A THREE TUBE PRESSURE INSTRUMENT FOR MEASURING THE LOCAL BED SHEAR STRESS IN SMOOTH AND ROUGH BEDS

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Abstract

A new instrument has been developed to measure the local bed shear stress in smooth and rough bed open channel flows. This instrument consists of three small diameter tubes which are vertically placed in the logarithmic part of the turbulent boundary layer. Accurate and high frequency pressure transducers have been used to measure the local dynamic pressures and a specific method has been used to convert the pressure readings to the local bed shear stress. The instrument has been verified against available wind tunnel data. Furthermore, the collected data for smooth bed open channel uniform flow has been compared to the Preston tube data and also with estimated bed shear velocities by indirect methods based on turbulent statistics, measured using ADV. Finally, the rough bed open channel results have been compared with results of indirect shear velocity estimation methods and it was found that results are in fairly agreement.

Introduction

Several experimental methods and devices are available for measurement of bed shear stress in water flows. A class of these methods is based on the principle of the similarity of flow about obstacles. These methods rely on the theory that the flow near the wall is governed by the wall variables. According to this principal, the velocity field about an obstacle immersed in the inner wall region is determined by the wall variables. The wall variables are bed friction, τ_w, density and kinematic viscosity of the water, ρ, υ, and a characteristic length of the obstacle, l. Dimensional analysis gives that the local dynamic pressure, Δp at the measuring point and wall variables has a functional dependence given by:

$$\frac{\Delta p l^2}{\rho \upsilon^2} = f\left(\frac{\tau_w l^2}{\rho \upsilon^2}\right) \qquad (1)$$

The function " f " can be determined experimentally for a given device. Some designs of instruments based on this principal are available such as Preston tube, Sublayer fence, Stanton tube, Yaw type Preston tube, static hole pair and etc. The most convenient device is the Preston tube. It is easy to make and use, and is applicable over a wide range of flow conditions (Hollick, 1976; Jin, 1995; Safarzadeh et al., 2010). Preston used the outer diameter of the measuring tube (d) as the characteristic length and he suggested a calibration function in the form of equation 1 to estimate the local bed shear stress in the smooth bed channels (Preston, 1954). The original calibration due to Preston is usually ignored in favour of the one by Patel, who suggested new calibration functions for three ranges of the tube Reynolds number (Patel, 1965). Some researchers have tried to extend the technique for measurement of bed shear stress in non-smooth bed flow condition (Hollick, 1976; Hollingshead & Rajaratnam, 1980; Wu & Rajaratnam, 2000). Although the Preston tube technique has been widely used for measurement of bed shear stress on smooth surfaces (Jin, 1995; Safarzadeh et al. , 2010), some problems arise when it is used on rough surfaces. In the latter case, an important independent variable, which is known as sand roughness length, k_s, has been added to the list of variables. Furthermore, the non-smooth surface leads to an uncertainty in the real datum of wall normal coordinate and the position of the tube from uncertain datum introduces another unknown length scale. So, the ambiguity of vertical position of the probe and the bed roughness length scale result in usefulness of the standard Preston tube for measurement of bed shear stress on non-smooth beds.

The main objective of the present paper is to make and test a new device for measurement of the local bed shear stress in rough bed condition using the wall similarity principal similar to the Preston tube, considering the aforementioned extra unknown variables. The new device should be able to measure the local bed shear stress without any need for calibration procedure regarding to the extra variables. The paper starts with the theoretical background of the bed shear stress and follows with experimental details and specifications of the developed device. Finally we will present the results of the measured bed shear stresses in wind tunnel, smooth bed open channel and rough bed open channel cases.

Theoretical Background

There exists a region far enough away from the channel bed where the velocity profile is logarithmic for both of the smooth and rough beds (Nezu & Nakagawa, 1993). In this region, the gradient of the time-averaged velocity is independent of both of the viscosity and surface roughness. If the surface roughness is not too large we can write the relation between the velocity gradient and the local bed shear velocity as following equation (Nezu & Nakagawa, 1993):

$$\frac{y}{u_*}\frac{dU}{dy} = \frac{1}{\kappa} \tag{2}$$

Where, U is time averaged velocity, y is bed normal vertical axis, $\kappa \approx 0.41$ is the von Karman constant and u_* is shear velocity.When the velocity gradient at a specific point is known, equation (2) can be used to estimate the local bed shear velocity. According to Fig. 1 if we simultaneously measure local velocities at three points which are vertically aligned in the logarithmic region over the rough bed and approximate the velocity gradient between points 1 and 2 by a linear interpolation, we can re-write equation (2) as:

$$\frac{y_1 + y_2}{2u_*}\left(\frac{U_1 - U_2}{y_1 - y_2}\right) = \frac{1}{\kappa} \tag{3}$$

