



Experimental investigation on bed shear stress distribution in the roughened compound channel

Akram Abbaspour¹

Received: 27 November 2019 / Accepted: 18 February 2020 / Published online: 4 March 2020
© The Author(s) 2020

Abstract

The roughness in the floodplains in a compound canal and its impact on hydraulic parameters such as the shear stress and their estimation are one of the problems that have attracted the attention of engineers. In this research, the aim is to investigate the effect of artificial on the floodplain of the compound channel on hydraulic parameters. In experiments, slope of channel bed was 0.0015 and three different discharges have been used. The four types of rigid roughness were used to investigate the effect of these parameters. These roughness elements were arranged with zigzag state with two distances of 4 k and 8 k (k is the height of roughness) in the floodplain. A Preston tube with an external diameter of 3 mm that equipped with dynamic pressure sensors was used to compute the shear stress. The Patel calibration curve was used in order to convert the difference between the static and dynamic pressure measured by the Preston tube to the shear stress values. The results showed that for the zigzag arrangement with the density of 4 k, the shear stress is reduced due to the high roughness density and the greater roughened area. In a rough bed, the shear stress in floodplain was significantly higher than smooth bed, and the stress distribution is such that it has descending trend from the main channel toward the wall of the floodplain. The shear stress increase for roughness with a spacing of 8 k is 22–36% higher than the similar hydraulic condition in a smooth bed and the shear stress for condition with the presence of a cylinder with $D = 3$ cm and roughness spacing of 8 k was 14–18% higher than the shear stress of bed without a cylinder and the same roughness density. The shear stress for condition of the presence of a cylinder with $D = 6$ cm and roughness spacing of 4 k is 24–30% more than the roughened plain with distances of 4 k.

Keywords Compound channel · Floodplain · Preston tube · Shear stress distribution · Roughness

Introduction

Compound channels are hydraulic sections that consist of a main section and floodplains. The main channel has a lower level of the floor and generally has a general section close to the rectangle or trapezoid. This section conveys the usual runoff and base flood, which flow mostly the river, and the floodplain is a part of the compound channel, that the bed level is above the main channel and is located on one or two sides of the main channel. This part does not play a role in the conveyance and only was used during occurrence of flood. It generally has a significant vegetation cover. In natural river, the flow is established in the main channel and the walls of the main channel are composed of stones

and sediment materials and it has poor vegetation, so the hydraulic roughness is less compared to the floodplain. The vegetation on the floodplain in the walls and bed produces a surplus hydraulic resistance against the flow that is very effective on hydraulic parameters such as water surface profiles and the bed shear stresses.

The flood in river and environmental adjustment depend on the flow structure in the channel with vegetation, so study of the environmental hydrology and flow characteristics is essential. The resistance against water flow and turbulence properties of flow on vegetation in the channel play an important role in flood control and environmental stability. The velocity of flow decreases due to the resistance of the vegetation and causes the water pollution has been adsorbed. i.e. in a stream channel and along the river banks it may be effective pollutant filters. On the other hand, the roughness on the bed reduces the destruction and erosion of the river bed, which helps to maintain stability of the channel. In addition, during flood periods, the presence of vegetation

✉ Akram Abbaspour
akabbaspour@yahoo.com

¹ Water Engineering Department, University of Tabriz, Tabriz, Iran

decreases the velocity, increases water level, reduces flood discharge capacity and ultimately reduces flood disasters.

Nikuradse (1933) and Perry et al. (1969) have studied the effect of rough-wall boundary condition on the mean velocity distribution in the inner region. The skin friction coefficient for trapped timber element was measured an average values of 4.11×10^{-3} . Also in equation of velocity profile, the variation in the constant values can be explained by the roughness geometry. Bisceglia et al. (2001) studied the effect of two different types of bed roughness on a turbulent boundary layer. The roughness consisted of square ribs and cylindrical rods with horizontal distances of 2 k and 4 k, respectively. For square ribs and cylindrical rods, the wall skin friction, C_f , was obtained 3.84×10^{-3} and 9.08×10^{-3} , respectively.

Stone and Shen (2002) have studied hydraulic resistance of flow in open channels with cylindrical. The apparent mean velocity and the surface layer velocity in rough beds were obtained by physical base formulas. Guo and Julien (2005) investigated the shear stress for bed and walls of a rectangular open channel. The bed shear stress has been determined by continuity and momentum equations.

Coleman et al. (2007) studied fully rough turbulent subcritical flow over the rib roughness with various spacing of $p/k = 1-16$ (roughness spacing/), with $k/H = 0.09$ (height/flow-surface elevation ratio). The Reynolds stress above the rib roughness increased with depth of flow and rib spacing. For tight ribs ($p/k < 5$), the form-induced stresses were nearly zero above the rib. Application of the double-averaging methodology to open channel flows over rough beds was done by Nikora et al. (2004). Volino et al. (2009) investigated turbulence structure of flow over the bar roughness, and they compared results to previous studies on a smooth wall. The instantaneous velocity vector fields were measured between and over the roughness elements. The two-dimensional bars caused to considerable variation in the turbulence in the outer flow.

