TRACTIVE SHEAR STRESS IN CHANNELS WITH RIGID VEGETATION

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ABSTRACT

The tractive shear stress in a movable bed of open channels covered with non-submerged rigid vegetation is investigated through experimental and numerical study. The experiments are conducted on non-uniform flow over movable sand bed with uniform particles. The total stress as well as tractive shear stresses are obtained from experimental results. The threshold movement of particles is experimentally observed wherein the flow characteristics are measured. A relation between total (apparent) shear stress and tractive shear stress within vegetation zone is developed based on the measuring data. The effect of vegetation density on the critical shear stress values is clarified. A finite difference algorithm is applied to solve a two-dimensional mathematical model depending on conservation of mass and momentum equations for depth-averaged flow. A comparison had been done between numerical and experimental results for water surface profile, total and drag stresses, and bed tractive shear stress along the simulated flume. The verification shows a good agreement.

Keywords: Vegetated channel flow, Movable bed, Tractive shear stress, Threshold motion, Critical shear stress.

INTRODUCTION

The existence of vegetation in natural streams plays a major role in the environment of the flowing water. Also, 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 intrinsic relationship between the total apparent shearing force and the tractive force on bed with vegetation is not revealed yet. Moreover, the major parameters affecting on the threshold motion of uniform sediment on a flat bed can be summarized in two dimensionless parameters; critical Shields stress, and particles Reynolds number. For vegetated bed, the vegetation density parameter should be taken into consideration.

In this study, an experimental work has been carried out. A relation between total (apparent) shear stress and tractive shear stress for bed roughness is developed based on the experimental results. The threshold motion of sediments in the bed covered by non-submerged rigid vegetation is observed at a specific section wherein the flow characteristics are measured. The density of vegetation effect is considered in the analysis. A numerical simulation is presented for non-uniform flow over vegetated bed. A comparison between both numerical and experimental models leads to a conclusion that the developed numerical simulation model is good enough to describe the flow and sediment characteristics in vegetated channels.

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FLUME EXPERIMENTS

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 0.3 cm and height of 25 cm over area of 0.4 x 6.8 m in spanwise, z, and streamwise, x, respectively. The sticks were arranged in staggered shape on the sand bed. Figure 1 shows a typical sketch of the experimental flume, and Figure 2 shows the arrangement of sticks. The spacing S is taken equal to 2.12, 3.11, and 4.24 cm, respectively. Sand bed material was uniform with particle diameter of 0.1291 cm. The length of sand bed was 9.8 m, as shown in Figure 1. At the tail end, water level was adjusted by vertical sliding gate. Non-uniform flow was allowed with several discharges Q, and bed slope i_b.

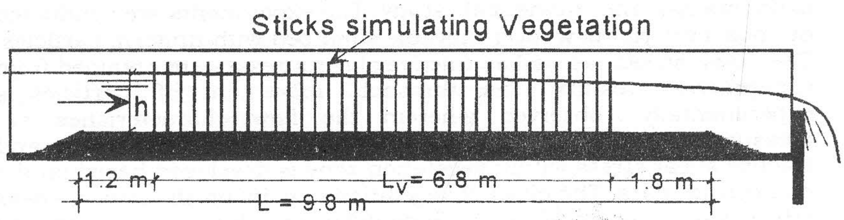

Figure 1 Typical sketch of simulating vegetation in a flume

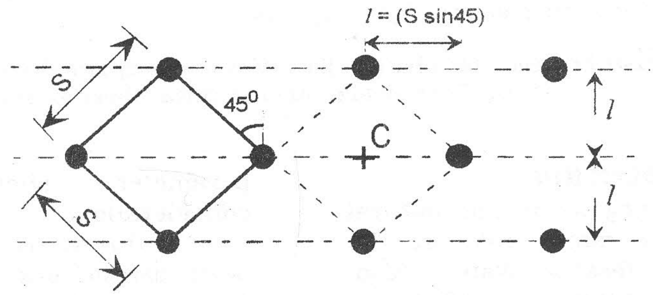

Figure 2 Arrangement of bamboo sticks simulating vegetation

Water levels along the channel were measured by using a point gauge. Magnetic currentmeter is used to measure two dimensional velocity distribution in several cross sections along the flume with cell size 25 x 5 cm. The threshold motion of sand particles was visualized and its location as well as the associated water depth were recorded. Experimental conditions and observations made are given in Table 1, where $\lambda = \pi D^2 / 4S^2$ is the vegetation density, S is the spacing between sticks, D is the diameter of one stick, h_c is the water depth at the threshold movement section. The parameter $\psi_c = u_{*c}^2 \; sgd$ is the dimensionless critical shear stress, where u_{*c} is the critical shear velocity, g is the gravitational acceleration, s = 1.65 is the specific gravity of particles, and d is the sand particles diameter.

