Boundary shear and incipient motion of sediment in streams with long vegetation

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The incipient motion in the bottom of streams covered with rigid vegetation is extensively investigated. Three patterns of uniform size bed material are experimentally studied. Two types of flume experiments are carried out for non-uniform and uniform flow conditions, respectively. Three densities of long non-submerged vegetation plants are alternatively simulated and arranged in staggered shape along the experimental flume bed. Parametric study for boundary tractive shear stress in vegetated channel is presented. The state of incipient motion is reached in several experiments wherein measurements are taken. The collected data for incipient motion are analyzed according to the Shields diagram for critical boundary shear stress. A modified Shields diagram for incipient motion of bed sediments is obtained. The effect of vegetation density on incipient motion is clarified. Analytical expression for critical boundary shear stress considering the vegetation density is presented.

فى هذا البحث تم دراسة جهد القص الإحتكاكى و بداية الحركة لحبيبات التربة فى قاع الأنهار المحتوية على سيقان جاسئة لنباتات طويلة. تمت الاختبارات المعملية فى ترعة طولها ٢٠ متر و عرضها ٠,٤ متر. و قد أجريت التجارب على ثلاثة أنواع من الرمل المنتظم التدرج. و بالنسبة لسيقان النباتات الطويلة فقد تم تمثيلها بمجموعة من أعواد خشب البامبو المستديرة ذات سمك ٣,١ مليمتر، و قد تم غرزها فى الرمل فى ترتيب تبادلى. و قد تم دراسة أهم المتغيرات المؤثرة فى نسبة جهد القص الإحتكاكى الى الجهد الكلى الناشئ عن الجريان. و قد أثبتت التجارب أنه كلما زادت كثافة الحشائش قلت نسبة القص الإحتكاكى. أما بالنسبة الى بداية حركة الحبيبات فقد إتضح من توقيع البيانات أن القيم الحدية لجهد القص الحرج أعلى من القيم المعروفة فى منحنى شيلدز. و أهم نتائج البحث هو الحصول على دياجرام معدل يشمل عدة منحنيات يعالج و جود الحشائش كل حسب كثافتها.

Keywords: Open channel flow, Vegetation, Boundary shear stress, Sediment transport, Incipient motion, Shields diagram.

1. Introduction

Incipient motion of sediment particles is often an interest subject for river engineers. Several realistic problems of sediment transport require the determination of critical velocity of bed material or the bed critical shear stress. Among of them, the estimation of sediment discharge, the determination of general scour rate, the design of stable channel, and the selection of the appropriate riprap size of bank or bottom protection.

When the streambed is composed of bed material with uniform size, and the flow is laminar, the only dominant factor is the time average velocity, or in other words, the time average shear stress. In case of fully developed turbulent flow, several variables may affect on the particle motion. Those variables may be summarized as follows:

1. The instantaneous bottom velocity of flow, which in turn is different from the average and causes pulsating values of the shearing force acting on particles. This has been proved by White (1940), see Vanoni [1].
2. The higher the turbulence intensity gives the cause for particle to move earlier than in case of low intensity condition. Raudkivi [2] reported that despite the fact that the mean shear stress and velocity are small near the stagnation point of a ripple, the longitudinal turbulence intensity is much larger than elsewhere on the ripple. This intense turbulence must cause the initiation of motion on rippled beds.
3. The coarser the particle size, the possibility of its crossing the viscous sublayer and reaching the turbulence

zone is high which in accordance accelerates its movement.

4. The orientation, composition and exposure effects to the coarse particles. On the other hand, the sheltering effect to the fine ones.

Several studies were presented for fully developed turbulent flow and artificially flattened beds of non-cohesive sediments. The main resulting criteria are derived from the shear stress approach or the velocity approach or the probabilistic approach. The first approach was adopted by Shields (1936), then followed by many investigators, among of them Rouse, White, Tison, Egiazaroff, Lane, Kramer, and Gessler, see Vanoni [1]. The velocity approach was first presented by Brahms (1753), then followed by others, among of them, Fortier and Scobey (1926), Hjulstrom (1935), and Yang (1973), see Yang[3]. The propapilistic approach was first presented by Einstein (1942), and then Gessler (1970), see Yang [3]. Another practical criteria were presented by Meyer-Peter and Muller (1948), Mavis and Laushey (1948), and U.S. Bureau of Reclamation (1987), see Yang [3]. Another workers, including Shields, White, Einstein and Barbarossa, and Sundborg, see Vanoni [1], show that the critical shear stress for given sediment is larger when the bed is dune-covered than when it is flat.