Similarly, for points 2 and 3(Storm & Newman, 1993):

$$\frac{y_2 + y_3}{2u_*}\left(\frac{U_2 - U_3}{y_2 - y_3}\right) = \frac{1}{\kappa} \tag{4}$$

In order to eliminate the y-coordinate origin effects, equation (4) is subtracted from equation (3) and leads to(Storm & Newman, 1993):

$$u_* = \frac{\kappa}{2}\frac{a_{12} + a_{23}}{\left[\frac{a_{12}}{U_1 - U_2} - \frac{a_{23}}{U_2 - U_3}\right]} \tag{5}$$

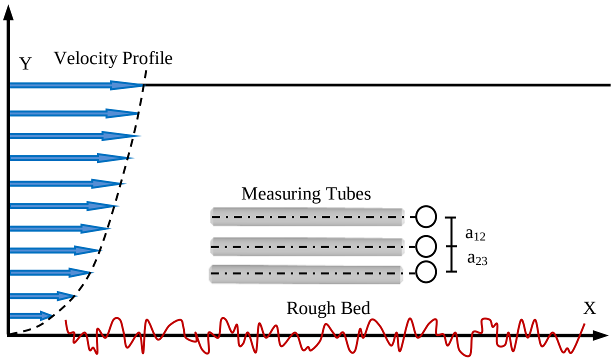

Figure 1: Three measuring points in the logarithmic region over the rough bed.

Where $a_{12}=y_1-y_2$ and $a_{23}=y_2-y_3$ denotes center to center distances between measuring tubes as depicted in Fig. 1. Since the main objective of the present paper is estimation of the bed shear stress using the pressure fluctuations, we can relate the local velocities and pressure reading at each tube as:

$$U_2 = \left[\frac{2}{\rho}\left(P_2 - p\right)\right]^{0.5} \tag{6}$$

$$U_1 = \left[\frac{2}{\rho}\left(P_1 - p\right)\right]^{0.5} = \left[\frac{2}{\rho}\left(P_2 - p + \Delta_{12}\right)\right]^{0.5} \tag{7}$$

$$U_3 = \left[\frac{2}{\rho}\left(P_3 - p\right)\right]^{0.5} = \left[\frac{2}{\rho}\left(P_2 - p - \Delta_{23}\right)\right]^{0.5} \tag{8}$$

Where, P_i is total pressure at tube i, $\Delta_{12}=P_1-P_2$ and $\Delta_{23}=P_2-P_3$ and p is the local static pressure at the measuring point.

Substituting equations (6)-(8) into equation (5), expanding velocities to second order in $\Delta_{ij}/(P_2\text{-}p)$ and dropping negligible terms with higher order gives (Storm & Newman, 1993):

$$\frac{1}{u_*} = \frac{\left[8\rho(P_2 - p)\right]^{0.5}}{\kappa(a_{12} + a_{23})}\left[\frac{a_{12}}{\Delta_{12}} - \frac{a_{23}}{\Delta_{23}} + \frac{a_{12} + a_{23}}{4(P_2 - p)}\right] \tag{9}$$

Based on equation (9), local shear stress can be determined from three measured pressure differences without any assumptions or limitations regarding to the bed roughness and the distance of the measuring tube off the bed. For this purpose a three tube device which has an extra tube for static pressure (p) has been made. It should be noted that the measurement should be conducted in the logarithmic region. This region extends from $y^+=yu_*/\nu=30$ near the wall and limits to $y/\delta=0.2$ where δ is the boundary-layer thickness (Nezu, 2005). In the following section details of the three tube device and measuring method will be presented.

Three tube instrument

This device, as shown in Figure 2 consists of three steel Pitot tubes of 1.27mm outside diameter and center to center separation of a_{12}=a_{23}=2.54mm. The small size of the instrument was dictated by the size of the logarithmic region. However, some numerical simulations were conducted in order to examine effects of the instrument on flow pattern and it was found that tubes have not flow disturbing effects on each other (Mohajeri, 2010). At 6.1mm distance from the entrance of the upper tube, three tubes were soldered and covered by PVC cover to form the rigid stem of the instrument.

The instrument also contains a 3.175mm CRES (Corrosion Resistance Steel) static tube. The holes of the static tube were in the same plane as the entrance of the total tubes. The manufactured probes were connected to four capacitive types, Keller 41X pressure transducers using silicon tubing. The accuracy and sampling rate of transducers were 0.1% of full scale and 100 Hz respectively. The control and processing of three tube device recorded time series accomplished with integrated software developed using the LabVIEW software. In the developed program, equation 9 is used to estimate the local bed shear velocity time series based on the measured pressure time series. This program removes eventual spikes in shear stress time series using the wavelet threshold method and replaces the erroneous data by a non-linear interpolation algorithm (Goring &Nikora, 2002).