Table 1 Experimental conditions

Run	i_b	Q (cm³/se)	λ	H_c (cm)	ψ_c
1	1/100	9551	0.01572	10.6	0.1814
2	1/100	12361	0.01572	13.6	0.2802
3	1/100	15617	0.01572	17.8	0.1284
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

TRACTIVE SHEAR STRESS

In a flowing stream, the motion of sand particles is under the interaction of two opposing groups of forces: The hydrodynamics applied forces, and the resistance force which is associated with the submerged weight. Flow turbulence near the bed also has a significant effect on the incipient motion of such particles. 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 near bed. The fundamental force balance equation may be represented by

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

where I_e is the energy gradient, ρ is the clear water density, h is the water depth, and U is the mean velocity of flow. The coefficient C_D is the drag coefficient for cylindrical bodies, which may be obtained from the well-known curve that relating drag coefficient C_D with Reynolds number $R_e = UD\nu$, where ν denotes the fluid kinematic viscosity. The parameter u_{*e} is the effective bed shear velocity. The energy slope I_e can be calculated from bed slope and water surface slope I_b by using the following equation

$$I_e = I_h + (i_b - I_h)\frac{U^2}{gh} \qquad (2)$$

Based the measured data of experiments, the total dimensionless shear stress, $\psi = u_*^2/\sqrt{sgd}$, is calculated, where $u_* = \sqrt{ghI_e}$. Based on Equation 1, the effective dimensionless shear stress for bed roughness, $\psi_e = u_{*e}^2/\sqrt{sgd}$, is obtained. Figure 3 shows the analysis of experimental results as a relation between ψ and ψ_g. This relation seems to figure the shape of the sigmoid function. The constants of the function are adjusted to fit with the obtained data. The final form of the equation is,

$$\psi_e = \frac{1}{2.2 + 95e^{(-3.55\psi)}} \qquad (3)$$

This relation is very useful for estimating the tractive shear stress in bed with rigid vegetation directly by using the measured values of water depth h, and energy slope I_e

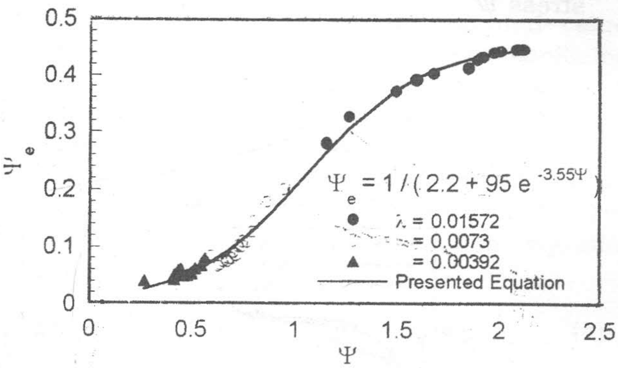

Figure 3 Relation between ψ and ψ_e in vegetated channel

CRITICAL SHEAR STRESS

In each run, the threshold movement of sand particles is observed at its specific section along the channel. By using the proceeding Equation 1 and the experimental data at that section, the critical shear velocity u_{*c} is calculated. In Figure 4, a relation between the dimensionless critical shear stress parameter $\psi_c = u_{*c}^2 / sgd$ and the Reynolds number for particles $R_{n*} = u_{*c} \, d / \nu$ are obtained. In the figure, the results are compared with Shields curve for critical shear stress. Both vegetation density and the Reynolds number for particles have a significant effect on increasing the tractive shear stress.

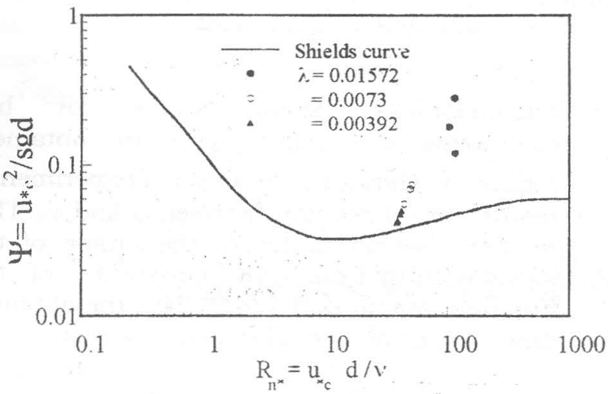

Figure 4 Effect of particles Reynolds number on ψ_c

The effect of the parameter representing vegetation density λ is clarified in Figure 5, where the abscissa is the vegetation density λ, and the ordinate is the critical shear stress ψ_c.

