A Review of Different Approaches for Boundary Shear Stress Assessment in Prismatic Channels

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Abstract The stress range of shear at the channel's boundaries has a direct bearing on the flow of fluid inside the channel. Hence, understanding it is critical for defining the fluid field and velocity profile. Many engineering issues, such as design of flood control structures, energy loss calculation, and sedimentation, require shear stress computation. The proportion analysis between width and depth has strong influence over the stress distribution at shear in direct channels. Sinuosity, aspect ratio, and meander length affect shear stress distribution in meandering channels. Henceforth, the necessity of scrutinizing the methods used to determine the stress distribution in the channels. This paper analyzes the pros and cons of several methodologies that helps to estimate the allocating the stress ranges of shear via the prismatic channels. The review states that the vertical depth method, the normal depth method, the Guo and Julien method, the Prasad and Manson method, the Knight et al. method, the merged perpendicular method, and the Preston tube technique are the most popular methods that assist to estimate the distribution of boundary shear passing through the channels. This is due to the fact that these methods are straightforward, reliable, and easy to implement. After examining a number of other approaches, it was determined that the Preston tube technique was by far the most effective way in order to determine the stress range for boundary shear in all different kinds of channel sections.

Keywords Open channel flow · Prismatic channels · Boundary shear stress distribution

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1   Introduction

It is well known wherein the allotment of stress ranges around boundary shear does not coordinate with route near the perimeter of wetted via channel cross-partition. It follows a steady flow in cross-partition structures. This phenomenon has been thoroughly researched and documented. This is primarily due to turbulence's anisotropy, resulting in transverse Reynold's stress gradients and secondary circulations. According to Tominaga et al. (1989) and Knight and Demetriou (1983), when secondary currents flow directing the wall, the boundary shear stress increases, and when they flow away from the wall, the shear stress decreases. Shear stress distribution in a straight open channel is controlled using the factors count comprising the geometrical properties of cross-partition, the distribution of roughness along the longitudinal and lateral boundaries, and the concentration of sediment (Khodashenas et al. 2008). The collected information states that the variant solutions available to estimate the stress value of boundary shear via directly or indirectly. The indirect estimation of stress value of boundary shear is done using Preston method. Due to this limitation and deficits, it is difficult to estimate the observed and predicted stress distribution across the wetted area (Patel 1965). Pertaining to it, a variant set of empirical, computational, and the analytical strategies are been introduced to forecast the stress value near the boundary shear.

2   State-of-Art

According to Leighly (1932), an estimation of stress distribution in public channel was studied using the conformal mapping process. Due to the mishandling of secondary order constraints, the weight analysis of water flow in upward comprised of boundaries that has to be balanced in orthogonal direction. The investigation of hydraulic radius was studied by Einstein (1942) has been widely used in many parts of academic sectors and also in practice. With the use of Bagnold's three-point suspension technique, the shear distribution in rough and smooth public channels holding the cross-partition of trapezoidal and rectangular was studied by Ghosh and Roy (1970). It was measured and isolated on the part of tested public channels. The outcomes of the distribution of boundary under two-stage channels on the plain and coarse borders are portrayed by Ghosh and Mehta (1974). Finally, the shear distribution is not consistent, and the placements of the various distances in free surface are summarized.

The Rajaratnam and Ahmadi (1979) explored the interaction analysis between direct primary channels with symmetrical plain under a smooth boundary condition was studied. The investigation revealed that the longitudinal momentum of the water was carried via the main river to the floodplain. The bed shear in the floodplain rose dramatically as a result of flow interaction, although it decreased in the primary channel itself. The floodplain is located at the point where the main channel meets

the floodplain. The interaction's influence became less significant since the flow analysis of the depth in floodplain was inclined. As per the knight (1981), the fractional analysis of shear is performed on the walls using breadth and depth proportion analysis. Along with that, the roughness size related to the bed and walls is being studied in Nikuradse. The separation of channels that has been explored in the laboratory research is symmetrical. The analysis of the boundary shear is to calculate the stress value of shear has been done via the primary channels and the floodplain. It is possible to encounter the boundary shear. The identification of channel allocation to compute the discharge value was been studied. By the use of direct channels, the characteristics of boundary shear stress and its distribution are explored in Knight and Demetriou (1983). It was designed on the basis of measuring the shear force under different flows in different sub-partitions.

