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Incipient Sediment Motion and Bed Load Transport in Streams with Rigid Vegetation

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INTRODUCTION

The existence of vegetation in natural streams plays a major role in the environment of the flowing water. Moreover, vegetation has a significant effect on suppressing turbulent motion which consequently lags the scour process and protects bed surface from erosion. Several studies were proposed for sediment discharge and turbulent structure in vegetated channels, among of them, Inoue et. al.[1], Hirano et al.[2]. The incipient motion criteria and the intrinsic relationship between the apparent tractive shearing force and the effective friction force on bed are not clarified yet. In this study, the incipient motion of sediments in the bottom of open channels covered by non-submerged rigid vegetation is investigated through an experimental study on non-uniform flow. The threshold movement of particles is observed at a specific section wherein the flow characteristics are measured. The Shields diagram for incipient motion is modified for streams with vegetation. A relation between total (apparent) shear stress and effective shear stress for bed roughness is developed based on the measured data. The effect of vegetation density on bed load discharge relation is illustrated.

EXPERIMENTAL PROCEDURES

A flume measuring 20 x 0.4 m and having depth of 0.4 m was used for conducting the experiments in the Hydraulics Laboratory, Saga University, Japan. The vegetation is simulated by vertical rigid cylinders of bamboo sticks with diameter 3 mm and same height of 25 cm over area of 0.4 x 10m in spanwise, z, and streamwise, x, respectively. The sticks were arranged in staggered shape on the sand bed. Figure 1 shows the arrangement of sticks. The spacing S is taken 2.12, 3.11, and 4.24 cm respectively. Sand bed material was uniform with particles diameter = 1.291 mm. At the tail end, water level was adjusted by vertical sliding gate. Non-uniform flow was allowed to flow with several discharges Q, and bed slope I_b. The incipient motion of sand particles was visualized and its location and the associated water depth were recorded. Water level along the channel was measured by using point gauge. Two dimensional velocity distribution was observed by using magnetic currentmeter for several cross sections along the flume with cell size 25 x 5 cm. Sediment discharges were measured by using sand trap. Experimental conditions and observations made are given in Table 1, where $\lambda = \pi D^2 / 4S^2$ is the vegetation intensity, h_c is the water depth at threshold movement section and Ψ_c is the critical shear stress.

Table 1 Experimental Conditions

Run	I_b	Q (cm^3/se)	λ	h_c (cm)	Ψ_c
1	1/100	9551	0.01572	10.6	0.3037
2	1/100	12361	0.01572	13.6	0.3711
3	1/100	15617	0.01572	17.8	0.4032
4	1/150	9551	0.0073	10.0	0.0555
5	1/150	12361	0.0073	13.0	0.0694
6	1/150	12976	0.0073	13.6	0.0744
7	1/200	9551	0.00392	10.2	0.0418
8	1/200	12361	0.00392	11.3	0.0432
9	1/200	12976	0.00392	12.2	0.0476
10	1/200	15617	0.00392	15.1	0.0505

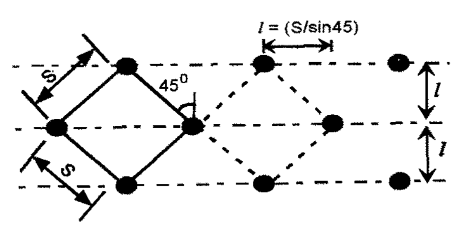

Fig.1 Arrangement of bamboo sticks simulating vegetation

INCIPIENT MOTION AND CRITICAL SHEAR STRESS

In a flowing stream, the motion of a specific particle is under the interaction of two opposing forces: The hydrodynamics applied forces and the resistance force which is associated with the submerged weight. The particle will be moved if the applied forces overcome the resistance. At the threshold of movement, the applied forces are just balanced the resisting force. Since it is the local forces acting on the sediment particles that move these particles, the existence of vegetation in the bottom significantly reduces the applied forces because of the drag resistance. On the other hand it increases the resistance because of the suppressing turbulent motion near bed. The fundamental force balance equation may be represented by

$$\rho u_{*e}^2 = \rho g h I_e - \frac{1}{2}\rho V^2 C_D D h \frac{1}{S^2} \tag{1}$$

where ρ is the density of water, u_{*e} is the effective bed shear velocity, g is the gravitational acceleration, h is the water depth at the measuring section, I_e is the energy slope at the same section, which can be calculated from bed and water surface slope, V is the mean velocity of the flow at the same section, C_D is the drag coefficient due to vegetation which is related to the Reynolds number, D is the diameter of one stick of bamboo, and S is the spacing between vegetation, as shown in Fig. 1.