Liu et al. (2013) proposed a method to model the velocity and bed shear stress distributions in compound channels with emergent and submerged vegetation. The secondary current coefficient K was obtained for vegetated floodplain, in range of 1–8% in a compound channels. The results showed that the proposed model can predict the lateral depth-averaged velocities and bed shear stress distributions with good approximation.

Zhao et al. (2014) have done experimental study of free surface fluctuation in open channel in the presence of cylinders the particle image velocimetry method was used to measure velocity vector fields by Zhao et al. (2014). Also the mean drag force was measured using a load on rigid cylinder arrays in open channel flows. The results showed that the relative drag fluctuation to mean value was obtained up to 133% for the Reynolds number in the range of 400–100.

Liu and Zeng (2016) conducted a series of experiments to estimate the drag coefficient (C_d), and an empirical equation was determined describing the relationship between C_d and Reynolds number, Froude number; and vegetation characteristics in subcritical flow.

Shan et al. (2016) suggested a new method to estimate the bed shear stress in smooth and vegetated compound channels using the Darcy–Weisbach equation. The present method is studied in two smooth compound channels with different geometries and in a compound channel with vegetated floodplain.

The objective of this research is to investigate the effect of the roughness and a rigid cylinder on the characteristics of a flow in a compound channel. Measurement of water depth, velocity distribution and the bed shear stress are done for different flow discharges.

Materials and methods

The experiments were conducted in a metal and glass flume with a rectangular cross section for half of the compound channel. The flume was 0.8 m wide, 0.5 m deep and 10 m long. The width of the trapezoidal main channel and the floodplain was same (40 cm), and the channel side slopes were 1:1. The slope of the channel was 0.0015. The discharge was measured with a rectangle sharp weir placed at the end of the flume. The discharge–head relationship ($Q-h$) for the rectangle weir in the experiments was $Q = 1.708(0.6 - 0.2h)h^{1.5}$ with h is hydraulic head on a weir crest.

In each test, the upstream subcritical depth and the water depths along the flow (water surface) were measured using point gauges of 0.1 mm accuracy. The experiments were conducted with three types of rigid roughness and three different Froude numbers. A total of 21 experiments were carried out including 3 experimental with smooth bed and 18 experiments with roughed bed (Table 1). The cylinder diameter was 0.03 and 0.06 cm, and the height (k) and length of cubes were 0.025 and 12 cm, respectively (Fig. 1).

The u velocity (in direction of flow) \times was measured using a micro-propeller velocity meter in 5–10 mm vertical spacing, and the instant pressure of the flow in the bed of the channel was measured using pressure transmitter (± 100 mm bar, accuracy of 0.4%). The pressure data were recorded using 6CH Pressure DAQ software.

The bed shear stress was measured by the Preston tube. The differential pressure between the high and low pressure port on the Preston tube was recorded in the center of the flume for each section. An average of the differential pressure readings was recorded in the form of pressure head. The shear stress was calculated from differential pressure with Patel (1965) method and calibration curve.

Table 1 Summary of experiments with roughed bed

Roughness arrangement	Slope of bed	Distances of roughness (k)	Length of roughness (cm)
E (1-1)	0.0015	8	12
E (1-2)		4	12
E (2-1)		8	12
E (2-2)		4	12
E (3-1)		8	12
E (3-2)		4	12
E (4-1)		8	12
E (4-2)		4	12

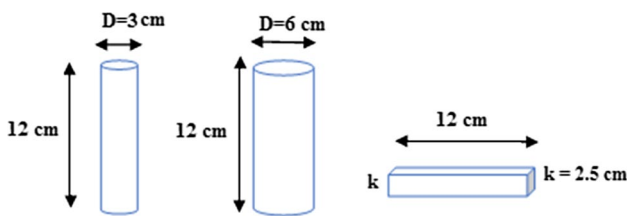


Fig. 1 Roughness element geometry

The non-dimensional differential pressure (x^*) and shear stress parameters (y^*) could be estimated from following Equations.

$$y^* = 0.5x^* + 0.037 \quad \text{for } 0 < y^* < 1.5, D^+ < 11.2$$

$$y^* = 0.8287 - 0.1381x^* + 0.1437x^{*2} - 0.006x^{*3} \quad \text{for } 1.5 < y^* < 3.5, 11.2 < D^+ < 110$$

$$x^* = y^* + 2 \log(1.95y^* + 4.1) \quad \text{for } 3.5 < y^* < 5.3 \quad (1)$$

where $x^* = \log\left(\frac{\Delta P d^2}{4\rho v^2}\right)$, $y^* = \log\left(\frac{\tau_w d^2}{4\rho v^2}\right)$, $D^+ = \frac{du^*}{\nu}$ = Reynolds number, d = diameter of Preston tube, ν = kinematic viscosity of water, τ_0 = wall shear stress, and u^* = shear velocity.

