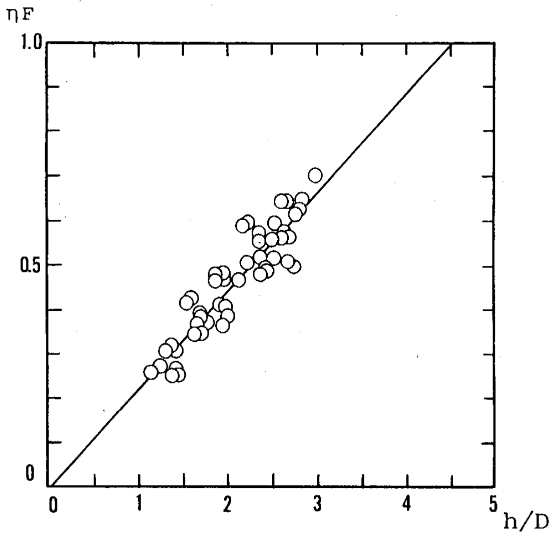


Fig. 7 -(2) elationship between transport effect η_F and dimensionless water depth h/D (d=0.048cm)

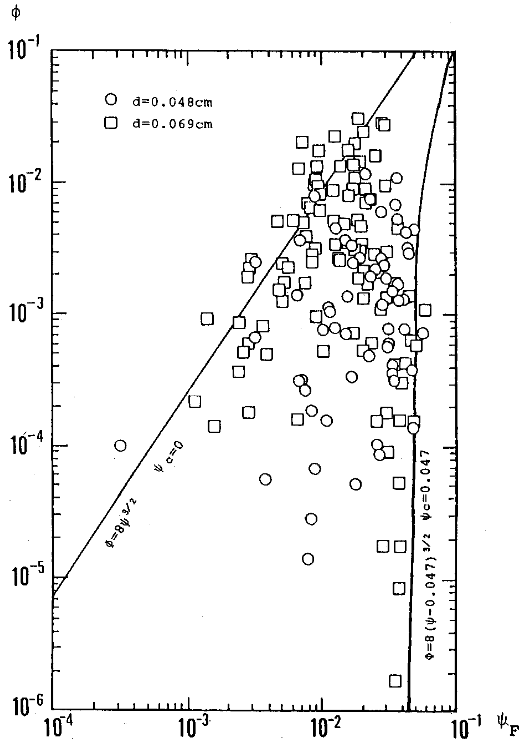


Fig. 8 Comparison between experiment results and bed-load function curve

Conclusion

This study shows that a simple mathematical model, based on the Meyer–Peter Müller's bed–load function, can be used to describe the effect of raindrop impact on the rate of transportation of detached soil, assuming there is no bed slope. Also, the effect of rainfall on the soil detachment, and on the soil transport by the surface flow can be described separately introducing two empirical parameters ξ_h, η_F in this model. Through the use of laboratory produced rainfall, the effect of varying the depth of rainfall detachment have been quantatively investigated for two kind of sand. As a result of the investigating laboratory data, the rate of soil detachment reaches the maximum value at different water depths depending on the sand diameter used. The maximum value for a sand with a 0.069 cm diameter is high compared with that for a sand a 0.048 cm diameter, but the mean water depth at which the maximum rate of soil detachment is reached for a sand of bigger size is less than that of smaller size. In the transportation processes, the parameter η_F increased in an approximately linear manner with the non–dimensional value of the water depth (h/D). The relationship between total load and tractive force of rainflow has been experimentally investigated by using a bed–load function which has a similar from to the Meyer–Peter Müller's function. Effect of raindrops on total load is significant, even if the rainflow is below the critical force.

References

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