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Shear stress estimation in the linear zone over impermeable and permeable beds in open channels

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ABSTRACT

This paper investigates the shear stresses in the linear zone of open channel flows with permeable and impermeable bed. The permeable bed is simulated using a flexible vegetation of 2 cm thickness. Laboratory experiments were used for the calculation of the turbulent velocity profiles. The measurements were obtained using a two-dimensional (2D) particle image velocimetry (PIV). This optical method of fluid visualization is used to obtain instantaneous velocity measurements related properties in the fluids. The PIV method assumes that the particles of a fluid faithfully follow the flow dynamics; hence the motion of these seeding particles is used to calculate the dynamic characteristics of the flow. The measurements were conducted at a $12 \times 10\ \mathrm{cm}^2$ region located 4 m away from the channel's entrance, where the flow is considered fully developed. The uniformity of the flow was checked measuring the flow depth at two cross-sections (2 m distance between the two regions). The total discharge was estimated using a calibrated venture apparatus. Measurements of velocity were taken for the horizontal channel slope. Results showed that the type of bed can significantly influence the shear stress definition in the linear zone.

Keywords: Linear zone; PIV; Turbulent flow; Shear stress; Experimental analysis

1. Introduction

The shear stress is an essential quantity to estimate in turbulent flows. Boundary shear stress in open channels is estimated based on observations of velocity across the flow geometry hence estimates the shear stress. Experimental measurements of velocity can provide a valuable contribution to understanding contaminant transport and the estimation of shear stress. Many investigators in river-related studies used an acoustic Doppler current profile to measure the velocity and determine the flow rate [1], turbulent characteristics [2], boundary shear stress [3], and additionally estimate local mean boundary shear

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stresses [4]. Velocity profiles are often used to determine viscous shear stresses in laminar zone. Several methods are available to determine the time-averaged local boundary shear stress [5–7] found following law of the wall for the turbulent flow over a porous bed, using a general expression for the shear stress (*uv*):

$$\frac{U}{U_*} = \frac{1}{\hat{e}} \ln\left(\frac{y + z_1}{z_1}\right) + \frac{U_{\text{int}}}{U_*} \tag{1}$$

where U_* is the shear velocity (equals (ghSo)1/2), $\kappa = 0.40$ is the von Karman constant, and z_1 is the coefficient dependent on porous characteristics. The application of the above equation is rather difficult since the interfacial velocity U_{int} and the von Karman constant must be known. The latter is not necessarily equal to 0.40 due to momentum transfer effects from the fluid to the porous region.

In study [8] a simple technique was presented that allows a numerical solution to be sought for the vertical variation of shear stress as a substitute for the vertical variation of velocity in a three-dimensional hydrodynamic model. The rationale for searching a solution for shear stress based on velocity is that shear stress tends to vary more slowly over the vertical than velocity, particularly near the boundaries [9]. propose a method that allows accurate estimates of the local wall shear stress from near wall mean velocity in fully developed pipe and channel flows. Direct numerically simulated were used to demonstrate the accuracy of the method and to provide the reliable requirements on the experimental data. To demonstrate the applicability of the method near the wall, Laser-Doppler Anemometer measurements in turbulent pipe and channel flows were performed. The authors concluded that the mean velocity data when normalized with the wall friction velocity are in excellent agreement with the available direct simulations at the corresponding Reynolds numbers [10]. propose a wall-function formulation applicable to any define-RANS turbulence model. The formulation is based on the assumption of wall layer universality, applied to the entire model. The approach is implemented using tables for the turbulence quantities and the friction velocity [11]. developed a transport model which showed that sediment transport rate is a function of bed-surface particle size instead of median particle size of the total sediment bed. The model is developed using a data-set of observations of flow, transport, and bed surface grain sizes of five different sediments. Finally [12] carried out particle image velocimetry (PIV) experiments over permeable bed. The authors concluded that the presence of permeable bed influence significant shear stress in the linear zone.

