Bed load transport and erosion rate in streams with rigid vegetation

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Bed load transport in vegetative channels is studied through an experimental work. A relation between bed load discharge and tractive shear stress is investigated. The experimental results of bed load discharge in vegetated channels are compared with the well-known curve of Meyer–Peter Muller for non-vegetated channels. A new expression considering vegetation density is developed for the determination of bed load discharge. In the same experiments, the effect of vegetation density and the tractive shear stress on the erosion rate of bed material has been highlighted and analyzed.

في هذا البحث، وهو يعتبر استكمال لدراسات سابقة، تم دراسة كمية الرواسب المتحركة فى قاع الترع والقنوات ذات الحشائش الجاسئه. وقد أجريت التجارب المعملية على الجريان المنتظم فى ترعة تحتوى على أعواد تمثل الحشائش. وقد تم دراسة العلاقة بين كمية الرواسب المتحركة وجهد القص الحدى. وقد تم مقارنة النتائج بالمنحنى الناتج من تطبيق أحد المعادلات الشهيرة لحساب كمية الرواسب المتحركة في الترع العادية (بدون حشائش). وقد تم الحصول على معادلة جديدة لتقدير كمية الرواسب مع الأخذ في الاعتبار كثافة الحشائش في القاع. وفى نفس التجارب تم دراسة معدل النحر في القاع نتيجة مرور مياه غير محملة بالرواسب لمدة طويلة. وتم دراسة المتغيرات المؤثرة في تغيير معدل النحر، ومدى تأثير كثافة الحشائش على تثبيت التربة وتقليل النحر.

Keywords: Open channel flow, Vegetative channels, Bed load transport, General scour, Boundary shear stress

1. Introduction

Recently, the study of vegetation in streams has become more interesting for engineers who are involved in sediment and erosion control works. Vegetation is the most cost-effective form of preserving the natural environment, and preventing sediment–related disasters.

Several works were done for sediment discharge and bed load concentration in non-vegetated channels. The presented approaches succeeded to illustrate this complicated problem and to give the suitable expressions for estimating the bed load discharge in rivers and natural streams. Very little detail work seems to have been done to improve the understanding of the mechanism of bed load transportation in vegetated channels. Some early work was done by Li and Shen [1] on the flow resistance and sediment yield. They investigated the effect of various vegetation patterns on sediment yield for given flow conditions. They used the force balance equation, the logarithmic law for velocity distribution and Shield's sediment transport equation for estimating sediment discharge. Their analysis is mainly for relative comparison, not for accurate estimation. Hirano et al. [2] assumed that flow resistance can be represented by the nonlinear summation of the drag force acting on vegetation and shear stress due to bed surface particles. The analysis considered the logarithmic law of velocity distribution. The sediment discharge was estimated as a function of shear stress and effective shear stress. Ishikawa et al. [3] conducted their experiments on woody vegetated models of trees. In their analysis, the effective tractive force is estimated as a ratio of the total tractive force taking into account the roughness concentration of trees and Manning roughness coefficient for bed surface. Hirano et al. [4] examined the transport rate through vegetation over a movable bed through their experimental study. Their study showed that the rate of transport through vegetation is less than that in channel without vegetation. As for erosion in vegetative channel lining, Jamal and Kouwen [5] made their experiments for investigating the soil detachment and erosion

2. Analysis of bed load transport

When tractive shear stress in the channel bottom exceeds the critical stress, the sediment particles start to move as a bed load discharge. For channels with rigid vegetation, bed load discharge is a product of two criteria: The first is the local scour around vegetation stems, the second is the general scour along the bottom of the channel. In the experiments, the collected samples from sand trap are analyzed, also sieve analysis for each sample is performed. It was detected that the mean diameter of collected samples is the same as the original bed material. Sediment discharge values are presented in the well-known dimensionless form $\Phi = q_b / \sqrt{sgd_{50}^{\,3}}$, where q_b is the bed load discharge per unit width, g is the gravitational acceleration, and $s = 1.65$ is the specific gravity of particles.

The dimensionless parameters that are important in the determination of bed load discharge are the tractive shear stress Ψ_e, the critical shear stress Ψ_c, and the vegetation concentration λ. The first two parameters were extensively studied by the writer, see Nagy and Watanabe [6], and the results will be summarized in the following two sections.