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By using the proceeding equation and the experimental data, the effective shear velocity at critical section of movement, u_{*c} is calculated. Shields conducted experiments with uniform sediment size for flat bed to develop his well-known incipient motion diagram, see Yang[3]. In case of the existence of vegetation, the diagram should be modified by analyzing the obtained data to form the same dimensionless parameters in addition to the parameter representing vegetation intensity. The results are shown in Fig. 2. Both the Reynolds number for particles, $R_{n*} = U_* d/\nu$, and the vegetation intensity, λ, have a significant effect on increasing of the dimensionless critical shear stress parameter, $\psi = u_*^2/sgd$, where ν is the kinematic viscosity, and s is the specific gravity of particles. Turbulence near bed has a great influence on particle movement. To elucidate the lag of particle motion within vegetation than over flat bed with no vegetation, velocity measurements were extensively carried out. It was detected that turbulence has relatively low intensity in all cases of vegetation which prevails the delay of particles movement.

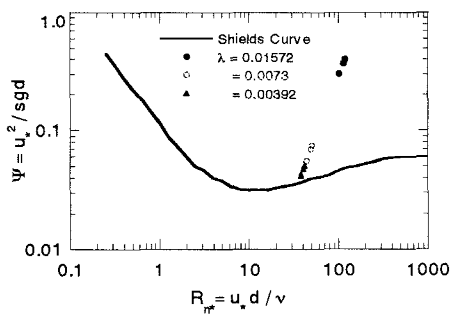

Fig. 2 Comparison of Shields curve and threshold data

SEDIMENT BED LOAD DISCHARGE

Based on the force balance equation and the measured data for experiments for several sediment and water parameters, the total dimensionless shear stress, Ψ, is calculated and the effective dimensionless shear stress for bed roughness, Ψ_e, is obtained by subtracting vegetation resistance term. Figure 3 shows the analysis of experimental results as a relation between Ψ and Ψ_e. This relation takes approximately the shape of a sigmoid function which can be formulated as the following,

$$\psi_e = \frac{1}{2.2 + 95\,e^{(-3.55\,\psi)}} \tag{2}$$

Using this expression facilitates the figuring of bed load sediment discharge within vegetation zone in terms of effective shear stress which depends mainly on particles roughness. Figure 4 shows the relation between dimensionless sediment discharge, $\phi_b = q_b/\sqrt{sgd}$, and dimensionless shear stress term $(\psi_e - \psi_c)$, with vegetation density parameter, λ. Another curve is plotted representing Meyer Peter-Muller equation for sediment discharge in flat bed, $\phi_b = 8(\psi - \psi_c)^{3/2}$, see Yang[3]. The figure shows that bed load discharge increases with increasing shear stress (the same trend of Meyer Peter-Muller equation). For the same value of shear stress, the bed load discharge in vegetated channel is less than in channel without vegetation. The vegetation density also has a remarkable effect on the amount of sediment discharge.

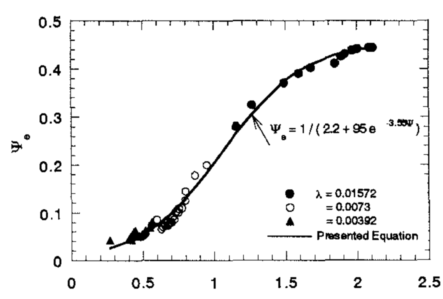

Fig. 3 Relation between Ψ and Ψ_e in vegetated channel

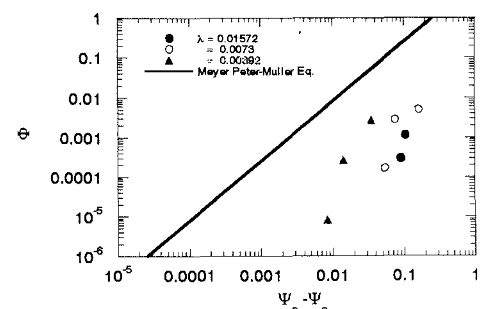

Fig. 4 Effect of vegetation density on bed load function

CONCLUSIONS

The critical shear stress values in vegetated streams are not the same values of flat bed streams. The Shields diagram for incipient sediment motion has been modified for vegetated stream. A relation between total shear stress and effective shear stress due to bed roughness in streams with rigid vegetation is presented through an explicit applicable equation. The effect of vegetation intensity on bed load discharge are obviously illustrated by presenting the sediment load as a function of a term representing the deduction of critical shear stress from effective shear stress. More data are strongly needed to complete the study of the change in critical shear stress for a wide range of Reynolds number values and vegetation intensity.

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