This was done in relation to two channel features that lacked dimensions: the floodplain and the compound section. Knight and Hamed (1984) concentrated their attention on rocky floodplains, following in the footsteps of Knight and Demetriou (1983). The investigation of the lateral momentum transfer to disclose the discrepancies in roughness is being studied among the primary channels and the floodplain. These floodplains are tightened in different stages to show the discrepancies. A set of equations has been formulated to analyze in vertical, horizontal, diagonal, and bisected interface plains to estimate the force value in shear. A set of equations that are based on four dimensionless channel properties has been supplied. Knight and Patel (1985) have given outcomes in finding out the relation between the stress distribution between the smooth and rectangular cross-partition that achieved the aspect ratios from one to ten. It was discovered that the distributions are controlled by the aspect ratio, as well as the aspect ratio's influence on the amount and type of secondary flow cells.

In order to investigate stress allotment in boundary shear by the use of smooth surface and complete circular parts, Knight and Sterling (2000) employed the Preston tube method as their method of analysis. It has been established that the Froude number and shape have an effect on the distribution of boundary shear stresses. After solving the continuity and momentum equations, Guo and Julien (2005) offered an approach to estimate the mean value for the bed and sidewall shear stress in smooth rectangular public-channel flows. This strategy was developed after the continuity, and momentum equations were solved. According to the findings of the experiment, the shear stresses are a result of three different components: (1) the shear stress at the interface between two different materials; (2) gravity; and (3) secondary flows. The amount of the total boundary shear force that may be attributed to the wall shear force was analyzed as part of a research that was carried out by Lashkar et al. (2010). They analyzed the data using nonlinear regression in order to construct equations that would allow us to calculate the percentages of shear stress near wetted regions that relying on the beds and sidewalls of rectangular cross-partition. In the case of meandering channels, the distribution of shear force was studied by Khatua and Patra (2010) that amends the sinuosity and geometrical properties of adopted channels. Similar to it, the Preston tube was studied by Naik and Khatua (2016) to determine the boundary of non-prismatic channels. Rather than the adoption of theoretical

approaches, the findings of those methodologies were far better than the findings of shear stress with the use of energy related gradient process. Using the Preston tube method, Prasad et al. (2022) were able to make a prediction about the border shear stress in diverging compound channels. According to the data, the strategy achieves favorable outcomes in both the smooth bed and gravel bed circumstances when compared to other approaches. This is the case regardless of the kind of bed. There has been progress made in the understanding of the relationships between boundary shear, geometry, and sinuosity. It is also possible to evaluate the models using data obtained from other researchers who have publicized the results of their study.

3 Classes of Variant Methodologies

3.1 Geometrical Methods

With the help of geometrical analysis, the cross-partitions are divided into the set of different sub-partitions. Each shear force may be calculated by first achieving a balance between the forces and fluid weight in each sub-region of the boundary that has been partitioned. Methods such as Leighly's (1932), Einstein's (1942), NDM, NAM, VAM, and NPM are also explored in this study.

3.2 Empirical Methods

Curve fitting to experimentally collected data is a common approach in empirical research. Knight's (1981) model may be the first of its sort. Other researchers have incorporated his approach into their work, including Knight and his colleagues (1984). Similar basic models for the boundary shear stress were proposed by Olivero et al. (1999).

3.3 Analytical Methods

Continuous, momentum, and energy transport equations are used in analytical approaches. It is possible to solve open-channel shear stress using some of these approaches. Yang and Lim (2005), Guo and Julien (2005), and Bilgil (2005) are a few examples of analytical methods.