2.1. Effective shear stress in vegetated channel

The motion of sand particles is under the interaction of two opposing groups of forces: the hydrodynamic applied forces, and the resistance force that is associated with the submerged weight. The existence of vegetation in the bottom significantly reduces the applied forces because of the drag resistance. In the same time, it increases the resistance because of suppressing the turbulent motion as been proved in Nagy and Watanabe [7]. The force balance equation may be represented by

$$\rho g h I_e = \rho u_{*e}^2 + \frac{1}{2} \rho U^2 C_D D h \frac{1}{S^2}, \qquad (1)$$

where ρ is the water density, h is the water depth, I_e is the energy slope at the same cross-section, and U is the mean velocity of flow. The coefficient C_D is the drag coefficient for a cylindrical body, which may be obtained from the well-known curve that relating drag coefficient C_D with the Reynolds number $R_e = UD/\nu$, where ν denotes the fluid kinematic viscosity. Based on the measured data of experiments, the total dimensionless tractive stress, $\Psi = u_*^2 / sgd_{50}$, is calculated, where $u_* = \sqrt{ghI_e}$. The effective dimensionless shear stress for grain roughness, $\Psi_e = u_{*e}^2 / sgd_{50}$, can be obtained by using eq. (1), where u_{*e} is the shear velocity referring to grains.

Nagy and Watanabe [6] studied the ratio of effective shear stress, ψ_e, to the tractive stress, ψ, through experimental work on vegetated movable bed and non-uniform flow conditions. The study proved that the increase of Reynolds number of particles, $R_{*e} = u_{*e} d_{50} / \nu$, increases that ratio, and increasing vegetation density decreases its value. A regression analysis was done for relating the most effective parameters. The following expression was obtained:

$$\eta = \frac{\psi_e}{\psi} = \ln\left(0.65557 \frac{R_{*e}^{0.15131} \, (D/d_{50})^{0.05719}}{(h/d_{50})^{0.111} \; \lambda^{0.043}}\right). \qquad (2)$$

2. 2. Critical shear stress in vegetated channel

The incipient motion for movable bed is considered one of the important chapters in the sediment transport science. Shields diagram which relates between Reynolds number for particles, R_{*e}, and dimensionless tractive shear stress, gives the boundary or the critical limit for sand particles movement for different flow conditions. The critical shear stress parameter, ψ_c, is the cornerstone for sediment discharge calculations, and it is mainly depending on the particle size. The turbulence level near bed is one of the important factors affecting on the threshold

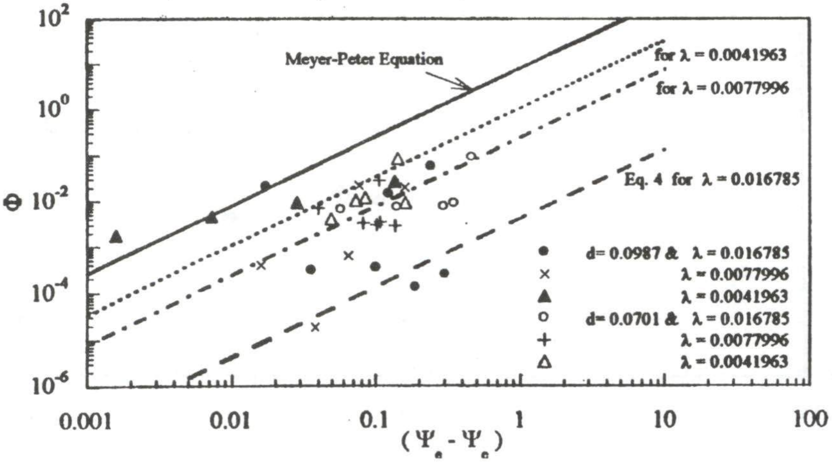

Fig. 4. Effect of vegetation density on bed load function.

motion of particles. For vegetated channels, the existence of vegetation suppresses the turbulence level near bed, which in turn causes the lag to the particles movement even the flow and sediment conditions are the same as in non-vegetated channel, see Nagy-Watanabe [7]. Nagy and Watanabe [6] presented a chart and an equation for calculating the critical shear stress in the bottom of vegetated channel considering the vegetation density as follows:

$$\psi_c = e^{42\lambda}\left[\frac{0.106}{R_{*e}} + 0.055\left(1 - e^{-0.16\sqrt{R_{*e}}}\right)\right]. \quad (3)$$