The wall and bed shear stress (τ_w and τ_b) can be expressed as a function of the independent variables of u^* ; L ; ν ; g ; v ; y_1 ; y_2 ; b_1 ; b_2 ; k ; S and D ; where u^* is the shear velocity, L is the length of roughened bed, g is the acceleration due to gravity, ρ is the density of water, ν is the viscosity of water, v is the mean velocity of flow, b_1 is the width of the main channel, b_2 is width of floodplain, y_1 and y_2 are depths of flow in the main channel and floodplain, k is the height of roughness, S is the slope of the bed, and D is rod diameter.

$$f(\tau_b, \tau_w, u^*, L, \rho, \nu, g, v, y_1, y_2, b_1, b_2, k, S, D) = 0. \quad (2)$$

By applying the Buckingham π theorem, the following equation was obtained:

$$\frac{\tau_b}{\gamma y_2 S} \text{ or } \frac{\tau_w}{\gamma y_2 S} = f_1\left(\text{Fr}, \text{Re}^*, \frac{k}{y_2}, \frac{b_1}{y_2}, \frac{b_2}{y_2}, \frac{y_1}{y_2}, \frac{L}{y_2}, \frac{D}{y_2}, S\right) \quad (3)$$

where Fr is the flow Froude number of compound channel, Re^* is shear Reynolds of flow, $\frac{k}{y_2}$ is relative roughness, $D_r = \frac{y_2 - y_1}{y_2}$ is the relative depth of flow, $\frac{b_1}{y_2}$, $\frac{b_2}{y_2}$ are the width–depth ratios, $\frac{\tau_w}{\gamma y_2 S}$ and $\frac{\tau_b}{\gamma y_2 S}$ are non-dimensional wall and bed shear stress.

$$\frac{\tau_b}{\gamma y_2 S} = \left(\text{Fr}, \text{Re}^*, \frac{k}{y_2}, \frac{b_1}{y_2}, \frac{b_2}{y_2}, D_r = \frac{y_2 - y_1}{y_2}, \frac{L}{y_2}, \frac{D}{y_2}, S\right) \quad (4)$$

$$\frac{\tau_w}{\gamma y_2 S} = \left(\text{Fr}, \text{Re}^*, \frac{k}{y_2}, \frac{b_1}{y_2}, \frac{b_2}{y_2}, D_r = \frac{y_2 - y_1}{y_2}, \frac{L}{y_2}, \frac{D}{y_2}, S\right) \quad (5)$$

Because b_1, b_2, L and S are constants, they can be ignored. Hence, Eqs. (4) and (5) are reduced to Eqs. (6) and (7):

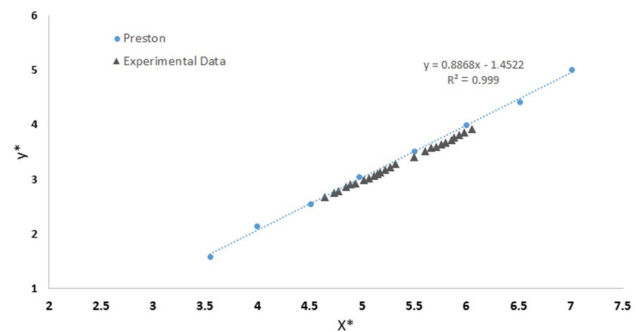


Fig. 2 Non-dimensional shear stress parameters y^* versus differential pressure x^*

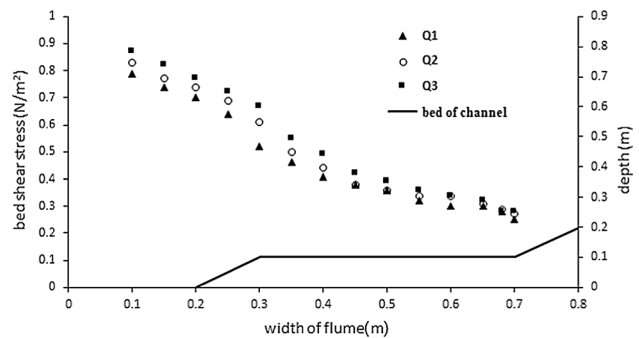


Fig. 3 Comparison between measured turbulent shear stress for different flow rates with the smooth plain