It is proved through several studies that Shields diagram can give good estimates for critical shear velocity for different bed and flow conditions. Shields presented his analysis through the well-known Shields parameters representing critical boundary Reynolds number and dimensionless critical shear stress. A modified Shields diagram was presented by Govers (1987) in accordance with Yalin and Karahan (1979), see Yang [3]. Also, Shields diagram was converted into a group of expressions by Iwagaki [4], and Yassin [5]. Wang et al. [6] summarize in their paper several studies done by others as well as themselves to modify Shields diagram for large and small particles, for laminar flow, and for flow under wave motion.

In case of bed covered with rigid vegetation, the threshold motion of particles has not been studied yet. Investigating the incipient sediment motion in vegetated streams has a particular interest in this study. Here, it is assumed that the existence of rigid vegetation in the flow field not only gives form resistance to the total applied force but also affects the flow structure. The existence of vegetation sticks suppresses the turbulence level in the flow near the bottom. Measurements for vertical velocity distribution inside vegetation zone show a decrease in turbulence level as well as its intensity with the increase of vegetation density, Nagy and Watanabe[7]. Consequently, there should be a visible effect on the incipient motion criterion.

An experimental study is carried out for two years examining three sizes of sand grains. As for the flow conditions, two groups of non-uniform and uniform experiments are conducted, respectively. Also, three groups of vegetation densities are simulated, respectively. In each run, the incipient motion condition is fulfilled and the hydraulic measurements are taken.

Fundamental force balance equation is utilized to calculate the effective and critical shear stresses. A parametric study is done for understanding the variables affecting on the ratio of boundary tractive stress to total applied stress, and to study the influence of vegetation density on that ratio. As for incipient motion, the obtained data are plotted comparatively with the Shields curve in one diagram. A modified diagram is obtained. The effect of vegetation density is illustrated as well. Finally, for calculation and programming computations, an analytical expression for the modified Shields diagram is presented including the vegetation density effect.

2. Experimental flume

The experiments are conducted in a tilting rectangular flume in the Hydraulics Laboratory at Saga University. The flume could be set at any slope between 0% and 3.33%. The flume has 0.4 m steel bottom width and Plexiglas walls of 20 m length and 0.4 m height. The disturbances due to the inlet transition are eliminated through the use of sheets of thick woven filters. At the flume end, there are two steel gates; one is a watertight vertical sliding gate to preserve the water in the flume to a certain level before starting, the other is a tilting steel gate, which is used to adjust the water level during experiments. Fig.1. is the schematic diagram of the flume.

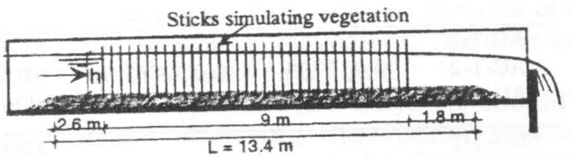

Fig. 1. Typical sketch simulating vegeation in a flume.

The bed material was selected as uniform natural quartz sand with grain diameters d_{50} of 0.1291, 0.09875, and 0.0701 cm, respectively. Before experiments, sieve analysis was done for five random samples of each size. The average was taken for each grain size, respectively. The design diameter d_{50} and geometric standard deviation σ_g are shown in Fig. 2. From a hydraulic point of view each type of sand is considered uniform since $\sigma_g < 1.5$. In each run the sand was placed on the flume bottom over a length of 13.4 m forming a depth of 6 cm mobile bed.