3.4　Computational Methods

The shear stress value near boundaries, the analysis of turbulence-based closure model, and the motion formulation are employed to yield the accurate outcomes. To forecast the shear stress at boundary in primary flow channels, Cacqueray et al. (2009) have considered the SSG-based Reynolds model in computational fluid dynamics software. Though it permits to resolve the formulation of motion, yet the determination of order in boundary shear is not comparable. Hence, the proper examination of sediments analysis is done to find out the allotment of stress value near the local shear. The accurate estimation of local shear stress is employed on all versions of turbulence model. The other usage of empirical, analytical, and computational techniques has been studied. The main intention of these techniques was to estimate the mean value of wall and bed shear either through prismatic or direct channels. It is applied on the number of assumptions that could lead to the independent shear stress. The adoption of quantitative analysis has led to the estimation of boundary shear stress in coordination with prior models. Each of these approaches was chosen because it makes it possible to calculate the boundary shear stress in a comprehensive manner while at the same time being simple enough to be used in engineering applications.

4　Relatable Survey of Prior Methods

4.1　Vertical Depth Method (VDM)

In this way, the local shear stress τi that is acting on one wetted perimeter point denoted by the symbol i is relative to the depth estimation of local water, denoted by the symbol h_i.

$$\tau_i = \rho \mathbf{g} h_i J \tag{1}$$

where

P　density representation of water;
g　acceleration representation of gravity;
J　slope value of the observed energy.

　　The VDM is adaptable to any cross-partition geometry that is considered. On the other hand, it does not encounter the second-order constraints among the channel flow and the relatable floodplains. Added upon, the distribution of roughness under wetted perimeter is consistent across the process.
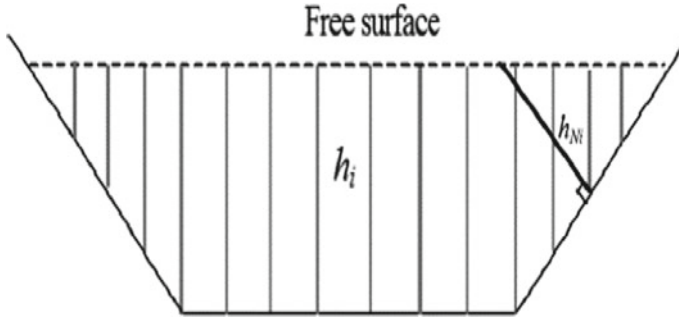
Fig. 1 Visualizations of the VDM and NDM in schematic form (Khodashenas et al. 2008)

4.2 Normal Depth Method (NDM)

The thought process of vertical depth analysis is not used in the estimation of boundary shear stress of the slope at steep side. Thus, NDM was introduced by Lundgren and Jonsson (1964). This is because the steep side slope has a greater potential for shear deformation. They decided to use the normal depth method (NDM) rather than the vertical depth method (VDM). This method involves replacing h_i in Eq. (1) with h_{Ni}, where h_{Ni} is the depth analysis of the flow which is being circulated along the line of the wetted part. It is expressed as follows (Fig. 1):

$$\tau_i = \rho g h_{Ni} J \tag{2}$$

4.3 Merged Perpendicular Method (MPM)

The geometric analysis of the local shear under non-rectangular regions is studied by Khodashenas and Paquier (1999). The merged perpendicular method (MPM) is predicated on the theory of detaching the radius of hydraulic explored by Einstein (1942). This concept is characterized as "a cross-sectional zone bounded by walls splitting into three sub-areas, corresponding to sidewalls and bed, respectively." With the help of transmission lines, the wetter regions are categorized into several sub-regions. These lines are perpendicular to the perimeter of the wetted region in accordance with the procedure (Fig. 2).

i. The perimeter p of the wetted region is partitioned into different tiny segments coordinating with the length P_{il}.
ii. The boundary of each segment is used to draw the perpendiculars L_{i-1} and L_i. These are scrutinized as first order.
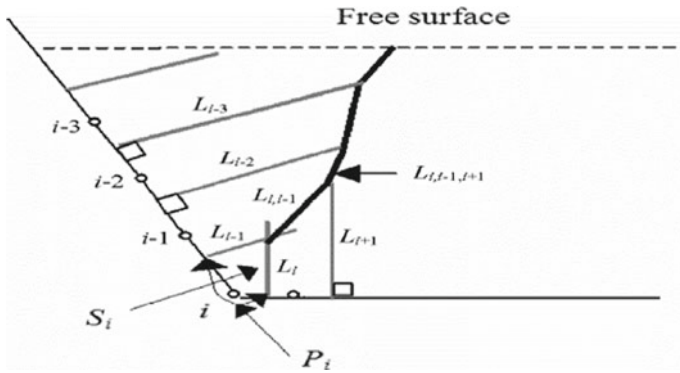
Fig. 2 Illustrations in schematic form of the MPM-determined regions