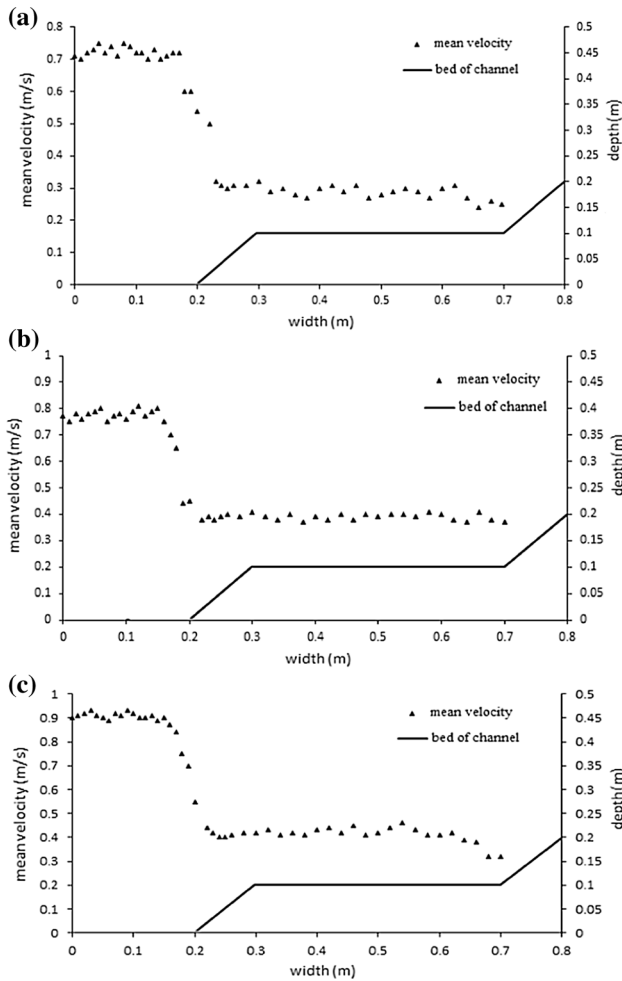


Fig. 4 The variation of mean velocity of flow in smooth compound channel a Q_1 , b Q_2 and c Q_3

$$\frac{\tau_b}{\gamma y_2 S} = \left(Fr, Re^*, \frac{k}{y_2}, D_r = \frac{y_2 - y_1}{y_2}, \frac{D}{y_2} \right) \quad (6)$$

$$\frac{\tau_w}{\gamma y_2 S} = \left(Fr, Re^*, \frac{k}{y_2}, D_r = \frac{y_2 - y_1}{y_2}, \frac{D}{y_2} \right) \quad (7)$$

Results

The experimental calibration curve is plotted in Fig. 2. The non-dimensional shear stress parameters y^* versus differential pressure x^* show good agreement between the experimental results and Preston method.

Figure 3 shows the bed shear stress for different rates of flow in smooth bed. It can be seen that the bed shear stress is decreasing from the main channel toward plain channel.

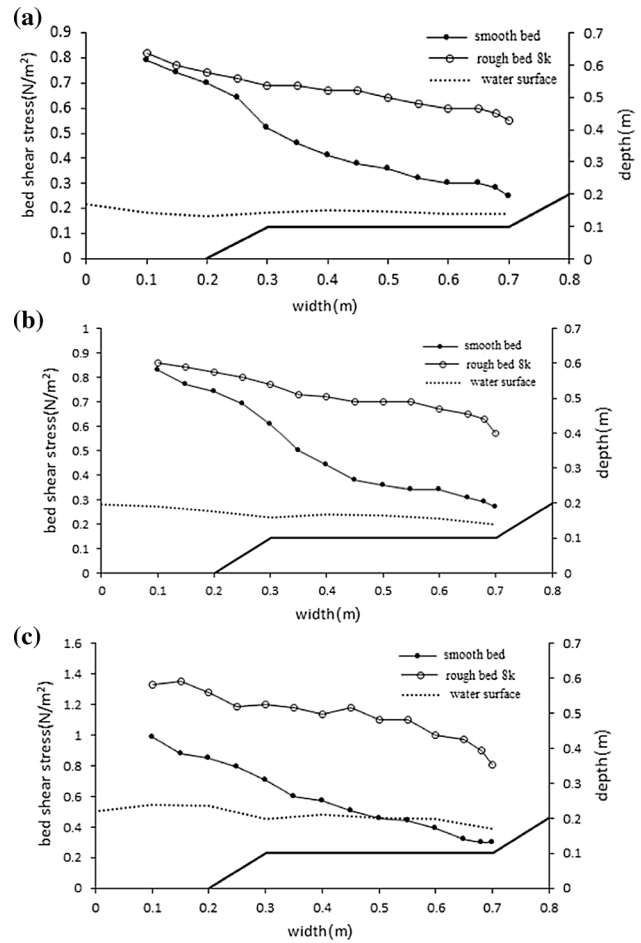


Fig. 5 Comparison of the bed shear stress in smooth and roughened compound channel (roughness distances of 8 k) a Q_1 , b Q_2 and c Q_3

Also the bed shear stress has increased by increasing of flow rate.