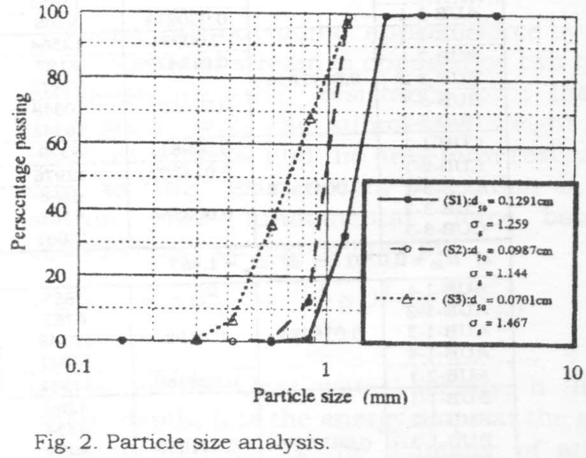

Fig. 2. Particle size analysis.

Rigid vegetation was simulated by woody cylindrical bamboo sticks with diameter D of 0.31 cm. The sticks tips were plunged into the sand bed and arranged in staggered shape for total distance of 9 m for non-uniform flow and 6.8 m for uniform flow experiments. The sticks were arranged in three different scales for spacing: 2.12, 3.11, and 4.24 cm, respectively, as shown in Fig. 3. The following procedures are followed for each run: Before starting, the 6 cm thickness of sand was scraped to a flat surface with scraper blade mounted on a carriage, which travels mechanically on rails over the channel. The woody sticks are fixed to the bottom of the flume in staggered arrangement, a photograph of the sticks are shown in Fig. 4. The longitudinal slope is adjusted, and then the flume is filled with water to a certain level.

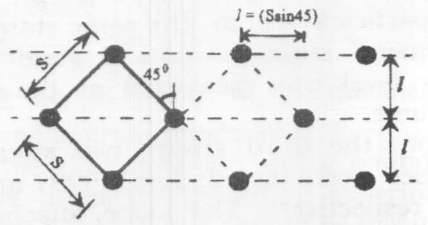

Fig. 3. Arrangement of vegetation sticks.

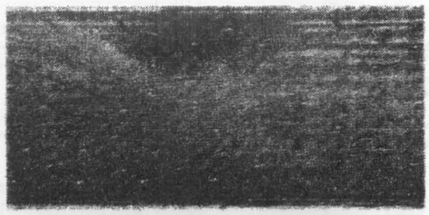

Fig. 4. Sticks simulating vegetation (S=3cm)

Three groups for experiments are done: series (A) for non-uniform flow, series (B) for uniform flow without bed load discharge and contains some cases of critical shear stress conditions, and series (C) for uniform flow with bed load discharge. The experimental conditions are shown in Tables 1, 2 and 3. Where λ is vegetation density, and Io the bed longitudinal slope.

For the first group, the three sizes of sand particles were tested. The non-uniform flow was allowed to pass in each run with several discharges, Q. The discharge value was observed on scaled manometeric tube connected with a channel has pre-calibrated V-notch and located over the upstream of the flume. The water depth along the flume was adjusted by the tilting gate. Only downward curve was allowed for the water surface profile. Since the flow has variant depths along the flume, there should be a critical cross section wherein its upstream side bed has no movement, while its downstream side has a movable bed. This section is judged as the location of incipient motion. Water levels along the flume were measured at its side wall with an interval of 10 cm.

For the second group, only the sand of d_{50} = 0.0987 cm is tested. In each run, uniform flow condition was reached by the consequent control of the slope, discharge and water depth. Since the flow is uniform, the whole bed particles are in the same state either no movement state or critical state condition. Water level was measured at the sidewall of the flume.

For the third group, two sizes of sand particles were tested: d_{50}= 0.0987 and 0.0701 cm, respectively. The slope, discharge, and water depth were adjusted to give uniform flow condition and sediment was allowed to move.

