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Investigation of Average Shear Stress in Natural Stream

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ABSTRACT

Average shear stress is an important parameter for prediction of sediment transport, bank protection and other river engineering problems in natural streams. For this purpose velocity measurements were taken on Kızılırmak River sub branch, named Sarimsakli stream and Barsama station in center of Turkey. Acoustic Doppler Velocimeter (ADV) was used for this purpose at six different periods and flow conditions. Nikuradse's equivalent sand roughnesses (k_s) for each vertical along the wetted perimeter were determined using measured velocity distributions. Shear velocity (u_*) and shear stress (τ_{meas}) were determined then average values were calculated for each flow condition. The commonly used one-dimensional mean boundary shear stress equation at cross-section was re-arranged according to entropy parameter M and it reflects the real flow condition in natural stream.

Keywords: Stream, velocity, shear stress

INTRODUCTION

Determination of shear stress distribution over the cross-section is necessary for many important issues such as river resistance, sediment and pollutant transport, riverbank stability, flood defense and river management. Modeling the boundary shear stress in river is not an easy task due to the many parameters, such as the shape of the cross-section, roughness, secondary flow etc., that affect the flow.

Flow in open channels and natural rivers are often described by the simplifying cross-section averaged one-dimensional hydraulic equations. In uniform flow condition, the simplest model for calculating the mean boundary shear stress at a cross-section is the flow depth method, which is:

$$\tau_0 = \gamma R S_0 \tag{1}$$

where τ_0 is the boundary shear stress, γ is the specific gravity of water, R is the hydraulic radius (=A/P in which A is the wetted area and P is wetted perimeter), and S_0 is the bed slope. However, this method is not appropriate for local, small-scale estimates of the variation in shear stress. In reality, river hydrodynamics is quite complicated because the river cross-sections and riverbed are usually complex and do not meet assumptions of one-dimensional flow. Because of the difficulties associated with direct measurement of the wall shear stress, τ_0, the shear velocity, u_*, is usually calculated by indirect methods.

Preston [1] developed a simple technique for measuring local shear on smooth boundaries in the turbulent boundary layer using a Pitot tube placed in contact with the surface. Kırkgöz [2] and Kırkgöz & Ardıçlıoğlu [3] computed shear velocities using the measured velocity distributions in the viscous sublayer. By assuming a linear velocity distribution in the viscous sublayer, the shear velocity (u_*) can be derived from Newton's law of viscosity as $u_* = \sqrt{\upsilon u/z}$ where u represents the point velocity in the viscous sublayer at a distance *z* from the bed and υ is the kinematics viscosity of the fluid. Another indirect method commonly used is based on the logarithmic velocity distribution after Prandtl–Karman and involves measurement of velocity profiles along lines normal to the boundary. The velocities are not uniformly distributed in the channel section, due to the existence of free surface and the friction along the channel wall. There are also some other factors which affect the velocity distribution in a channel section, such as the unusual shape of the section, the roughness of the channel and the presence of bends. However, the Karman–Prandtl velocity distribution generally gives satisfactory results for flow in channels. Therefore, investigation of a pressure–shear relationship based on logarithmic velocity distribution seems to be reasonable [4], [5].

In this study, based on the field velocity measurements, average shear stresses for natural streams were investigated for different flow conditions. The one-dimensional average shear stress is also calculated and depends on flow conditions. The differences between one dimensional model and measurements results were examined using an entropy approach.

VELOCITY and SHEAR STRESS DISTRIBUTION

The vertical distribution of streamwise velocity in turbulent open-channel flows is very complex. The velocity distribution on rough surfaces is affected by the grading, shape, and spacing of the surface roughness elements. The velocity distribution in a two-dimensional open-channel flow over a fully rough, impermeable bed is usually considered to follow the law of the wall;

$$\frac{u}{u_*} = \frac{1}{\chi} \mathrm{Ln}\left(\frac{z}{k_s/30}\right) \tag{2}$$

where, *u* is the streamwise velocity at *z*, u_* ($=\sqrt{\tau_0/\rho}$, in which ρ is the water density) is the shear velocity, χ=0.4 is the universal von Karman constant, k_s is the Nikuradse's original uniform sand grain roughness height and *z* is the distance from the bottom of the roughness elements. The values of Nikuradse's equivalent sand roughness were reported in the literature for various wall roughness, and they are generally in the range $k_s \cong (2\text{-}4)k$, with k being the average height of roughness elements [6], [7].