iii. The common point that meets the perpendicular has the option to elongate for the single line transmission. This is termed as bisector. Henceforth, the angle between the planes and intersection of perpendiculars is represented as

$\hat{L}_{i,i-1} = 1/2(\hat{L}_i + \hat{L}_{i-1})$, wherein the "^" denoting the analysis between the planes and line L_i.

iv. In the case of joining, the common points of order j and k are added up to form order $j + k$. The angle formed among the line and the plane is used to estimate the weighted mean of those lines and planes.

Consider an instance, the order of 1 and 2 are 3. Similar to it, Fig. 2 presents the estimation of angles as:

$$\hat{L}_{i,i-1,i+1} = 1/3(2\widehat{L}_{i,i-1} + \hat{L}_{i+1})$$

v. Every segment of local hydraulic is used to measure the radius as $R_{hi} = S_i/P_i$. This shows the discrepancies with the final lines and the flow area. Therefore, the stress value of the local shear τ_i is then

$$\tau_i = \rho g R_{hi} J$$

The numerical integration of the local values is used to get the mean boundary stresses, which are denoted by the symbols $\overline{\tau}_{(b)}$ and $\overline{\tau}_{(w)}$ represent, respectively, the bed and the sidewall.

Relied on the stress value of local shear, the corners in convex are higher than the corners in concave due to the lower flow of velocity. This proves that MPM model yields better solution than the other models such as VDM, NAM, and NDM (Khodashenas and Paquier 1999). This is because the MPM takes into account the fact that the local shear stresses obtained at convex corners are larger than in concave

corners. This approach, on the other hand, does not take into account the processing of main channels via momentum to the floodplains and the structural flow of secondary constraints. In addition, when the wetted zone is subdivided into smaller sections, the roughness distribution that exists outside the wetted perimeter is not taken into consideration.

4.4 Guo and Julien Method (GJM)

The mean estimation of bed and sidewall shear under rectangular part is estimated using Guo and Julien method. It assists to resolve the momentum and continuity criteria of the formulated part. With use of mapping the conformal constraints, the average of bed and stress value of sidewalls are calculated. On the other side, it eliminates the second constraints and also added the eddy viscosity which is shown in Eq. 3. By the use of Eq. 4, these two factors are integrated.

The formula for calculating the mean value of stress under bed shear is as follows: The secondary constraints are

$$\frac{\overline{\tau}_{(b)}}{\rho g h J} = \frac{4}{\pi^2} \frac{b}{h} \sum_{n=1}^{\infty} (-1)^n \frac{t^{2n-1} - 1}{(2n-1)^2} \text{ with } t = e^{-\frac{\pi h}{b}} \tag{3}$$

With corrections factors

$$\frac{\overline{\tau}_{(b)}}{\rho g h J} = \frac{4}{\pi} Arctg \exp\left(\frac{-\pi h}{b}\right) + \frac{\pi}{4} \frac{h}{b}\left(\frac{-h}{b}\right) \tag{4}$$

The average of the shear stress at sidewalls is given as:

$$\frac{\overline{\tau}_{(w)}}{\rho g h J} = \frac{b}{2h}\left(1 - \frac{\overline{\tau}_{(b)}}{\rho g h J}\right) \tag{5}$$

4.5 Prasad and Manson Method (PMM)

An analytical equation was presented by Prasad and Manson (2002) for the purpose of determining the proportion of shear force, $\%SF_w$. It is analyzed on the cross-partition of trapezoidal shape with the prismatic transfer mode. It was not taken into consideration that there were secondary currents. The proportion among the width and depth, b/h, is multiplied by to arrive at the percentage shear force, $\%SF_w$.