This study focuses on the estimation of the shear stress in the linear zone in open channel flows over permeable and impermeable beds. Laboratory experiments were used for the calculation of turbulent velocity profiles. The measurements were obtained using a two-dimensional (2D) PIV. The permeable bed is simulated with flexible vegetation with 2 cm thickness. Results showed that the type of bed influence significantly the shear stress definition at the linear zone.

2. Experimental procedure

In total, 24 experiments were carried out in the laboratory of Hydraulics in the Department of Civil Infrastructure Engineering of Alexander Technological Educational Institute of Thessaloniki, Greece. The channel has a length of 6.5 m, width of 7.5 cm, and height of 25 cm. The vegetation of 2 cm (fiber diameter of 0.3 cm) was attached to a 1.0 cm thick wood, so that it remains fixed to the bed during the experiments. Hydraulic characteristics were measured at four different total flow depths (*h* equals 7, 9, 11, and 13 cm) both for impermeable and permeable beds and for three different discharges (0.735, 0.845, and 0.970 l/s). The flow depth over the permeable bed (h') was equal to 5, 7, 9, and 11 cm for the vegetation of 2 cm. Note that we keep the total flow depth constant equal to 7, 9, 11, and 13 cm for both impermeable and permeable beds ($h = h' + h_v$, h_v: height of vegetation). The vegetation blades were made from plastic. Measurements of velocity were taken for horizontal channel slope. The geometrical characteristics of the flow are presented in Figs. 1 and 2. The morphology of the vegetation is illustrated in Fig. 3.

Measurements of velocity were taken for horizontal channel slope. PIV is an optical method of fluid

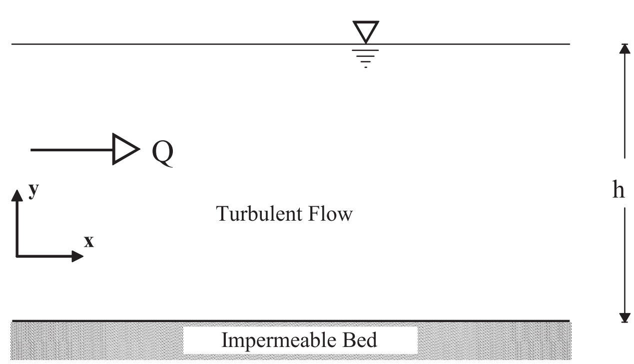

Fig. 1. Geometrical characteristics of the flow over impermeable bed.

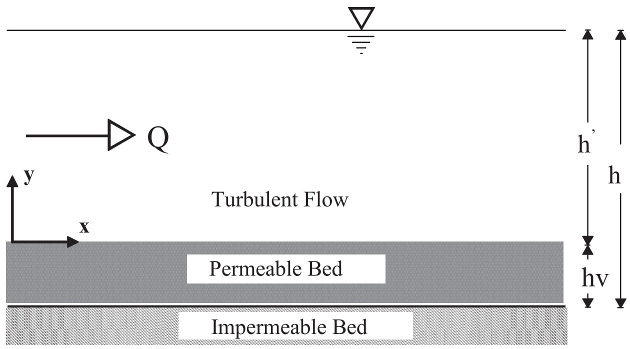

Fig. 2. Geometrical characteristics of the flow over permeable bed.

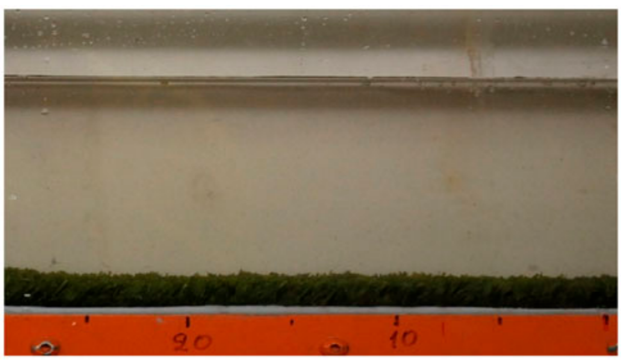

Fig. 3. Morphology of the vegetation.