Chiu [8, 9 and 10] investigated flow properties by using probabilistic approaches and proposed an entropy-based, two-dimensional velocity distribution function for the simulation of the velocity field in open channel flow. Using this probabilistic formulation, the mean velocity U_m can be expressed as a linear function of the maximum velocity u_{max}, through a dimensionless entropy parameter M. The M value is an essential measure of information about the characteristic of the channel section, such as changes in bed form, slope and geometric shape [11]. The entropy parameter M is a function of the ratio of U_m, u_{max} and can be derived as the following function of M. Chiu and Said [12] showed that M is a constant for each channel section and invariant with the discharge or flow depth.

$$\frac{U_m}{u_{max}} = \frac{e^M}{e^M - 1} - \frac{1}{M} \tag{3}$$

FIELD MEASUREMENTS

Field measurements were undertaken on Kızılırmak basin, which is in central Anatolia in Turkey. Field measurements achieved on Sarimsakli stream at Barsama station, which is a tributary of the Kızılırmak River. The velocity measurements were undertaken through the use of the SonTek/YSI FlowTracker Handheld ADV (Acoustic Doppler Velocimeter). Velocity measurements were carried out six times at different periods and under several flow conditions. For the velocity measurements, the cross-section was divided into different slices depending on the stream width. Point velocity measurements were made at different positions on the vertical direction starting 4 cm from the bed. Free surface velocity was then estimated by extrapolating the upper two measurements. The flow characteristics are summarized in Table 1. As shown in Table 1, flow measurements have done at Barsama station from 2005 to 2010. In this table, Q is the integrated discharge, U_m (=Q/A) is the mean velocity, A is the cross-section area, R is the hydraulic radius, and S_0 is the bed slope. In Figure 1, sample bed and water surface slope distributions were given for the Barsama_6 measurement. As shown in figure, flow is uniform, bed and water surface slopes are found S_{ws}=S_0=0.012. Similar results are observed for other measurements and determined slopes are given in Table 1. Using Equation (1), average shear stresses (τ_0) were calculated for six different flow conditions and given Table 1 column (7). In this equation the specific weight of water was taken γ=9810N/m^3.

Table 1 Flow characteristics

No -	Date (d/m/y)	Q (m^3/s)	U_m (m/s)	R (m)	S_0 -	τ_0 (N/m^2)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Barsama_1	28.05.05	1.81	0.89	0.244	0.009	21.54
Barsama_2	19.05.06	2.44	1.05	0.256	0.009	22.60
Barsama_3	19.05.09	3.93	1.21	0.310	0.009	27.37
Barsama_4	31.05.09	0.96	0.60	0.185	0.009	16.33
Barsama_5	24.03.10	1.51	0.81	0.250	0.014	34.34
Barsama_6	18.04.10	2.15	0.87	0.399	0.012	46.92

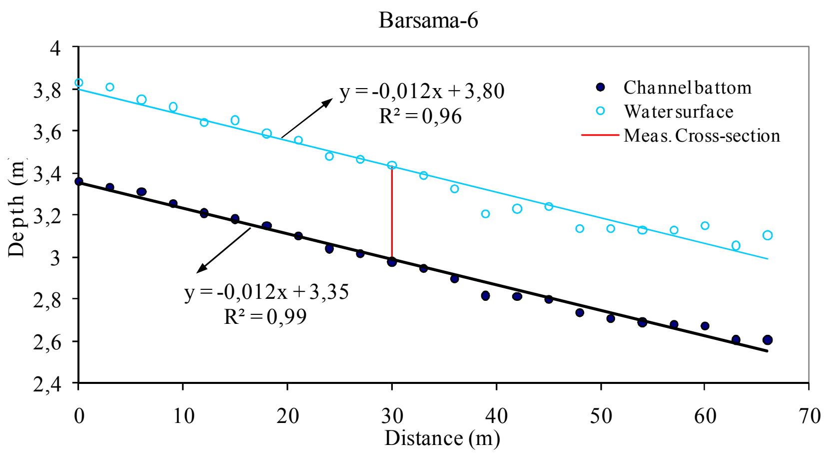
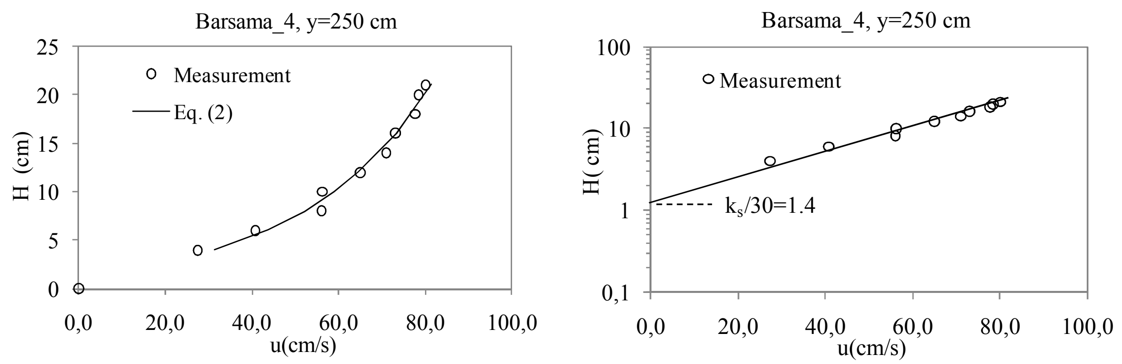


