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COMPUTATION OF SEDIMENT YIELD FROM RAINFALL IMPACT ENERGY

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1. INTRODUCTION Most of the models which are currently used for computation of sediment yield were empirically derived and often have limited transferability outside their conditions of calibration. Though a few models exist that have been derived from mainly physical principles and therefore have a general nature of application, there is still need for models that incorporate both the characteristics of applied rainfall and the slope material. The proposed model computes sediment yield from bare slopes by using information about the rainfall impact energy through a rainfall impact parameter as well as bed material characteristics.

2. RAINFALL IMPACT ENERGY Slope erosion is mainly caused by rainfall and the resulting overland flow. The rainfall impact energy itself is not directly related to sediment detachment since the total energy of a raindrop is first transmitted through the water depth before it affects sediment detachment. However at low depths of flow, the rainfall impact energy would have a more significant influence on soil detachment. In such conditions therefore, relating rainfall energy to sediment yield is relevant. In order to determine the rainfall impact energy, the physical properties of the applied rainfall and bed material should be accurately determined: rainfall intensity, r (mm/hr), mean raindrop diameter, D (cm); terminal raindrop velocity, w_f (m/s); mean bed material diameter, d (mm); slope length, L (m) and bed gradient, S_0 or bed slope, θ in degrees. The critical rainfall intensity, r_c, for a particular slope, below which no sediment discharge will occur should also be determined. The rainfall intensity, r, can easily be determined in a number of ways. The drop diameter and drop impact velocity can be determined indirectly by a number of established models from knowledge of rainfall intensity. The representative raindrop diameter, D can be determined from published relations such as that of Laws & Parsons (1943, fig. 1) which in cgs units becomes: $D = 0.124r^{0.182}$ .... (1). The terminal raindrop velocity, w_f can be computed from the drop diameter, by an empirical formula given by Best (1950): $w_f = 9.32\left\{1-\exp\left[-(D/0.177)^{1.147}\right]\right\}$ .... (2). The total rainfall energy delivered in time T can then be expressed as; $E = \int_0^T (1/2)\rho A_3 D\left\{w_f(D)\right\}^2 r(t)dt$ .... (3), in which, ρ = density of water, A_3 = three dimensional geometrical coefficient (= π/6 for a sphere), and r(t) = rainfall intensity at time t. By expressing the number of raindrops per unit time and unit area, $N_r = r/\left\{\left(3.6\times10^4\right)\left(A_3D^3\right)\right\}$ .... (4), the total kinetic energy brought to the unit area of the water surface on the slope in a finite time interval Δt is; $e_0 = \frac{1}{2}.N_r.\rho A_3 D^3 w_f^2.\Delta t$ .... (5). Even when e_0 is constant, the detachment rate will increase with increase in slope angle due to decrease of flow depth. The effect of slope can therefore be introduced in Eq. (5) by a simple index expressed as the sine of the slope angle; $E_0 = e_0 \sin\theta$ .... (6). The number of sediment particles exposed to the rain drops are determined by the ratio of their projected areas; $\left(A_2D^2\right)/\left(A_2d^2\right)$ ..... (7), in which A_2 = two dimensional geometrical coefficient (= π/4 for a sphere). By expressing the energy to lift a given sediment particle through height k_1d as $(\sigma/\rho-1)gA_3d^3k_1d$ .... (8), in which σ = density of sediment, g = acceleration due to gravity and k_1 = constant, the sediment detachment rate is expressed as a ratio, D'_{ro} between Eq. (6) and Eq. (8) through Eq. (7) as; $D'_{ro} = \left\{1.8\times10^{-3}A_2/(k_1A_3)\right\}.\left\{\left[w_f^2/(\sigma/\rho-1)gd\right].(r\Delta t\sin\theta)/d\right\}$ ...... (9). Considering the characteristic velocity scale and length scale of the sand particle itself and expressing the time scale in Eq. (9) as $\Delta t = k_T\sqrt{(d/g)}$ ... (10), in which k_T, is a constant, Eq. (9) is modified as follows; $D_{ro} = k_T D'_{ro}$ .... (11) Assuming that the constant terms in Eq. (11) do not change significantly for the same bed material, the dimensionless raindrop impact parameter can be expressed from Eq. (11), excluding the constants as;

$$D_r = \left\{w_f^2/\left[(\sigma/\rho-1)gd\right]\right\}.\left\{r\sin\theta/\left(\sqrt{gd}\right)\right\} \quad \text{........................} \quad (12)$$

3. SEDIMENT YIELD MODEL By relating volumetric sediment yield q_B (cm²/s) , which represents energy expenditure to the rainfall impact parameter, D_r, which represents conditions for energy supply, a sediment yield model can be expressed as follows; $q_B/\left\{\sqrt{(\sigma/\rho-1)gd^3}\right\} = f_L D_r^m\left[1-\left(D_{rc}/D_r\right)\right]^n$ .... (13), in which