$$\% \mathbf{SF_w} = \frac{100\overline{\tau}_{(w)}}{\overline{\tau}_{(w)} + \overline{\tau}_{(b)}\left(\frac{P_{(b)}}{P_{(w)}}\right)} = \left\{ \begin{array}{l} 25\left(4 - \frac{b}{h}\right)\frac{b}{h} \leq 2 \\ \frac{100}{\frac{b}{h}} \frac{b}{h} \geq 2 \end{array} \right\} \tag{6}$$

Here, the perimeter of bed is represented as $P_{(b)}$, and the perimeter of the sidewall is represented as $P_{(w)}$. Pertaining to it, the percentage analysis of shear stress value is resolved by exploration of $\overline{\tau}_{(b)}$ and $\overline{\tau}_{(w)}$ as:

$$\frac{\overline{\tau}_{(b)}}{\rho g h J} = (1 - 0.01\,\%\,SF_w)\left(1 + \frac{P_{(w))}}{P_{(b)}}\right) \tag{7}$$

$$\frac{\overline{\tau}_{(w)}}{\rho g h J} = (1 - 0.01\,\%\,SF_w)\left(1 + \frac{P_{(b)}}{P_{(w)}}\right) \tag{8}$$

4.6 Knight et al. Method (KAM)

Empirical formulae are provided in order to measure the fraction of the shear force that is being taken up by the sidewall with the cross-partitions of trapezoidal and the roughness estimation of borders by following prismatic transfer mode. A significant number of different experimental data sets were used in order to refine this model. These featured, among other things, subcritical ($F < 1$) flows in straight channels with rectangular and trapezoidal cross-sections, as well as supercritical ($F > 1$) flows in straight channels.

Where $F = u/(gS/b)^{1/2}$ represents value of Froude constant, flow of the velocity as u, width of the surface as b, and the cross-partition area as S. Experiments that were carried out later on by Knight and Sterling (2000) investigated stress range of boundary shear under smooth circular regions under flatbed. They discovered that for $P_{(b)}/P_{(w)} > 1$, denoting the contribution of the force in shear walls by considering a uniform stress values as:

$$\% \mathbf{SF_w} = C_{cf}\mathbf{exp}\left[-3.23\log_{10}\left(\frac{P_{(b)}}{P_{(w)}C_2} + 1\right) + 4.6052\right] \tag{9}$$

For $F < 1$: $C_2 = 1.50$, $C_{cf} = 1$ for $P_{(b)}/P_{(w)} < 6.546$, $C_{cf} = 0.5875(P_{(b)}/P_{(w)})0.28471$ for $P_{(b)}/P_{(w)} \geq 6.546$, and

For $F > 1$: $C_2 = 1.38$, $C_{cf} = 1$ for $P_{(b)}/P_{(w)} < 4.374$, $C_{cf} = 0.6603(P_{(b)}/P_{(w)})0.28125$ for $P_{(b)}/P_{(w)} \geq 4.374$.

4.7 Preston Tube Technique

As a result of how simple it is to use and make the tubes using Preston. It is a kind of technique of measuring stress value of shear that is used rather often. Because of the development of diverse features such as length value of the roughness and the displacement analysis of zero-plane, it is challenging to apply this method to a rough bed, despite the fact that it is straightforward and dependable when used to a bed with a smooth surface. Mohajeri et al. (2017) established a novel Preston tube technique that is applicable for determining the volume of stress value of bed shear in both rough and smooth loose-flow channels. This new device could make formula usage of wall similarity model and the double averaging method. This is in contrast to Preston tube comprising of three tubes of Pitot with a static Prandtl tube. In coordinating to it, other strategies such as laws of logarithmic, stress profile analysis using Reynolds, slope measurement of energy, and the prior use of Preston tube were also tested in order to assure the collection of data quality. In order to do mathematical estimates of the boundary shear stress, Patel (1965) presented the correlations that are as follows:

$$x^* = \log_{10}\left(\frac{\Delta p d^2}{4\rho v^2}\right) \tag{10}$$

$$y^* = 0.5x^* + 0.037 \text{ for } 0 \ < \ y* < 1.5 \text{ and } 0 < x* < 2.9 \tag{11}$$

$$y^* = 0.8287 - 0.1381x^* + 0.1437x^{*2} - 0.0060x^{*3}$$
$$\text{for } 1.5 < y^* < 3.5 \text{ and } 2.9 \ < \ x^* < 5.6 \tag{12}$$

$$y^* = \log_{10}\left(\frac{\tau d^2}{4\rho v^2}\right) \tag{13}$$

Here, the diameter of outer region of Preston tube is represented as d, Δp is the pressure difference between static and total pressure, the density of the liquid is given as ρ, and v is the viscosity of fluid in kinematic. The equations listed above were tested, and one of the following was selected as the best fit for calculating the stress value of wall shear relying on the count of x^* values. The aggregate force value of shear to the unit length is carried on the compound parts of walls that combine with the perimeter of entire region. This allowed for the accurate determination of the total shear force. The analyzed component of the weight force exerted by the liquid along the streamwise direction was compared to the total shear that was measured. It portrays the reliability of the considered ranges. In situations when the experiments were not repeated, the error percentages ranged within ± 5%.

5 Conclusions

Several unique approaches are introduced to perform a comparative study on the boundary shear stress distribution using prismatic channels. In specific to, a simple cross-sectional shapes like circular, rectangular covering the planar and compound sections under uniform boundary roughness. The experiments were conducted on the strategies such as Preston tube technique, the vertical depth method, the normal depth method, the merged perpendicular method, the Guo and Julien method, the Ramana Prasad and Russell Manson method, the Knight et al. method, and the merged perpendicular method.

Each strategy has shown the incredible support of employing it. Consider an instance, the mean calculation of bed and the sidewall shear stresses with respect to the stress value of local shear stress and perimetric distance are explored and discussed. In line to the experimental analysis, the stress value of local boundary shear and the mean of bed and sidewall shear have strong influence over the cross-sectional shape and the roughness estimation of boundary. However, the VDM strategy cannot express accurately of the local shear stress. The most accurate prediction of mean value of bed and the wall shear is obtained by using GJM method. The adoption of varying the eddy viscosity, factors related to presented and observed effects are employed. This conclusion illustrates the need of taking into consideration the secondary current repercussions. Therefore, the PMM and the KAM strategies has been widely employed to forecast the stress value of the wall and the shear. It is mainly tested on the flatbeds in cross-sections of rectangular and circular. Estimates of the local shear stress may be obtained using MPM for cross-sections that have a trapezoidal, rectangular, or circular shape. The MPM has the advantage of being able to adapt to geometries that have an uneven cross-section as well. For compound cross-sections, the MPM provides a fair estimate of the local shear stress provided that the cross-section is not curved, does not have a sharp edge, and does not intersect the main channel-floodplain interface zone of all compound partition. Because the MPM does not take into account lateral flow exchange among primary channel and the floodplain that could unleash the discrepancies. It affects the exchange of lateral flow in the MPM. In other words, the lack of inclusion of lateral flow exchange in the MPM is the cause of these local discrepancies. The outcomes of Preston tube method have the ability to measure the accuracy ranging from ± 15.0 to $\pm 24\%$, respectively, depending on whether the bed is smooth or rough. Because of these precision ranges, it is certain that this device will be useful in open-channel flow research in the future. The procedures described here are effective engineering tools that are not difficult to implement into numerical models. Even when looking at flows in flumes with trapezoidal or complex cross-sections, it might be difficult to identify the boundary shear stress distribution. This is because of the practical difficulties involved. Any cross-sectional shape that has a roughness distribution that is not uniform may be quickly treated using these procedures. For the overall validation of the approaches that have been provided, there has to be a greater number of boundary shear stress

measurements taken in smooth, intermediate, and rough channels with a variety of cross-sectional forms.