Table 1 Conditions of non-uniform flow experiments

Index	λ	I_0	Q (cm³/s)
1 : d_{50}= 0.1291 cm & σ_g= 1.259			
A-1-1			9551
A-1-2	0.016785	0.01	12361
A-1-3			15617
B-1-1			9551
B-1-2	0.0077996	0.0067	12361
B-1-3			12976
C-1-1			9551
C-1-2	0.0041963	0.005	12361
C-1-3			12976
2 : d_{50}= 0.0987 cm & σ_g = 1.144			
A-2-1			8791
A-2-2	0.016785	0.01	10078
A-2-3			11862
B-2-1			9040
B-2-2	0.0077996	0.005	9379
B-2-3			10808
C-2-1			8546
C-2-2	0.0041963	0.0025	10168
C-2-3			10996
3 : d_{50}= 0.0701 cm & σ_g = 1.467			
A-3-1			8385
A-3-2	0.016785	0.01	9551
A-3-3			10996
B-3-1			8385
B-3-2	0.0077996	0.005	9208
B-3-3			9551
C-3-1			7608
C-3-2	0.0041963	0.0025	8385
C-3-3			8627

Table 2 Conditions for uniform flow experiments

Index	λ	I_0	Q (cm³/s)
2: d_{50}= 0.0987 cm & σ_g = 1.144			
AU-1-1			5175
AU-1-2	0.016785	0.016471	8709
AU-1-3			12061
BU-1-1			3956
BU-1-2			7913
BU-1-3	0.0077996	0.009933	12564
BU-1-4			15157
CU-1-1		0.004878	6664
CU-2-1			4323
CU-2-2	0.0041963		6947
CU-2-3		0.006444	8546
CU-2-4			10168
CU-2-5			11764

Table 3 Conditions for uniform flow experiments (with sediment movement-no critical shear stress).

Index	λ	I_0	Q (cm³/s)
1) d_{50} = 0.0987 cm & σ_g = 1.144			
AUB-1-1			4486
AUB-1-2		0.023514	6734
AUB-1-3			12462
AUB-2-1			4269
AUB-2-2	0.016785		6664
AUB-2-3		0.02	9551
AUB-2-4			12021
AUB-2-5			15851
AUB-3-1		0.030833	9208
BUB-1-1		0.00993	12564
BUB-2-1		0.012429	6187
BUB-2-2	0.0077996		12872
BUB-3-1		0.016533	10348
BUB-3-2			16342
CUB-1-1		0.009811	9379
CUB-2-1		0.014302	12976
CUB-3-1	0.0041963		6664
CUB-3-2		0.008364	8385
CUB-3-3			12061
2) d_{50} = 0.0701 cm & σ_g = 1.467			
AUB-1-1			3855
AUB-1-2			6762
AUB-1-3	0.016785	0.0198	10348
AUB-1-4			14041
AUB-2-1		0.028169	11961
BUB-1-1			4269
BUB-1-2			6254
BUB-1-3	0.0077996	0.011053	9074
BUB-1-4			11627
BUB-1-5			14260
BUB-2-1		0.014269	10623
CUB-1-1			5604
CUB-1-2			7608
CUB-1-3	0.0041963	0.008235	11280
CUB-1-4			13673
CUB-2-1		0.0125	11090

The procedures taken to defined the section of incipient motion are:

1. The sand grains that should be observed are the yellow uniform size ones.
2. The observation should be in large area of a sediment bed between two raw of sticks for the critical movement. The area around sticks should be ignored.
3. A short period (few minutes) should pass before observing the criterion because the first movement will be for the small size and light particles. On the contrary, the delay in time is not acceptable because of effect of changing water depth and armoring process as well.
4. What should be observed is the grains of mean diameter in the area which are in motion in numbers too large to be countable, and the rest of grains still have unstable feature. The removed particles from scour holes around sticks should not be taken into consideration.
5. In case of uniform flow condition, additional quantitative evident should be taken that the grains movement should not produce any sediment discharge at the end of the flume.

4. Theoretical considerations

The hydrodynamic applied force by flow in a vegetated stream is opposed by two types of resistance; the resistance force that is associated with the submerged weight and grain roughness, and the drag form resistance due to the existence of vegetation in the stream. The fundamental 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 $\rho$is the clear water density, h is the water depth, I_e is the energy slope at the same cross-section, D is the diameter of sticks-simulating vegetation, S is the spacing between sticks, g is the gravitational acceleration, and U is the mean velocity of flow. The coefficient C_D is the drag coefficient for a cylindrical body that may be obtained from the well-known curve relating drag coefficient C_D with the Reynolds number R_e $=UD/\nu$, where ν is the fluid kinematic viscosity.