visualization and is used to obtain instantaneous velocity and related properties in fluids. The fluid is seeded with tracer particles which, for the purposes of PIV, are generally assumed to faithfully follow the flow dynamics [13]. The motion of the seeding particles is used to calculate the velocities in magnitude and phase. The distance between two neighbor velocity vectors is 1.62 mm. From the velocity field we can find the profile of the flow at each vertical direction or the mean space profile in the area. PIV method uses the particle concentration method to identify individual particles in an image and follow their flow; however, tracking particles between images is not always a straightforward task. Individual particles could be "followed" when the particle concentration is low, a method called particle tracking velocimetry, whereas laser speckle velocimetry is used for cases where the particle concentration is high [14]. The experimental uncertainty of the measured velocity with this technique is approximately ±2%. In this study, PIV was used to measure velocity distribution.

The measurements were conducted at a 4 m distance from the channel's entrance where the flow is considered fully developed. The full development of the flow was evaluated comparing the velocity distributions above the vegetation in two vertical sections with a 60 cm separation distance. The uniformity of the flow was checked measuring the flow depth with point gages at two cross-sections. The desirable flow depth in the downstream section could be controlled using a sluice gate at the channel's outlet. The error of the measured flow depth with the point gage was ±0.1 mm. The total discharge was measured at the channel's outlet using a Venturi apparatus. The measurements were made at the mid-plane of the flow channel. Individual experiments are performed and were observed that the two side walls influence the measurements for only 0.2 cm along the wall.

3. Analysis of results

Experiments were performed for the flow determination over the permeable and impermeable bed. Two hundred (200) pair of pictures for each experiment were taken. The download taking time of pictures for each experiment was 8 min. The difference in time between the two photos in each pair was approximately 1.5 ms apart. From the moving of the luminous particles in each pair of photos, the respective field of the velocities resulted. Within a second were taken approximately 4.3 photo pairs, therefore 4.3 was the frequency appearance of the fields of the velocities. The validation of the images was further based on the INSIGHT 3G program. The velocity profiles at various positions were determined by the fields of the velocities with the use of MATLAB, which is integrated in the INSIGHT 3G program. There is also the possibility to find the spatial mean value of the velocity profiles. The area could be the entire photographed range or a part of it. The choice depends on the available reliability of the measurements.

Figs. 4–6 present the profiles of the mean spatial velocities for the three different discharges and for both bed types (impermeable and permeable). Every discharge for different flow depth, gives a different mean value of velocity (u_0) and each curve corresponds to a different u_0. In the curves appear the linear zones. For each curve the linear equation in the region of the linear zone was determined. All the equations appear in the respective figures.

In the region of the linear zone, the shear stress is constant as a result of the equation:

$$\tau = \mu \frac{du}{dy} = \mu a = \text{constant} \quad (2)$$

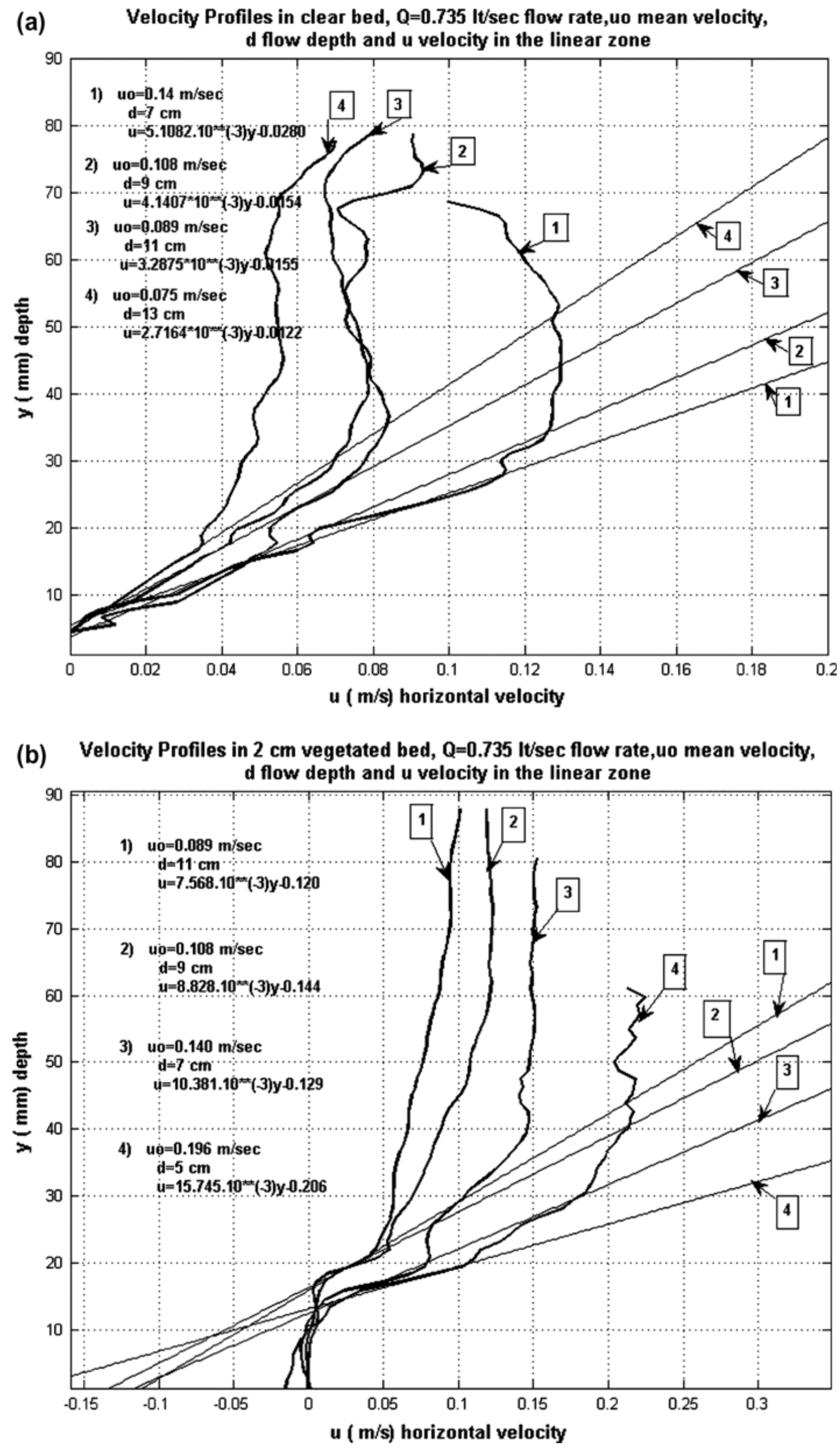

Fig. 4. Velocity profiles for different depths with the same flow rate $Q = 0.735\,\mathrm{l/s}$ for: (a) impermeable bed and (b) permeable bed.