References

Bilgil A (2005) Correlation and distribution of shear stress for turbulent flow in a smooth rectangular open channel. J Hydraul Res IAHR 43(2):165–173

Cacueray N, Hargreaves DM, Morvan HP (2009) A computational study of shear stress in smooth rectangular channels. J Hydraul Res IAHR 47(1):50–57

Einstein HA (1942) Formulas for transportation of bed load. Trans Am Soc Civil Eng ASCE 68(8, Part 2):561–577

Ghosh SN, Mehta PJ (1974) Boundary shear distribution in compound channel with varying roughness distribution. Proc Inst Civ Engg 57:159–164

Ghosh SN, Roy N (1970) Boundary shear distribution in open channel flow. J Hydraul Div ASCE 96(4):967–994

Guo J, Julien PY (2005) Shear stress in smooth rectangular open-channel flows. J Hydraul Engg 131(1):30–37

Khatua KK, Patra KC (2010) Evaluation of boundary shear distribution in a meandering channel. In: Proceedings of ninth international conference on hydro-science and engineering IIT Madras Chennai India ICHE 74

Khodashenas SR, ElKadi AK, Paquier A (2008) Boundary shear stress in open channel flow. J Hydraul Res IAHR 46(5):598–609

Khodashenas SR, Paquier A (1999) Geometrical method for computing the distribution of boundary shear stress across irregular straight open channels. J Hydraul Res IAHR 37(3):381–388

Knight DW (1981) Boundary shear in smooth and rough channels. J Hydraul Div ASCE 107(7):839–851

Knight DW, Demetriou JD (1983) Flood plain and main channel flow interaction. J Hydraul Eng ASCE 109(8):1073–1092

Knight DW, Demetriou JD, Hamed ME (1984) Boundary shear in smooth rectangular channels. J Hydraul Eng ASCE 110(4):405–422

Knight DW, Hamed ME (1984) Boundary shear in symmetrical compound channels. J Hydraul Eng 110(10):1412–1430

Knight DW, Patel HS (1985) Boundary shear in smooth rectangular ducts. J Hydraul Eng ASCE 111(1):29–47

Knight DW, Sterling M (2000) Boundary shear in circular pipes running partially full. J Hydraul Engg 126(4):263–275

Lashkar et al (2010) Boundary shear stresses in smooth channels. J Food Agric Environ 132–136

Leighly JB (1932) Toward a theory of the morphologic significance of turbulence in the flow of water in streams. University of California Press, vol 6, no 1–9

Lundgren H, Jonsson IG (1964) Shear and velocity distribution in shallow channels. J Hydraul Div ASCE 90(1):1–21

Mohajeri SH, Akbar S, Salehi N (2017) An innovative Preston tube for determination of shear stress on smooth and rough beds. Iran J Sci Technol Trans Civil Eng 41(2):187–195

Naik B, Khatua K (2016) Boundary shear stress distribution for a converging compound channel. ISH J Hydraul Eng. https://doi.org/10.1080/09715010.2016.1165633

Olivero M, Aguirre-Pey J, Moncada A (1999) Shear stress distribution in rectangular channels. In: Proceeding of XXVIII IAHR Congress Graz Austria p 6

Patel VC (1965) Calibration of the Preston tube and limitations on its use in pressure gradients. J Fluid Mech 23:185–208

Prasad BSS, Sharma A, Khatua KK (2022) Distribution and prediction of boundary shear in diverging compound channels. Water Resour Manage 36(13):4965–4979. https://doi.org/10.1007/s11269-022-03286-y

Prasad R, Manson JR (2002) Discussion of a geometrical method for computing the distribution of boundary shear stress across irregular straight open channels. J Hydraul Res 40(4):537–539

Rajaratnam N, Ahmadi RM (1979) Interaction between main channel and flood-plain flows. J Hydraul Div 105(5):573–588

Tominaga A, Nezu I, Ezaki K, Nakagawa H (1989) Three dimensional turbulent structure in straight open channel flows. J Hydraul Res 27(11):149–173

Yang SQ, Lim SY (2005) Boundary shear stress distributions in trapezoidal channels. J Hydraul Res 43(1):98–102