Based on the measured data, the total dimensionless shear stress, $\Psi = u_*^2 / sgd_{50}$, is calculated, where $u_* = \sqrt{ghI_e}$, and s = 1.65 is the specific gravity of particles. The dimensionless boundary shear stress for grain roughness, $\Psi_e = u_{*e}^2 / sgd_{50}$, is obtained by using Eq. 1, where u_{*e} is the shear velocity referred to grain roughness.

For the determination of the boundary shear stress from the preceding experiments, the following procedures should be followed:

In non-uniform flow experiments, from the recorded water levels and the bed slope, the energy slope was calculated for the whole length of vegetation zone with interval of 50 cm. Consequently, the total dimensionless shear stress Ψ , and the tractive shear stress Ψ_e are calculated for every point by using Eq. 1. For uniform flow experiments, since the water depth is constant, every run provides a single value for Ψ and Ψ_e as well. The total number of data points for the three groups are 514 points.

5. Parametric study on the boundary shear stress ratio

The interest here is to get the tractive shear stress Ψ_e as a ratio of the total applied stress Ψ, and to perform a parametric study for the dominant variables affecting on this ratio. The presented force balance equation

Table 4 Range of calculated data variables obtained from the experiments.

Ψ_e / Ψ	$u_{*e} d_{50} / \nu$	h/d_{50}	λ	D/d_{50}
0.046 ~ 0.4	12.57 ~ 147.27	18.126 ~ 251.87	0.0041963 ~ 0.016785	2.4 ~ 4.42

allows us to determine the value of tractive shear stress, however it can not explicitly afford the parameters affecting on its ratio to the total stress. Major variables that are in relation with that ratio are h, d_{50}, ρ, ρ_s, ν, g, D, S, u_* and u_{*e}, where ρ_s is the density of the particles. The dimensional analysis yields

$$\frac{\Psi_e}{\Psi} = f\left(\frac{u_{*e}\, d_{50}}{\nu}, \frac{\rho_s}{\rho}, \frac{h}{d_{50}}, \frac{\pi D^2/4}{S^2}, \frac{D}{d_{50}}\right). \quad (2)$$

Practically speaking, the value of ρ_s / ρ is constant and its influence can be included in the coefficient of the final equation. Then the relation takes the form

$$\frac{\Psi_e}{\Psi} = f\left(\frac{u_{*e}\, d_{50}}{\nu}, \frac{h}{d_{50}}, \frac{\pi D^2/4}{S^2}, \frac{D}{d_{50}}\right). \quad (3)$$

Each variable in the right term has its physical meaning; the first variable is the Reynolds number of particles R_{*e}, the second is the roughness parameter h/d_{50} related to water depth, the third is the vegetation density in unit area λ, and the last one is the roughness parameter related to the size of vegetation unit element D/d_{50}. The range of experimental data for the variables of Eq. (3) is shown in Table 4.

Figure 5 shows the relation between the Reynolds number of particles R_{*e} and the shear stress ratio Ψ_e / Ψ obtained from the experimental data from both uniform and non-uniform flow experiments. It can be noticed that the obtained data for R_{*e} fall in the two regions: transition boundary ($5<R_{*e}<70$), and rough boundary state ($70<R_{*e}<500$). Also, the shear stress ratio is proportionally increases with the increase of Reynolds number of particles.