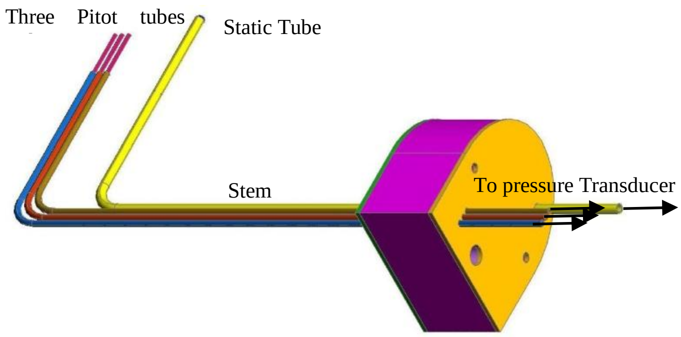

Figure 2: Schematic layout of the three tube device for measuring bed shear stress in rough bed flows.

Experimental details

Wind tunnel

The aim of the experimental investigation is to test the accuracy of the collected data in both of the wind tunnel and open channel. In order to examine the validity of equation (9) in open channel, a set of laboratory experiments were carried out in available open channel in hydraulic laboratory of Tarbiat Modares university. In addition, some wind tunnel experiments were conducted in order to check the efficiency of the device in wind tunnel. The shear stress from three tube pressure instrument was compared to those determined by other techniques such as: Preston tubes, turbulent statistics, logarithmic law, energy slope in open channel and skin friction law in wind tunnel. The skin friction law is as follows (White, 1991):

$$C_f = \frac{0.455}{\left(Ln(0.06\,\mathrm{Re}_x)\right)^2} \tag{10}$$

Where skin friction (C_f) is equal to $C_f = 2(u_* / u_o)$ in which u_o is free stream velocity.

Open channel

The laboratory experiments were conducted in a straight rectangular flume, 11m long and 1m wide. A pump supplies water in the flume and water depth is regulated by a fully automated flap weir located at downstream end of the flume. Small surface waves at the entrance of the flume were eliminated with a 1.5m long by 0.95m wide polystyrene plate held parallel to the upper water surface just downstream of the intake (Safarzadeh, Salehi Neyshabouri, Zarrati, & Ghodsian, 2010). Water surface profiles were measured with a digital point gauge with an accuracy of 0.01 mm. Measurements were carried out at a fixed test section located in centerline and 7m downstream from the channel entrance where the flow is fully developed.

Two different instruments were used during measurements. The first device was the vectorino type 10MHZ down looking ADV (Nortek) with an accuracy of 0.5% measured value, capable of measuring point-wise instantaneous 3D velocity field. The measured time series were filtered using the Wavelet Thresholding method (Goring & Nikora, 2002). The second device was a Preston tube for local bed shear stress measurement. This instrument was manufactured using two brass tubes with external diameters of 3.1 mm. The manufactured probes were connected to two capacitive types, Keller 41X pressure transducers using silicon tubing. Each quantity was sampled for at least 180s in smooth bed and for 300s in rough bed tests.

The three tube pressure instrument was tested on three different surface conditions. The first surface condition was smooth and the two others were rough bed condition (both rough condition are consists of sandy material with the properties of d_{90}=4.7mm, d_{50}=3.1mm, σ_g=1.42 for first sheet and d_{90}=9.5mm, d_{50}=7.0mm, σ_g=1.41 for the second one). The rough elements were distributed on the surface in completely random arrangement.

Results and discussion

The computed shear stress based on collected data on smooth wall in wind tunnel has been shown in Figure 3 for three different vertical position values in wind tunnel. As shown, the results are independent of orthogonal position of the device. This fact caused by independency of pressure fluctuation and normal position of device in logarithmic region.

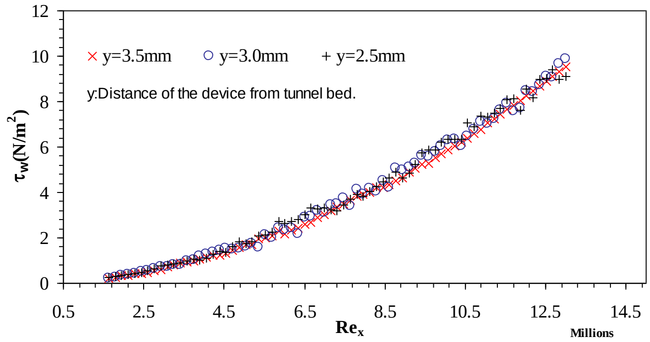

Figure 3: Bed shear stress variations against Reynolds number measured by three tube device in wind tunnel.