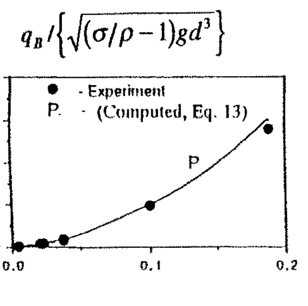

Fig. 1 Computed and Measured Sediment Yield for Uniform Sand under Laboratory Conditions

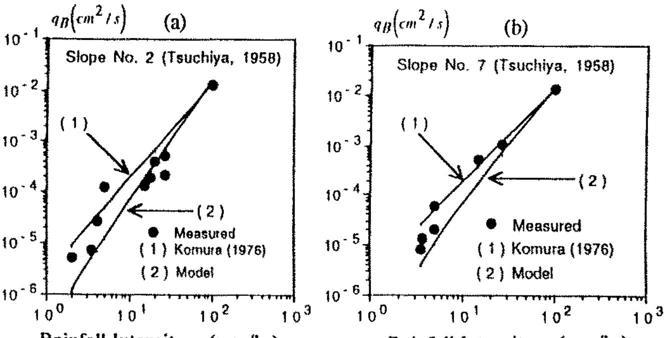

Fig. 2 Computed Sediment Yield for Field Plots under Natural Rainfall

m , n are calibration parameters, D_{rc} = critical impact parameter for intensity r_c and f_L = function which takes into account bed slope, bed material diameter and slope length .The function, f_L is expressed as follows; $f_L = K\left[(L/d)^c \tan\theta\right]^e$ ...... **(14)** , in which K, c and e are empirical constants.

4. LABORATORY EXPERIMENTS BY UNIFORM SAND Simulated rainfall with intensities of 70, 255 and 390 mm/hr, was applied to uniform sand of mean diameter d = 0.875 mm, at two slopes of S_0 = 0.05 and 0.01. The sand beds measured 2.74 m long, 1.5 m wide and 40 mm thick. The sand beds were maintained at an initial moisture content of about 15 % in all experiments. Rainfall was applied for a total duration of 60 minutes and sediment collected throughout the time of rainfall application.

Table 1 Summary of Laboratory Experiments and Main Results

Run	$\tan\theta$	r ($\times 10^{-4}$) (m/s)	w_f (m/s)	D (10^{-3}) (m)	D_r ($\times 10^{-3}$)	$\frac{q_B}{\sqrt{(\frac{\sigma}{\rho}-1)gd^3}}$ (Measured)	$\frac{q_B}{\sqrt{(\frac{\sigma}{\rho}-1)gd^3}}$ (Computed)
A01	0.05	1.0833	5.11	2.07	107.65	219.81	233.93
A02	0.05	0.7083	4.62	1.64	57.53	96.32	77.38
A03	0.05	0.1944	4.18	1.14	21.56	7.62	5.24
A04	0.01	1.0833	5.11	2.07	12.93	1.93	1.65
A05	0.01	0.7083	4.62	1.64	11.52	0.60	0.52
A06	0.01	0.1944	4.18	1.14	2.59	0.00	0.00002

The measured sediment yield and tresults computed by Eq. (13) are presented in Table 1 and plotted in Fig. 1. for K = 43.86 x 10^{-9}, c = 2.0, e = 1.3, m = 1.75, n = 0.6 and D_{rc} = 0.002.

5. APPLICATION OF MODEL TO ACTUAL SLOPE EROSION By using the same calibration factors as for uniform sand under laboratory conditions, the model was applied to the measured slope erosion by Tsuchiya (1958) in Tajimi City, Gifu Prefecture, Japan. The slopes (Slope No.2 and 7) had the following details: L = 9.8 m, S_0 = 0.316, d = 7 mm and area of each plot A = 104 m^2. The same field data was used in the application of the slope erosion model by Komura (1976). The critical rainfall impact parameters were estimated from the lowest recorded rainfall rate at which sediment was measured: Slope No. 2, r_c = 0.7 mm/hr, D_{rc} = 3.62 x 10^{-5} ; Slope No. 7, r_c = 1.6 mm/hr, D_{rc} = 1.06 x 10^{-4}. Computed sediment yield by the model and by Eq. (35) of Komura (1976) are compared with the measured values in Fig. 2(a) and Fig. 2 (b) for Slope No. 2 and 7 respectively.

6. CONCLUSIONS A new model which computes sediment yield from bare slopes due to rainfall impact is explained. The model computes sediment yield through a dimensionless rainfall impact parameter, D_r, derived from rainfall impact energy on the shallow water depth on a slope which is typical of overland flow conditions in upland sedimentation. An application of the model to slope erosion under natural rainfall by using parameters calibrated under laboratory conditions shows good agreement with the measured sediment yields.

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