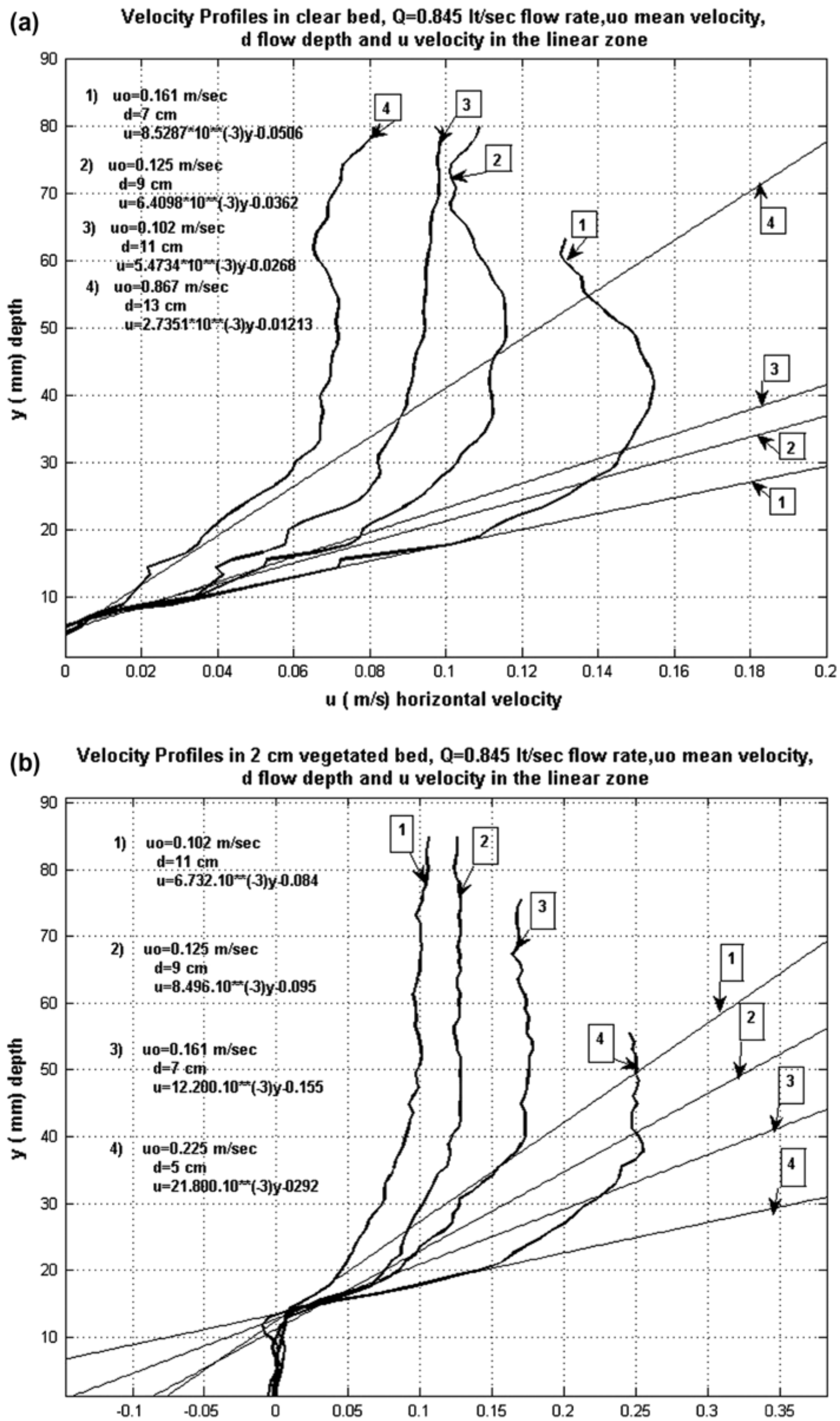

Fig. 5. Velocity profiles for different depths with the same flow rate $Q = 0.845\,\text{lt/s}$ for: (a) impermeable bed and (b) permeable bed.