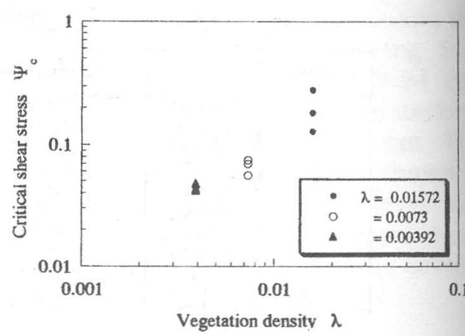

Figure 5 Effect of vegetation density on ψ_c

TURBULENT STRUCTURE OF FLOW OVER VEGETATED BED

It is fact that turbulence near bed has a great influence on particle movement. To elucidate the lag of particle motion within vegetation than over flat bed, two dimensional velocity measurements were carried out at the cross-section of incipient motion within vegetation at point C, see Figure 2. Figure 6 shows a comparison of velocity turbulence intensity components u', v' and Reynolds stress $\sqrt{|u'v'|}$ for three examples representing different vegetation density and the same discharge Q = 12361 cm^3/sec. In the figures, it is detected that turbulence has relatively low intensity near bed in all cases of vegetation, and flow with high density of vegetation has low turbulence values than flow with low density.

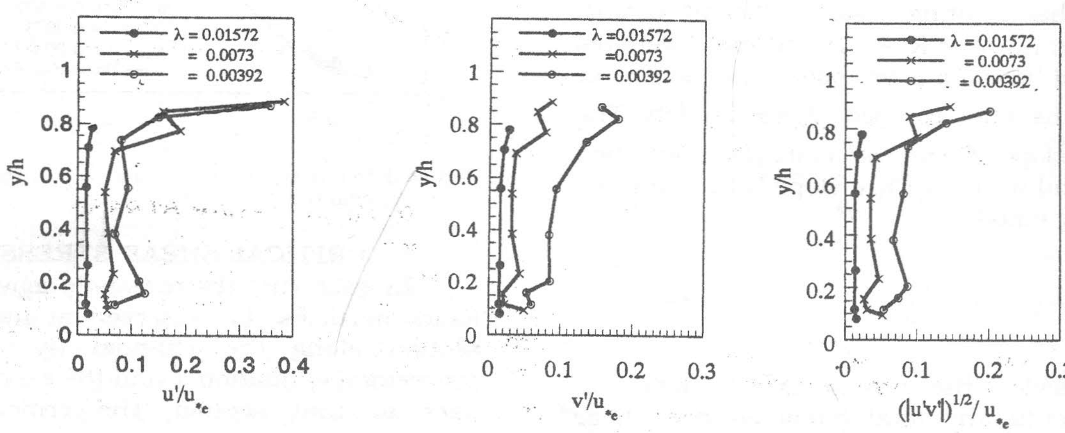

Figure 6 Distribution of flow turbulence within vegetation

Figure 7 shows that the ratio of transverse component of turbulence intensity v' to the longitudinal component u' decreases for high density of vegetation.

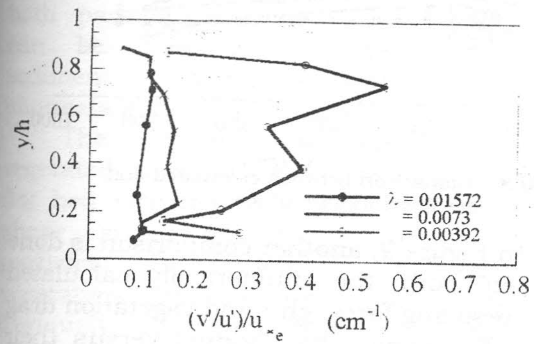

Figure 7 Ratio of turbulence components for different vegetation density

NUMERICAL ANALYSIS

The flow over vegetated bed is simulated by a mathematical model. Continuity and momentum equations for depth-averaged flow in two dimensions are presented. In vegetated zone, the effect of drag force due to existence of vegetation is taken into consideration during formulation.

Governing Equations

Two dimensional mass conservation equation is presented in the following form

$$\frac{\partial h}{\partial t} + \frac{\partial (hU)}{\partial x} + \frac{\partial (hV)}{\partial y} = 0 \tag{4}$$

in which t is the time, x and y are the streamwise and spanwise coordinates, respectively, U and V are the components of depth-averaged velocity in x and y directions, respectively, and h is the corresponding flow depth.