A regression analysis is done for the five variables presented in Eq. (3) by using the available data from the three groups of experiments. A new expression is resulted in the following form

$$\frac{\Psi_e}{\Psi} = \ln\left(0.65557\ \frac{R_{*e}^{0.15131}\,(D/d_{50})^{0.305719}}{(h/d_{50})^{0.111}\ \lambda^{0.043}}\right). \quad (4)$$

Figure 6 shows the verification of Eq.(4) by plotting the values of the observed Ψ_e / Ψ versus the calculated ones from Eq.4. The verification shows a good agreement with standard error of the mean equal to 0.0045. In Fig. 7, the obtained Eq. (4) is applied to study the effect of vegetation density on shear stress ratio. The figure shows the relation between the shear stress ratio Ψ_e / Ψ and the Reynolds number of particles R_{*e} with parameter of vegetation density λ and considering a constant values for h/d_{50} = 100 and D/d_{50} = 3. It is clear from the figure that increasing vegetation density decreases the ratio of tractive shear stress for the same flow and sediment conditions. This may be due to the increase of the drag force.

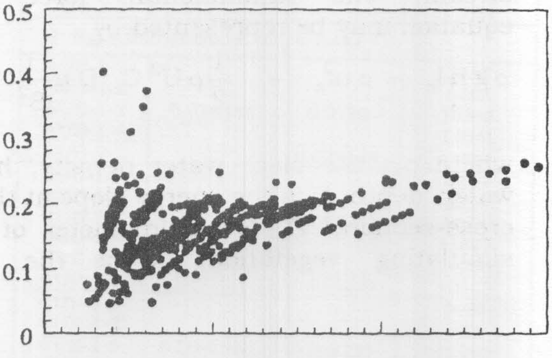

Fig. 5. Effect of reynolds number of particles .

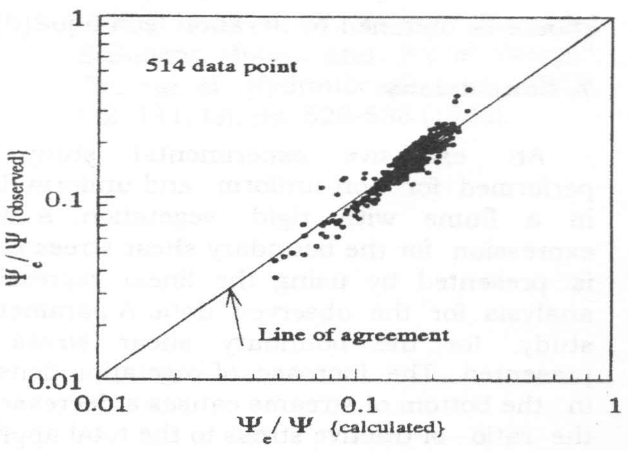

Fig. 6. Comparison of observed and calculated data for tractive stress ration.

6. Modified shields diagram for incipient motion

The early work that was done by Shields is considered a cornerstone for several studies on the initiation of motion of sediments. His diagram has gained a wide acceptance. According to his analysis, major variables that affect incipient motion of uniform sediment on a level bed include, the critical shear stress τ_c, the particle diameter d, the fluid density ρ, the different in specific weight between sediment and fluid $(\gamma_s - \gamma)$, and the kinematic viscosity ν. From dimensional analysis, they may be grouped into the following dimensionless parameters

$$\frac{\tau_c}{(\gamma_s - \gamma)d} = F\left(\frac{u_{*c}\,d}{\nu}\right), \tag{5}$$

where $u_{*c} = \sqrt{\tau_c / \rho}$ is the critical friction velocity. The left-hand side of this equation is the dimensionless critical shear stress Ψ_c. The right-hand side is called the critical boundary Reynolds number and is denoted by R_{*c}. The Shields diagram is obtained by plotting the experimental data for those two variables.

One important factor affecting on the threshold movement, however it is not mentioned in Shields analysis, is the turbulence level near the stream bottom. For flow within vegetation, it is noticed that there is lag in the initiation of motion for particles, i.e. the particle needs a higher shearing force to move than the case of no vegetation. This is because of the decrease of the near bed velocity and also the existence of vegetation suppresses the turbulent motion near bed, which in turn has a great influence on particle movement. Increasing vegetation density affects the fluctuation intensity near bed, as been illustrated by Nagy t l. 7], and consequently affects the critical shear stress.