In order to verify the instrument, the skin frictions based on shear stresses (equation (11)) are computed. The computed skin frictions are compared to equation (10) and have shown in Figure 4. As shown in Figure 4, the results are in good agreement with analytical equation. Below Re_x=2500000, several data points are far from the expected values of skin friction. This scattering in skin friction coefficient is due to the inaccuracy in the small pressure fluctuation measurement, which also has been reported by Storm and Newman (Storm & Newman, 1993).

$$C_f = \frac{\tau_w}{0.5 \rho U^2} \tag{11}$$

Where $Re_x=Ux/\nu$ streamline velocity Reynolds and U is free stream velocity, ν kinematic viscosity, y vertical position of measurement point from bed and x is longitudinal position of instrument that in this study is 2.5m.

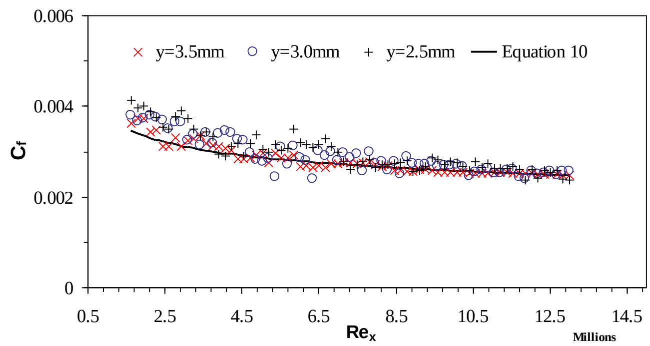

Figure 4: skin friction coefficient in smooth wall based on new device data and skin friction law.

It should be mentioned that the uncertainty of computed skin friction based on ASME method is about 1.9% (ASME, 1986).

Computed shear velocity based on collected data in open channel summarized in Table 1. Shear velocities associated to logarithmic profile and turbulent statistic resulted by vectorino collected data. Moreover, shear velocities were measured by available Preston tube. For these data, Reynolds number ($R_e=Uy/\nu$) varies between 20000-40000 and Froude number ($Fr=U/(gy)^{0.5}$) varies in a range of 0.2-0.3.

Table 1: Bed shear velocity in open channel (m/s) using various methods.

No.	Bed type	Water depth(cm)	Energy slope	Logarithmic profile	Turbulent statistics	Preston tube	3 tube device
			Bed shear velocity (m/s)				
1	smooth	13	0.0183	0.0210	0.0222	0.0202	0.0198
2	smooth	14	0.0188	0.0240	0.0209	0.0205	0.0201
3	smooth	15	0.0193	0.0250	0.0219	0.0209	0.0206
4	smooth	16	0.0198	0.0280	0.0231	0.0215	0.0217
5	1st rough sheet	13	0.0183	0.0216	0.0150	-	0.0222
6	1st rough sheet	14	0.0188	0.0226	0.0160	-	0.0215
7	1st rough sheet	15	0.0193	0.0227	0.0170	-	0.0224
8	1st rough sheet	16	0.0198	0.0240	0.0180	-	0.0230
9	2nd rough sheet	13	0.0183	0.0213	0.0210	-	0.0214
10	2nd rough sheet	14	0.0188	0.0215	0.0220	-	0.0216
11	2nd rough sheet	15	0.0193	0.0229	0.0230	-	0.0229
12	2nd rough sheet	16	0.0198	0.0246	0.0230	-	0.0232

Table 1 demonstrates that the three tube device is capable of determining shear velocity on both of the smooth and non-smooth surfaces. The average errors of three tube device in evaluating shear velocity on smooth and rough bed are 3.11% and 9.83% respectively. In addition, the uncertainty of computed shear velocity based on ASME method is about 6.1% (ASME, 1986). Therefore, new device is able to measure shear velocity accurately.

Conclusion

A new method for bed shear stress measurement has been presented in both smooth and rough wall conditions. In order to estimate the efficiency of this method, a three tube pressure instrument has been built and tested on both of wind tunnel and open channel. This instrument consists of three Pitot tube located in logarithmic region of a turbulent boundary layer, together with one static tube. The results show good agreement with other methods of determining shear stress on both smooth and non-smooth surfaces. If the instrument is confined to logarithmic region of the boundary layer, the results will be independent of y-position of the instrument. Moreover, no roughness characteristic of bed materials is required. These issues are clear advantages of the new method in comparison to other similar instruments.

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