General form of two dimensional momentum conservation equations for flow in both directions x and y are presented as

$$\begin{aligned}&\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y}\\ &= g\,i_b - g\frac{\partial h}{\partial x} + \frac{1}{h}\frac{\partial}{\partial x}\left(2\upsilon_t\, h\,\frac{\partial U}{\partial x}\right)\\ &+ \frac{1}{h}\frac{\partial}{\partial y}\left\{\nu_t\, h\left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y}\right)\right\} - \frac{\tau_{bx}}{\rho h} - F_x\end{aligned} \tag{5}$$

$$\begin{aligned}&\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y}\\ &= -g\frac{\partial h}{\partial y} + \frac{1}{h}\frac{\partial}{\partial y}\left(2\upsilon_t\, h\,\frac{\partial V}{\partial y}\right) +\\ &\frac{1}{h}\frac{\partial}{\partial x}\left\{\nu_t\, h\left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y}\right)\right\} - \frac{\tau_{by}}{\rho h} - F_y\end{aligned} \tag{6}$$

in which v_t is the eddy kinematic viscosity = $(\kappa\ 6)u_* h$, κ is Karman constant ≈ 0.4, and u_* is the shear velocity which can be obtained from the following equation

$$u_*^2 = \frac{f}{8}(U^2 + V^2) \tag{7}$$

where f is Darcy-Weisbach friction factor which is equal to $8gn^2/h^{1/3}$.

In the numerical scheme, applying Manning coefficient as a friction factor of vegetated bed gave under-estimated values for bed shear stress. Hence, a new coefficient for bed roughness in vegetated channel is developed by using regression analysis for the obtained data from experiments. This coefficient is a function of vegetation density, the Reynolds number for flow and equivalent roughness ratio. The obtained equation yields,

$$f = 0.0035\,\frac{R_e^{2.3}\ \lambda^{1.75}}{(h/k_s)^{2.5}} \tag{8}$$

where R_e is the Reynolds number Uh/ν and k_s is the equivalent bed roughness which is equal to sand particle diameter d. The parameters τ_{bx} and τ_{by} are the bed shear stresses which may be represented by roughness coefficient as follows:

$$\left(\frac{\tau_{bx}}{\rho}, \frac{\tau_{by}}{\rho}\right) = \frac{f}{8}(U, V)\sqrt{U^2 + V^2} \tag{9}$$

The parameters F_x and F_y representing the drag forces can be related to vegetation density λ by the following equation

$$(F_x, F_y) = \frac{1}{2} C_D \lambda_1 (U, V) \sqrt{U^2 + V^2} \qquad (10)$$

where $\lambda_1 = Dh/S^2h = D/S^2$ is the projected area of the plants per unit volume of water, and C_D is the drag coefficient which is related to the Reynolds number R_e, and may be obtained from the well-known curve that relating drag coefficient C_D with Reynolds number for cylindrical bodies.

Numerical Procedure

The presented equations are solved by using finite difference method. The utilized scheme is the explicit staggered grid scheme, which is named Leapfrog scheme, Ito [3]. The grid mesh size is $\Delta x = 0.01$m and $\Delta y = 0.005$m. The channel length for simulation is $L = 8$ m in total; the lengths of the upstream non-vegetated part is 1.2 m, while the vegetated part is $L_v = 6.8$ m. The boundary conditions are the unit discharge q at $x = 0$, the water depth h at x = 8 m, and the slip condition of velocity at the side walls. The friction coefficient and the drag coefficient are obtained from iteration technique. The obtained results are the water surface profile along the channel, the depth average velocity in two directions, the total resisting force, the drag force, and the tractive shear stress along the channel. A typical computer run required 6~7 hours of CPU time on a personal electronic computer with speed of 500 MHz.

COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

The calculated results for water surface profile along the channel are compared with measured results in Fig. 8. In the figure, the abscissa is the longitudinal distance in the channel, x from upstream to downstream. The ordinate is the corresponding water depth, h. A good agreement is noticed between the predicted water levels and the observed data.

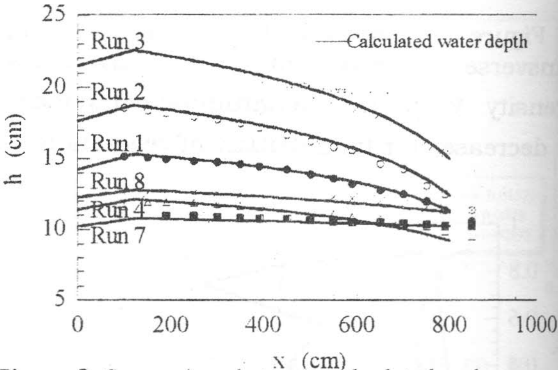

Figure 8 Comparison between calculated and measured water surface

In Figure 9, another comparison is done between both the numerically calculated total resisting force, ghI_e and vegetation drag force, F_x along the channel versus their corresponding measured values for three examples of vegetation density. Figure 10 shows the agreement between numerically calculated and experimentally obtained tractive shear stress ψ_e for three runs of one case of vegetation density. The comparison gives a good agreement.