In each run of non-uniform flow experiments, the threshold movement of sand particles is observed at one specific cross-section along the flume, and the water depth is measured at that section. For uniform flow experiments, in case of occurrence of incipient motion, all particles in the vegetation zone are in state of incipient motion. Using the preceding Eq. 1 and the experimental data, the critical shear velocity u_{*c} is calculated.

In Fig. 8, a relation between the dimensionless critical shear stress parameter $\Psi_c = u_{*c}^2 / sgd_{50}$ and the Reynolds number for particles $R_{*c} = u_{*c}\,d_{50} / \nu$ is depicted for several flow conditions in both non-uniform and uniform flow experiments and for three types of vegetation density as well. In the figure, the results are compared with the Shields curve for critical shear stress of leveled bed. From the figure, it is clear that both the vegetation density λ and the Reynolds number for particles R_{*c} have a significant effect on increasing the tractive shear stress than the common values of leveled bed.

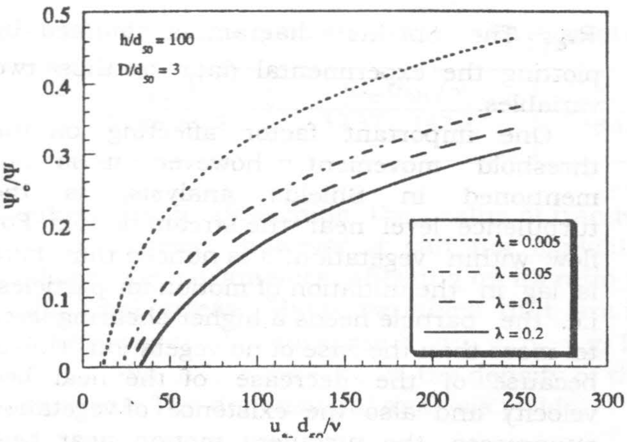

Fig. 7. Effect of vegetation density on shear stress ratio.

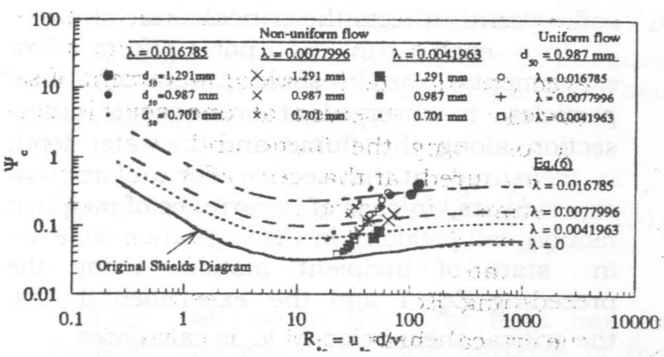

Fig. 8. Modified shields diagram for incipient motion of sediments.

For simplicity in computation, the depicted graph may be presented in a new analytical expression, which is obtained by statistical modeling of the data of the original Shields curve since it takes the analogous form of the well-known exponential decay function with initial value. The obtained expression may be presented as follows

$$\Psi_c = e^{c\,\lambda^{0.75}}\left[\frac{0.106}{R_{*c}} + 0.055\left(1 - e^{-0.16\sqrt{R_{*c}}}\right)\right]. \qquad (6)$$

The coefficient c has the range of (30 ~ 50) due to data scatter, and its average value is taken equal to 42. It should be notified that the obtained expression contains the critical shear stress Ψ_c as an implicit variable that should be obtained by iteration technique.

7. Conclusions

An extensive experimental study is performed for non-uniform and uniform flow in a flume with rigid vegetation. A new expression for the boundary shear stress ratio is presented by using the linear regression analysis for the observed data. A parametric study for the boundary shear stress is presented. The increase of vegetation density in the bottom of streams causes a decrease in the ratio of tractive stress to the total applied stress.

The critical shear stress values in vegetated streams are not the same values of non-vegetated bed streams. A modified Shields diagram for incipient motion in streams with rigid vegetation is obtained. For programming and calculations, a suitable expression for critical shear stress is presented. The obtained diagram for critical shear stress or the new expression will be groundwork for several problems such as the determination of sediment discharge and the scour rate in streams with vegetation in the feasible future.

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