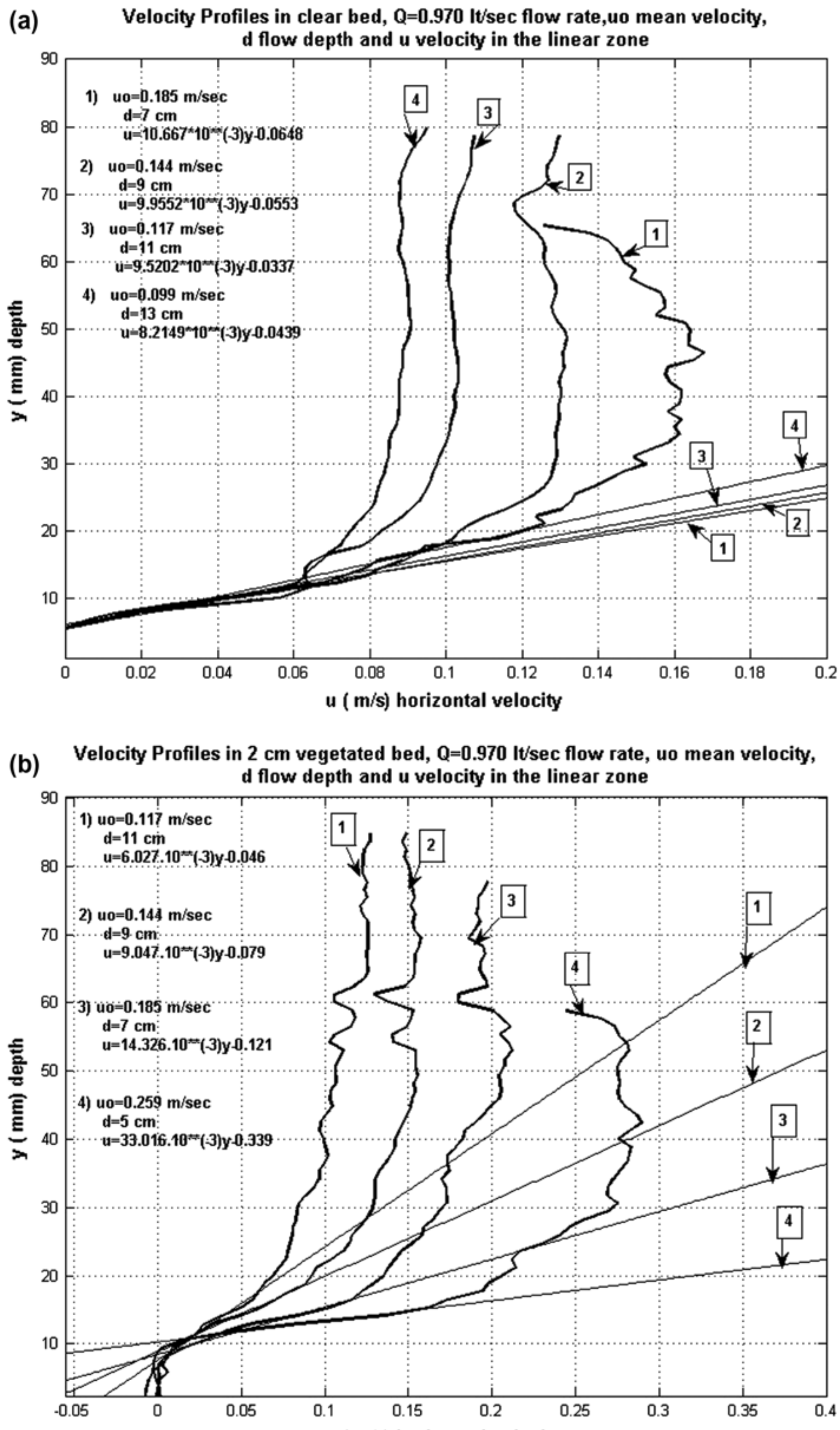

Fig. 6. Velocity profiles for different depths with the same flow rate $Q = 0.970$ lt/s for: (a) impermeable bed and (b) permeable bed.