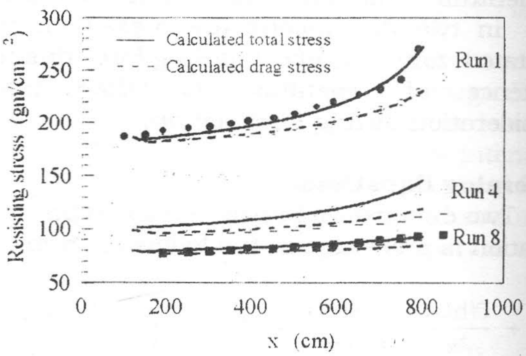

Figure 9 Comparison between numerical and experimental resisting forces

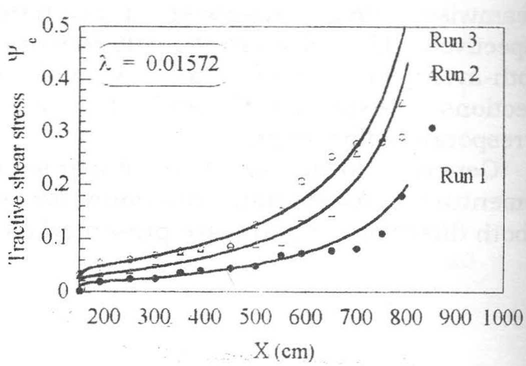

Figure 10 Comparison between numerical and experimental values of ψ_c

CONCLUSIONS

A flume experiments were carried out to examine flow over vegetated bed. The obtained results are used to calculate the total resisting forces and to estimate the bed tractive shear stress. The relation between both parameters is formulated. This formula can be used for the determination of sediment discharge within vegetated channels in further studies.

The critical shear stress values in vegetated streams are not the same values of flat bed streams. A relation between critical shear stress and Reynolds number for particles is presented. The effect of vegetation density on that relation is obviously illustrated. More experiments are strongly needed to complete the study of the change in critical shear stress for a wide range of Reynolds number values and vegetation density.

A numerical model, based on the fluid dynamics equations for non-uniform two-dimensional flow, is presented. The results showed that, this model is a powerful tool to estimate the surface water levels, mean cross sectional velocity, drag force due to existence of vegetation and tractive bed shear stress along the channel.

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إجهاد القص الإحتكاكى فى القنوات المائية المحتوية على حشائش جاسئة

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ملخص البحث

فى هذا البحث تم دراسة إجهاد القص الإحتكاكى فى قاع القنوات ذات التربة القابلة للحركة والمغطاة بحشائش جاسئة وغير مغمورة، وذلك من خلال دراسة معملية ورياضية عددية. تمت الاختبارات المعملية على الجريان غير المنتظم فوق تربية رملية قابلة للحركة قطر حبيباتها منتظم. ومن خلال النتائج المعملية تم الحصول على الجهد الكلى لمقاومة الجريان وكذلك جهد القص الإحتكاكى. ومن النقاط التى درست أيضا بداية حركة الحبيبات، حيث تم ملاحظتها معمليا وتحديد القطاع العرضى فى الترعة عند مكان حدوثها، كما تم دراسة خصائص الجريان عند هذا القطاع.

من النتائج المعملية تم عمل تحليل للبيانات واستنتاج علاقة تربط بين الاجهاد الكلى لمقاومة الجريان واجهاد القص الإحتكاكى فى منطقة الحشائش الجاسئة. وتم توضيح تأثير كثافة الحشائش المتواجدة على اجهاد القص الإحتكاكى الحرج.

وفى الجزء الثانى من هذا البحث إستخدمت الطريقة الرياضية العددية المعروفة باسم "الفروق المحدودة" لحل نموذج ريلضى فى اتجاهين y,x . هذا النموذج معادلاته الاساسية هى معادلة الاستمرار ومعادلة كمية الحركة للجريان ذو العمق المتوسط وقد تم عمل مقارنة بين النتائج النظرية والمعملية وذلك لشكل سطح الماء، والمقاومة الكلية للجريان ومقاومة السحب وكذلك اجهاد القص الاحتكاكى بطول الترعة الممثلة وقد أظهرت المقارنة إتفاق تام وجيد بين النتائج النظرية والمعملية