Figure 4 shows the mean velocity of flow in the smooth main and plain sections of the compound channels for different rates of flow. It can be concluded that the mean velocity of flow is decreasing from the main channel toward plain channel because the width of plain section is more than the main section of the compound channel. The resistance coefficient is a key parameter to determine the general resisting shear forces on the bed. The boundary shear stresses can be expressed in terms of the corresponding resistance coefficients as: $\tau_0 = f \frac{\rho v^2}{8}$ where ρ is water density, f is the effective resistance coefficient, and v is mean velocity in floodplain. The resistance coefficient f is estimated 0.016–0.028 in smooth floodplain.

Figure 5 shows the bed shear stress in smooth and roughened plain channel (with distances of 8 k) for different rates of flow. It can be seen the bed shear stress is decreasing from the main channel toward plain channel. Also the bed shear

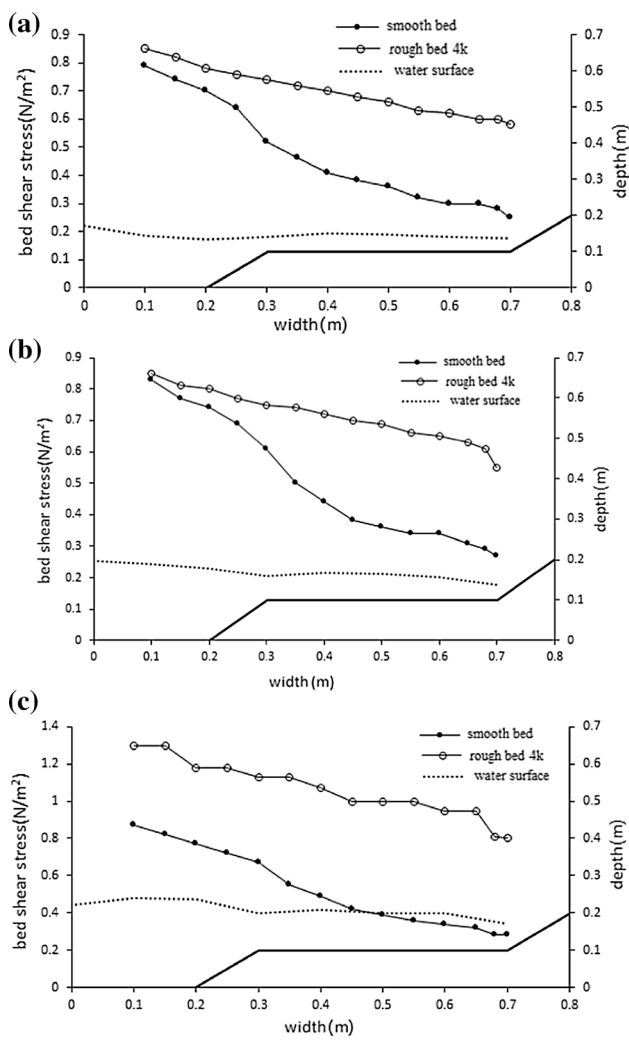


Fig. 6 Comparison of the bed shear stress in smooth and roughened plain channel (roughness distances of 4 k) **a** Q_1 , **b** Q_2 and **c** Q_3

stress has increased by increasing of flow rate. The shear stress increase for roughness with a spacing of 8 k is 22–36% higher than the similar hydraulic condition in a smooth bed. The resistance coefficient f is estimated 0.25–0.28 in roughened plain channel with distances of 8 k.

Figure 6 shows the bed shear stress in smooth and roughened plain channel (with distances of 4 k) for different rates of flow. It can be seen that the bed shear stress is decreasing from the main channel toward plain channel. The resistance coefficient f is estimated 0.3–0.4 in roughened plain channel with distances of 4 k.

Figure 7 shows the bed shear stress in the roughened plain (with distances of 8 k) and roughened plain with the presence of a pier ($D = 3$ cm) for different rates of flow. It can be concluded that the bed shear stress in the roughened plain