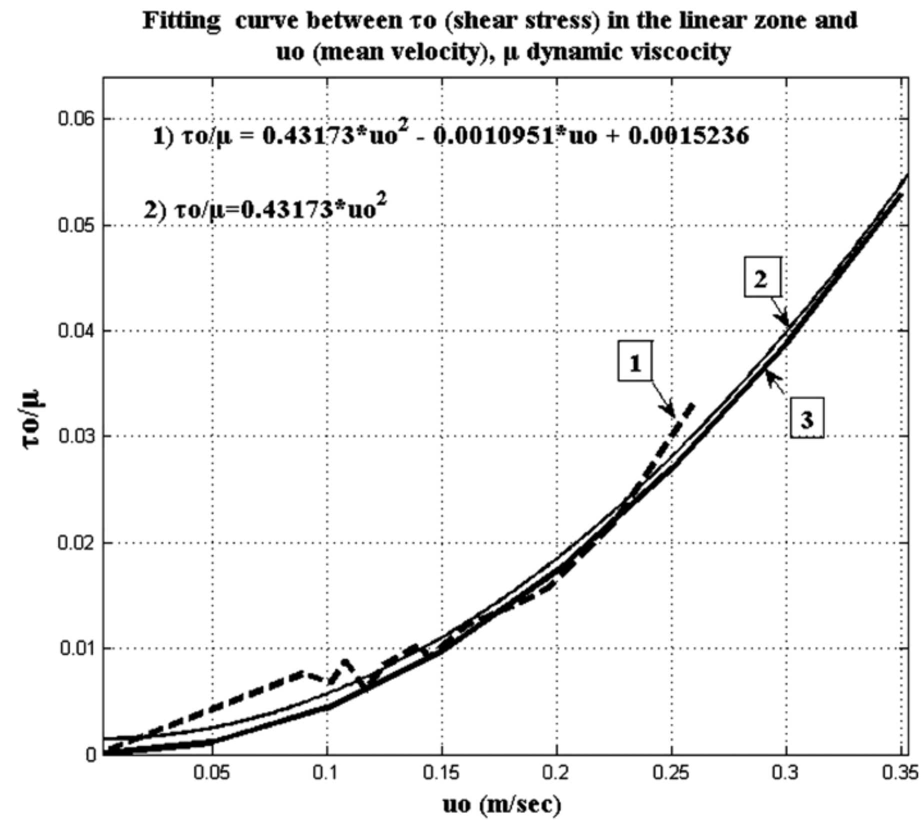

Fig. 7. Fitting curve of shear stress of the bed and mean velocity.

Table 1
Velocity equation in the linear zone for all experiments

Q (lt/s)	Depth (mm)	Velocity in the linear zone with impermeable bed	Velocity in the linear zone with permeable bed
0.735	70	$u = 5.1082 \times 10^{-3} \times y - 0.287$	$u = 15.745 \times 10^{-3} \times y - 0.206$
	90	$u = 4.1407 \times 10^{-3} \times y - 0.0154$	$u = 10.381 \times 10^{-3} \times y - 0.129$
	110	$u = 3.2875 \times 10^{-3} \times y - 0.0155$	$u = 8.828 \times 10^{-3} \times y - 0.144$
	130	$u = 2.7164 \times 10^{-3} \times y - 0.0122$	$u = 7.568 \times 10^{-3} \times y - 0.120$
0.845	70	$u = 8.5287 \times 10^{-3} \times y - 0.0506$	$u = 21.800 \times 10^{-3} \times y - 0.292$
	90	$u = 6.4098 \times 10^{-3} \times y - 0.0362$	$u = 12.200 \times 10^{-3} \times y - 0.155$
	110	$u = 5.4734 \times 10^{-3} \times y - 0.0268$	$u = 8.496 \times 10^{-3} \times y - 0.095$
	130	$u = 2.7351 \times 10^{-3} \times y - 0.0121$	$u = 6.732 \times 10^{-3} \times y - 0.084$
0.970	70	$u = 10.667 \times 10^{-3} \times y - 0.0648$	$u = 33.016 \times 10^{-3} \times y - 0.339$
	90	$u = 9.9552 \times 10^{-3} \times y - 0.0553$	$u = 14.326 \times 10^{-3} \times y - 0.121$
	110	$u = 9.5202 \times 10^{-3} \times y - 0.0337$	$u = 9.047 \times 10^{-3} \times y - 0.079$
	130	$u = 8.2149 \times 10^{-3} \times y - 0.0439$	$u = 6.027 \times 10^{-3} \times y - 0.046$