2.3. Sediment discharge formulation

A relation between sediment discharge Φ and the expression $(\Psi_e - \Psi_c)$ with vegetation density parameter, λ is shown in fig. 4. In the same graph the results are compared with the curve simulating the equation of Meyer-Peter et al., see Yang [8]. In the figure, despite the scatter of experimental data, it is clear that the increase of shear stress causes increase in sediment discharge value, same as Meyer-Peter curve. For the same value of shear stress, the bed load discharge in vegetated channel is less than in channel without vegetation. Also, for channels with high density of vegetation, it needs a higher tractive shear stress than the low density of vegetation to get the same sediment discharge. A modified expression for Meyer-Peter formula considering both the vegetation density and the critical shear stress calculated by eq. (3), is presented in the following form

$$\Phi = 8\, e^{-450\lambda}\, (\Psi_e - \Psi_c)^{3/2}. \quad (4)$$

3. Determination of scour rate

When shear stress in the bottom of channel exceeds the critical stress due to clear water discharges, sand particles start to move, and uniform discharge of bed load is produced and the balance of sediment load has to come from the channel itself. After long period, the channel starts to degrade, the non-equilibrium state of sediment transport takes place and the general scour criterion is developed. The experiments aimed to investigate the rate of scour under several flow and sediment conditions considering the vegetation density. From the measurements, the difference between the bed patterns before and after experiment gives the volume of detached sand. Knowing the time passed during experiments and the planner area, allows calculating the values of scour rate $\partial S_r/\partial t$ in several cross sections in cm per second.

$$\frac{\partial S_r}{\partial t} = \frac{V_s}{A_p \times T}\ , \quad (5)$$

where V_s is the cut minus fill volume within a certain strip in cm³, A_p is the area planner of

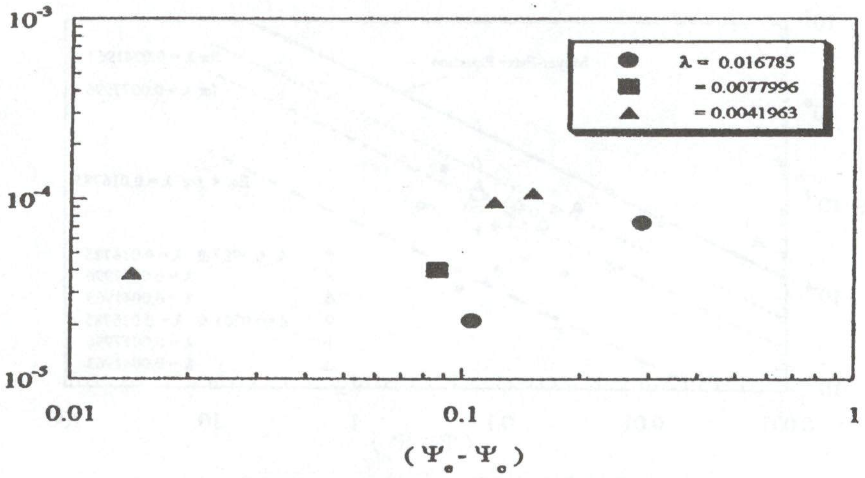

Fig. 5. Effect of vegetation density on scour rate.

that strip in cm², and T is the time of experiment in seconds. Fig. 5 shows the relation between the effective dimensionless shear stress and the dimensionless scour rate S_r^*, where $S_r^* = \frac{\partial S_r}{\partial t} / u_{*c}$, where u_{*c} is the critical shear velocity. It is noticed from the graph that the scour rate increases with the increase of effective shear stress, and the increase of vegetation density decreases the scour rate values.

4. Conclusions

Bed load discharge values in vegetated channels are not the same as the values of non-vegetated channel. A relation between sediment discharge and tractive shear stress is well clarified. The effect of vegetation density on bed load quantity is illustrated. A comparison with Meyer-Peter formula of bed load discharge is done. A new expression for calculating sediment discharge considering vegetation density is presented. Similarly, the scour rate in vegetated channels passing clear water discharges is studied. Increasing vegetation density has a noticeable effect on decreasing the scour rate values.

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