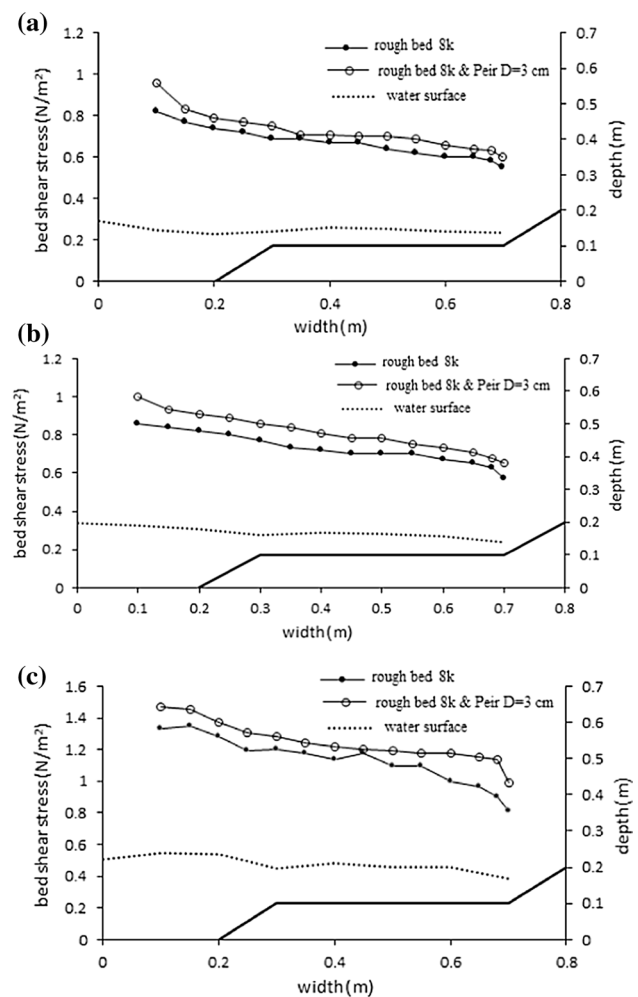


Fig. 7 Comparison of the bed shear stress in a roughened plain with the presence of a pier ($D = 3$ cm) and roughened plain (distances of 8 k) **a** Q_1 , **b** Q_2 and **c** Q_3

with the presence of a pier ($D = 3$ cm) is 14–18% more than the roughened plain with distances of 8 k. Also the bed shear stress has increased by increasing of flow rate. The resistance coefficient f is estimated 0.28–0.33 in roughened plain channel (with distances of 8 k) with the presence of a pier ($D = 3$ cm).

Figure 8 shows the bed shear stress in the roughened plain (with distances of 8 k) and roughened plain with the presence of a pier ($D = 6$ cm) for different rates of flow. It can be seen that the bed shear stress in the roughened plain with the presence of a pier ($D = 6$ cm) is 18–23% more than the roughened plain with distances of 8 k. Also the bed shear stress has increased by increasing of flow rate. The resistance coefficient f is estimated 0.3–0.33 in roughened plain

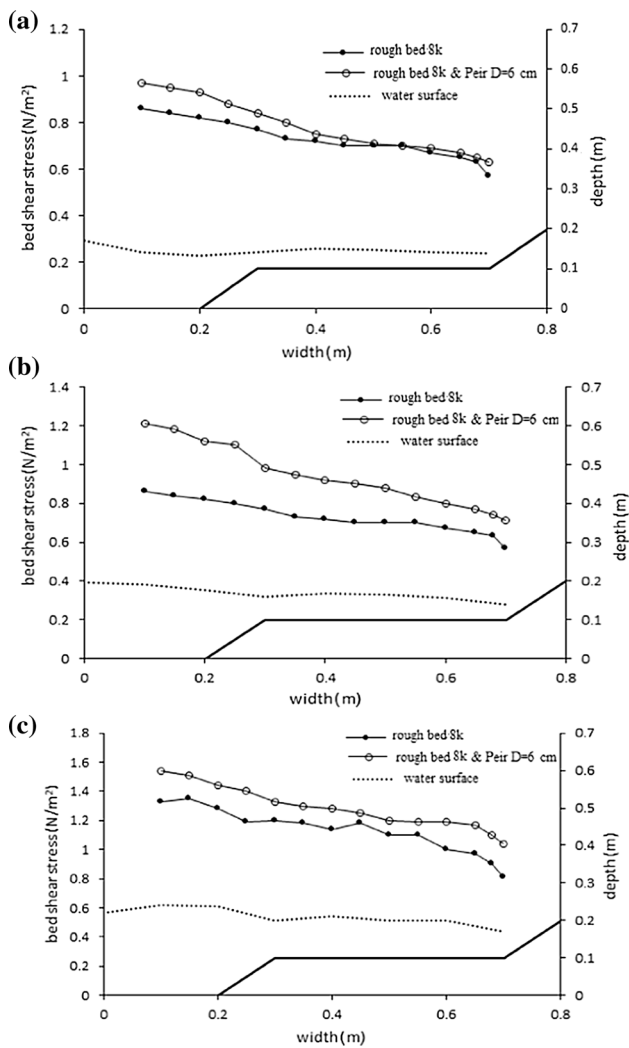


Fig. 8 Comparison of the bed shear stress in a roughened plain with the presence of a pier ($D=6$ cm) and roughened plain (distances of 8 k) **a** Q_1 , **b** Q_2 and **c** Q_3

channel (with distances of 8 k) with the presence of a pier ($D=6$ cm).