After the derivation of $u = ay + b$. In each case of flow, the coefficient of the linear equation indicates the value of the shear stress τ by the coefficient of the dynamic viscosity μ. By measuring the velocity in the linear zone, the shear stress τ_0 of the bed is determined. From this, the shear velocity u_* is determinate. Results show a continuous increase of the shear stress τ_0 with the increase of the mean velocity. The coefficients (the rates τ_0/μ) are presented in Fig. 5 in relation with the velocity u_0. The fitting curve of these points is of a second degree given by:

$$\frac{\tau_0}{\mu} = 0.43173 \cdot u_0^2 - 0.0010951 \cdot u + 0.0015236 \tag{3}$$

From this relation we see that the first term is the most important. For a velocity of 0.1 m/s the first term is approximately 43 times greater than the other two. We could consider only the existence of the first term. The error with the default value of the other two terms would be less than 1% because they are removed together (abstracted). Fig. 7 shows with bold black color the curve with only the first term and the fitting curve is adequate. Hence Eq. (3) can now take the form:

$$\frac{\tau_0}{\mu} = 0.43173 \cdot u_0^2 \tag{4}$$

and then

$$u_0 = 1.5219\sqrt{\frac{\tau_0}{\rho}} \cdot \frac{1}{\sqrt{v}} = \frac{1.5219}{\sqrt{v}} \cdot u_* \tag{5}$$

The solid black curve (4) Eq. (5) in Fig. 7 shows only the first term. From Eq. (5) it is possible to determine the shear stress velocity for fluid with known coefficient of kinematic viscosity (v) and from Eq. (4) the shear stress of the bed can be determined. From the curves of the velocity profiles, we observe a jump (inner of the ellipse) of the Curve (2) and (3) in the region of the linear zone (Fig. 4(b)) for permeable bed (flexible vegetation). This is due to the harmonic movement that the flexible vegetation present is due to the increase of the velocity; a phenomenon that one can observe experimentally.

Table 1 presents the velocity equation in the linear zone for all experiments and for both bed types. From this table it is obvious that we have a significant reduce of the shear stresses of the bed (τ_0). It is observed that for the same value of the mean velocity the bed shear stress for the impermeable bed change from 1 until 1/3 approximately of the bed shear stress for the impermeable bed. Also for high values of velocity the shear stresses are almost triple and for low velocities for over 110 mm depth the values of shear stresses come close together. This is obvious from the rates $\frac{\tau_0}{\mu}$ which are the coefficients of the velocity equations which appear in Table 1. Table 2 shows these rates and the comparison between impermeable and permeable bed.

Table 2
Comparison of rates $\frac{\tau_0}{\mu}$ for impermeable and permeable bed

(1) Impermeable bed	(2) Permeable bed	(2)/(1)
0.0051082	0.015745	3.082299
0.0041407	0.010381	2.507064
0.0032875	0.008828	2.685323
0.0027164	0.007568	2.78604
0.0085287	0.021800	2.556075
0.0064098	0.012200	1.903336
0.0054734	0.008496	1.552234
0.0027351	0.006732	2.461336
0.010667	0.033016	3.095153
0.0099552	0.014326	1.439047
0.0095202	0.009047	0.950295
0.0082149	0.006027	0.733667

4. Conclusions

This study examines the shear stress in turbulent boundary layers in open channel flows. Laboratory experiments were used for the calculation of turbulent velocity profiles. The measurements were obtained using a two-dimensional (2D) PIV. The experiments were conducted for impermeable and permeable bed. The permeable bed is simulated with flexible vegetation with 2 cm thickness. We present the relation between the mean velocity and the shear stress of the bed. The shear stresses also determine the shear velocity u_*. The mean velocity u_0 has the same form that the shear velocity has with the shear stress of the bed. The above relation allows determination of shear stress of the bed and also the determination of the shear velocity. From the experiments it is observed that for the same value of the mean velocity the bed shear stress for the impermeable bed change from 1 until 1/3 approximately of the bed shear stress for the impermeable bed. Further experiments in this region and with various types of permeable bed will lead to safer and more general conclusions as it regards the estimation of the bed shear stress as a function of mean velocity.

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