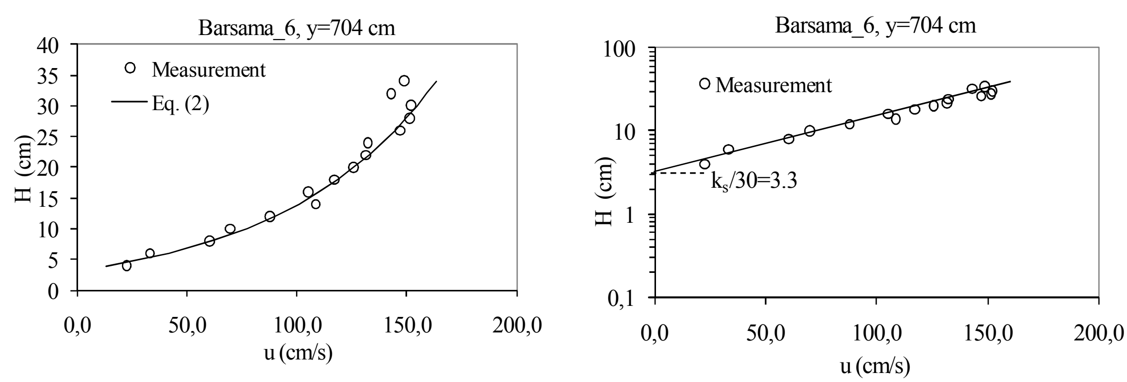
Figure 1 Channel bed and free surface slope for Barsama_6 measurement

DATA ANALYSIS and DISCUSSION

Sümer [13] introduced that for given measured velocity profile u(z), and taking χ=0.4, the quantities u_* and k_s can be determined from Equation (2). When we plot u in semi log graphs against z, the $0.1H \leq z \leq (0.2\text{-}0.3)H$ interval shows us where the logarithmic layer is supposed to lie, while H shows water depth at a measured vertical. Extend the straight line portion of the velocity profile to find its z-intercept; this is equal to $k_s/30$. Using $k_s/30$ values and shear velocities (u_*) having the best fit with measured data can be determined using Equation (2). In Figure 2 (a) and (b) two sample vertical velocity measurements were given for Barsama_4 and 6, at y=250 cm and y=704 cm respectively. As mentioned above, first of all the measured velocities, u was plotted in a semi log graph against z, and the logarithmic layer was determined for measured vertical, as seen on the right hand side of the figures. Using this straight line, $k_s/30$ value was assigned as 1.4 and 3.3 respectively. Then shear velocities (u_*) having the best fit with measured data was determined using Equation (2) by trial and error method. Left side figures showed that best fit velocity distributions were obtained for measured data by known shear velocities. For six different flow conditions, shear velocities have been determined considering each measured verticals. When shear velocity (u_*) known local shear stress could be calculated with $\tau_{meas} = u_*^2 \rho$. So, average shear stresses are calculated by using obtained local shear stresses.



(a)



(b)

Figure 2 Velocity distributions for Barsama station

When investigating sediment transport in open-channel flows, it is often necessary to remove sidewall effects for computing effective bed shear stress. A lot of sidewall correction methods are subject to some assumptions that have not been completely verified. Different values of the bed shear stress may be obtained depending on these approach used in making sidewall corrections [14]. They also informed that the shear stresses corrected in different ways may vary significantly.

Average shear stress values (τ_{0_meas}) for each flow condition were calculated using determined local bed shear stress. In Table 2 both values for mean shear stresses were calculated with equation (1), τ_0, and average values of the measured shear stresses along the wetted perimeter, τ_{0_meas}, are given in colon (2) and (3) respectively. In Figure 3 these two different values of mean shear stress were given for six different flow conditions. As shown in this figure, average shear stresses calculated equation (1) is smaller than measured ones.