Figure 9 shows the bed shear stress in the roughened plain (with distances of 4 k) and roughened plain with the presence of a pier ($D=3$ cm) for different rates of flow. It can be concluded that the bed shear stress in the roughened plain with the presence of a pier ($D=3$ cm) is 23–29% more than the roughened plain with distances of 4 k. The resistance coefficient f is estimated 0.35–0.45 in roughened plain

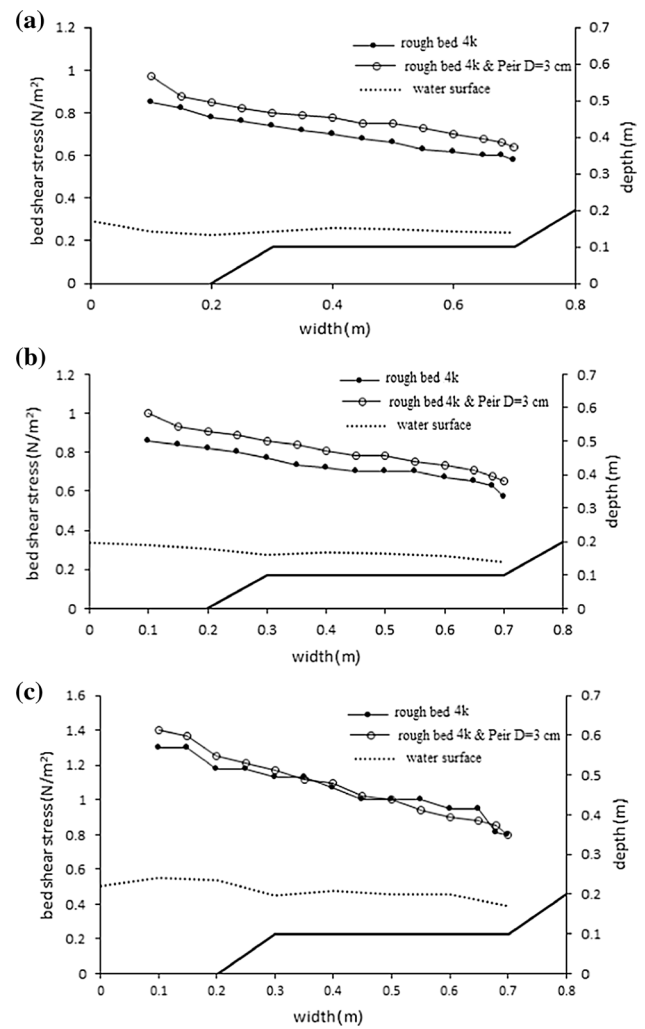


Fig. 9 Comparison of the bed shear stress in a roughened plain with the presence of a pier ($D=3$ cm) and roughened plain (distances of 4 k) **a** Q_1 , **b** Q_2 and **c** Q_3

channel (with distances of 4 k) with the presence of a pier ($D=3$ cm).

Figure 10 shows the bed shear stress in the roughened plain (with distances of 4 k) and roughened plain with the presence of a pier ($D=6$ cm) for different rates of flow. It can be seen that the bed shear stress in the roughened plain with the presence of a pier ($D=6$ cm) is 24–30% more than the roughened plain with distances of 4 k. The resistance coefficient f is estimated 0.32–0.45 in roughened plain channel (with distances of 4 k) with the presence of a pier ($D=6$ cm).

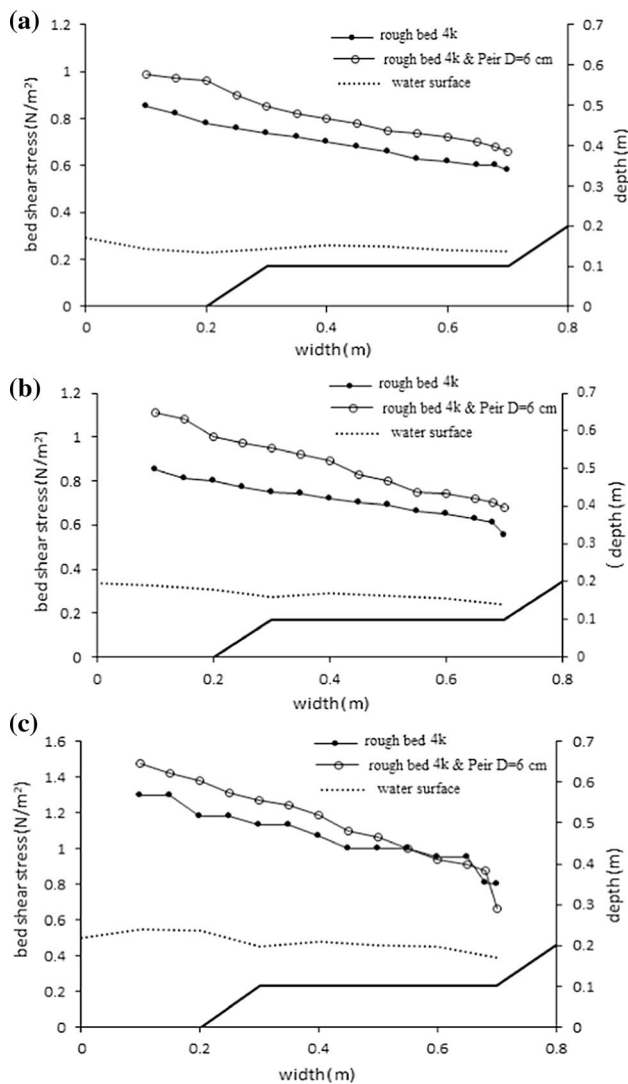


Fig. 10 Comparison of the bed shear stress in a roughened plain with the presence of a pier ($D=6$ cm) and roughened plain (distances of 4 k) **a** Q_1 , **b** Q_2 and **c** Q_3

Conclusions

The objective of these experiments was to predicting bed shear stress in the rough compound channel. The results showed the bed shear stress increased with roughness element density and presence of a pier.

In particular, the bed shear stress distribution was seen to decrease more rapidly along the flume near the main channel and floodplain interface in smooth floodplain compared to the roughened cases. This phenomenon can be regarded as a consequence of the greater resistance generated by the roughness elements. Further away from this interface, differences between the bed shear stress values are small.

For resistance calculations, combining the effects of the channel bed and roughness interfaces were used. The results showed that f was dependent on the roughened bed type. A value of $0.016 \leq f \leq 0.028$ was obtained for smooth floodplain channel, while the range of $0.25 \leq f \leq 0.45$ is estimated for roughened floodplain. As the diameter of a pier (D) has increased the resistance coefficient, f has not changed for same roughness element density (4 k or 8 k) due to the presence of single cylinder so the effect of cube roughness on the flow resistance was more important.

Funding This study was funded by University of Tabriz.

Compliance with ethical standards

Conflict of interest The author has received research grants from University of Tabriz.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Bisceglia S, Smalley RJ, Djenidi L, Antonia RA (2001) Structure of rough wall turbulent boundary layers at relatively high Reynolds number. In: 14th Australasian fluid mechanics conference, Adelaide, Australia, pp 195–198
- Coleman SE, Nikora VR, McLean SR, Schlicke E (2007) Spatially averaged turbulent flow over square ribs. *J Eng Mech ASCE* 133:194–204
- Guo J, Julien PY (2005) Shear stress in smooth rectangular open-channel flows. *J Hydraul Eng* 125(3):30–37
- Liu XG, Zeng YH (2016) Drag coefficient for rigid vegetation in sub-critical open channel. *Procedia Eng* 154:1124–1131
- Liu C, Luo X, Liu X, Yang K (2013) Modeling depth-averaged velocity and bed shear stress in compound channels with emergent and submerged vegetation. *Adv Water Resour* 60:148–159
- Nikora V, Koll K, McEwan I, McLean S, Dittrich A (2004) Velocity distribution in the roughness layer of rough-bed flows. *J Hydraul Eng ASCE* 130:1036–1042
- Nikuradse J (1933) Laws of flows in rough pipes, NACA Technical Memorandum 1292. Verein Deutscher Ingenieure, Berlin
- Patel VC (1965) Calibration of the preston tube and limitations on its use in pressure gradients. *J Fluid Mech* 23:185–208
- Perry AE, Schofield WH, Joubert PN (1969) Rough wall turbulent boundary layers. *J Fluid Mech* 37:383–413
- Shan Y, Liu C, Luo M, Yang K (2016) A simple method for estimating bed shear stress in smooth and vegetated compound channels.

J Hydrodyn Ser B 28(3):497–505. [https://doi.org/10.1016/s1001-6058\(16\)60654-6](https://doi.org/10.1016/s1001-6058(16)60654-6)

Ston B, Shen HT (2002) Hydraulic resistance of flow in channels with cylindrical roughness. J Hydraul Eng 128(5):500–506

Volino RJ, Schultz MP, Karen AF (2009) A Turbulence structure in a boundary layer with two-dimensional roughness. J Fluid Mech 635:75–101

Zhao K, Cheng NS, Wang X, Tan SK (2014) Measurements of fluctuation in drag acting on rigid cylinder array in open channel flow.

J Hydraul Eng 140(1):688–721. [https://doi.org/10.1061/\(asce\)hy.1943-7900.0000811](https://doi.org/10.1061/(asce)hy.1943-7900.0000811)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.