Table 2 Average shear stresses for Barsama station

No -	τ_0 (N/m^2)	τ_{0_meas} (N/m^2)	τ_{0_cor} (N/m^2)	$\varepsilon_{3\text{-}2}$ %	$\varepsilon_{3\text{-}4}$ %
(1)	(2)	(3)	(4)	(5)	(6)
Barsama_1	21.54	30.83	30.16	30.13	2.18
Barsama_2	22.60	31.06	31.64	27.24	1.87
Barsama_3	27.37	35.69	38.32	23.31	7.36
Barsama_4	16.33	25.54	22.87	36.04	10.46
Barsama_5	34.34	51.43	48.07	33.24	6.54
Barsama_6	46.92	62.28	65.69	24.67	5.47
			Mean	29.11	5.65

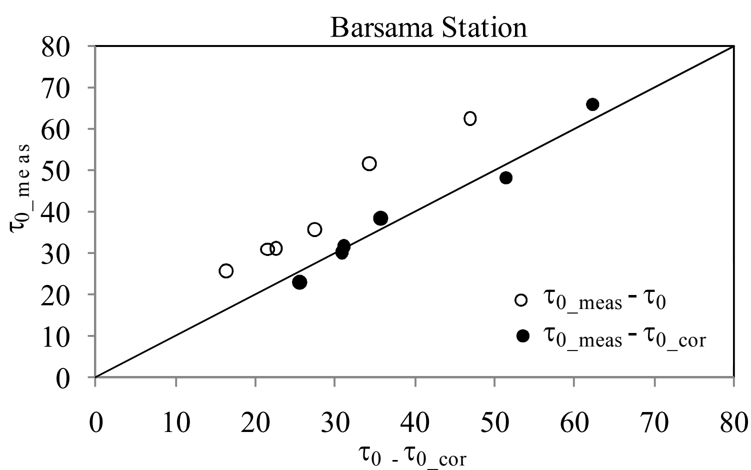


Figure 3 Measured and calculated average shear stresses for Barsama station.

Entropy parameter M is an important constant which is related with most of the flow properties for given cross-section. Figure 4 shows the relationship between the maximum velocities (u_{max}) versus the cross-sectional mean velocity (U_m) for six different flow conditions at Barsama station. As shown in the figure u_{max} and U_m present a linear relationship and the M value for Barsama station was calculated by Equation (3) as 1.4.

Using this M=1.4 value, mean shear stresses, which are calculated by equation (1), are multiplied and given in Table 2 at column (4) as τ_{0_cor}, which in turn denotes the corrected mean shear stress value. The relation between τ_{0_meas} and τ_{0_cor} is shown in Figure 3. It's show that there is a good relation between these two mean shear stress values. Relative errors ($\varepsilon = \left|\tau_{0\_meas} - \tau_0 / \tau_{0\_meas}\right| x100$) between column (3) - (2) and (3) - (4) for each flows are given in Table 5 at column (5) and (6) respectively. Average values of these errors were also calculated and given in Table 3 as 29.11% and 5.65% respectively. It was found out that common equation (1) for average shear stress could be corrected by entropy parameter M, as given in equation (4). This equation represents non-uniformity and real flow conditions for natural streams.

$$\tau_{0\_cor} = M\gamma RS_0 \qquad (4)$$

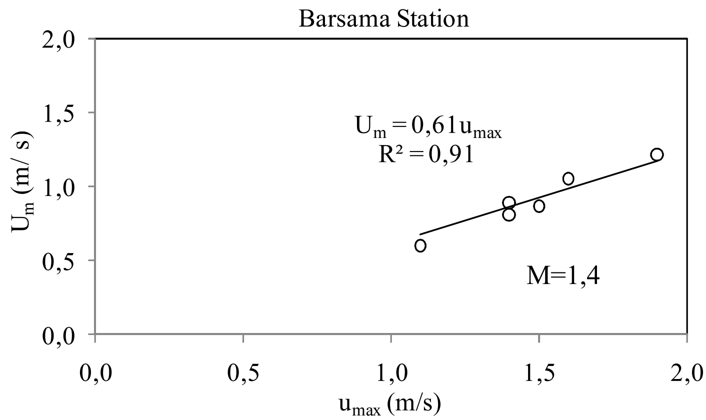


Figure 4 Relation between U_m and u_{max} for Barsama station

CONCLUSION

The one-dimensional boundary shear stress equation is commonly used for average stress in natural streams. Using this equation, average shear stresses are determined for Barsama station for six different uniform flow conditions. In reality, open channel hydrodynamics is quite complicated because the stream cross-sections and bed properties are usually complex. A lot of factors effect flow so that velocity and shear stress distributions show differences. Using the logarithmic velocity distribution valid in the fully turbulent part of the inner region, the bottom shear stresses were calculated over different vertical lines along the cross section. Average values were also determined for each flow condition. When calculated, these average values are bigger than the one-dimensional formula result. Entropy parameter M is an important constant which is related with most of the flow properties for given cross-section. Entropy parameter M was calculated as 1.4 for six different flow conditions at Barsama station. Using this constant value, one dimensional average shear stress equation was rearranged and this rearranged equation represents non-uniformity and real flow conditions for natural streams.

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