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Generalization of Shear Stress Distribution in Rectangular Compound Channels

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Abstract

Experimental testing of 5 different types of boundary shear stress distribution in a symmetrical rectangular compound section channel was conducted. Shear stress distributions in the main channel and floodplains of 6 different rectangular compound cross-sections are presented. Numerical values of regression coefficients for the resulting 36 single-variable models representing 5 types of shear stress for each of the 6 cross-sections have been derived. All obtained statistics indicate that the derived regression models are quite good, and can effectively be used to estimate shear stresses with a high degree of reliability for constructed compound cross-sections using relative depth as the single independent variable. A generalized multiple-variable regression model has been derived to predict each of the 5 experimentally measured shear stresses as a function of 3 dimensionless parameters. These 3 dimensionless parameters combine both the depth and horizontal dimensions of the constructed cross-sections. All obtained regression statistics indicate the high reliability of the derived regression model in estimating presented shear stress types in an open channel of a rectangular compound cross-section. A single multi-variable regression model for estimating mean shear stress at the bottom of a rectangular compound cross-section has been formulated using average values of obtained regression coefficients of the multiple-variable regression model.

Key words: Open channel, Compound cross-section, Shear stress generalization.

Introduction

The compound cross-section channel consists mainly of a main channel and floodplain(s). The reduced hydraulic radius of the floodplain and the often higher hydraulic roughness result in lower velocities in the floodplains compared to the main channel. These differences result in a bank of vortices as demonstrated by Knight and Hamid (1984), referred to as "turbulence phenomenon." Therefore, there is a lateral transfer of momentum that results in an apparent shear stress. There will be a reduction in shear stress at the floodplains when compared with the main channel.

Boundary shear stress distribution information in a flowing stream is necessary for many reasons: to give a basic understanding of the resistance relationship, to understand the mechanism of sediment transportation, to design stable channels and to design revetments for channels where meandering phenomena are predominant (Ghosh and Jena, 1971). Flood-routing methods assume a simple cross-section for the purpose of calculating stage-discharge characteristics of rivers. These methods, therefore, ignore the transformation of momentum that results between the main channel and its floodplains (Al-

Khatib and Dmadi, 1999).

Boundary shear stress distribution and flow resistance in compound cross-section channels have been investigated by several authors (Al-Khatib and Dmadi, 1999; Knight and Cao, 1994; Rhodos and Knight, 1994; Rhodos and Lamb, 1991; Myers and Brennan, 1990; Lai and Knight, 1988; Lai, 1986). Al-Khatib and Dmadi (1999) described the effect of the interaction mechanism on shear stress distribution in a channel of compound cross-section. Specifically, the effect of the main channel width and step height on the variation of shear stress distribution has been investigated in both the main channel and its floodplains for constant flow discharges. None of the above mentioned studies had generalized the shear stress distribution in compound cross-section channels.

This paper presents generalized regression models for predicting shear stress distribution as a function of dimensionless variables in symmetrical rectangular compound channels using variable geometries. Six different cross-section geometries have been constructed for this purpose, and 5 different shear stresses have been used to derive single- and multi-variable regression models. The single-variable regression models are derived using relative depth as the only independent variable, whereas the multi-variable regression models utilized 3 dimensionless variables that are related to both the vertical and horizontal dimensions of the constructed compound cross-sections.

Experimental Apparatus and Measurement of Wall Shear Stress

The experimental apparatus and procedure were described in detail by Al-Khatib and Dmadi (1999), and a summary is included here for the benefit of the reader. The experiments in the course of this study were conducted at the Hydromechanics Laboratory of Middle East Technical University, Turkey, using a glass-walled horizontal laboratory flume 9.0 m long, 0.67 m wide and 0.75 m deep. The flow discharge was measured using a rectangular sharp-crested weir. Head measurements over the crest of this weir were performed using a point gauge of 0.01 cm accuracy, and a predetermined calibration curve of the weir was used to determine the discharges. The maximum discharge capacity was about 110 l/s.

For head measurements, a point gauge was used along the centerline of the flume. All depth measurements were made with respect to the bottom of the flume. A pitot tube of circular section with an external diameter of 7 mm was used to measure the static and total head pressures. These pressures were then used for estimating flow velocities and shear stresses at specified channel cross-section points in the experiments conducted.

Six distinct models of rectangular compound cross-sections were manufactured from Plexiglas, and placed about mid-way on the laboratory flume. The plan view, longitudinal profile and typical cross-section of the manufactured models with symbols designating various geometric dimensions are shown in Figure 1. The specific dimensions defining the 6 distinct compound cross-sections were given in Table 1. In this study, tested model types are manufactured by varying the dimensions of the main channel width (B) and main channel step height (Z) of the rectangular compound cross-section. This has resulted in a variable channel floodplain width (B_f) using a constant flume width of 67 cm.

Table 1. Values of dimensions and dimensionless compound cross-section parameters.

Compound Cross-Section Type (j)	B (cm)	Z (cm)	B_f (cm)	$\left(\frac{B_f}{Z}\right)$	$\left(\frac{B_f}{B}\right)$
1	20	5	23.5	4.70	1.18
2	20	10	23.5	2.35	1.18
3	30	5	18.5	3.70	0.62
4	30	10	18.5	1.85	0.62
5	45	5	11.0	2.20	0.24
6	45	10	11.0	1.10	0.24

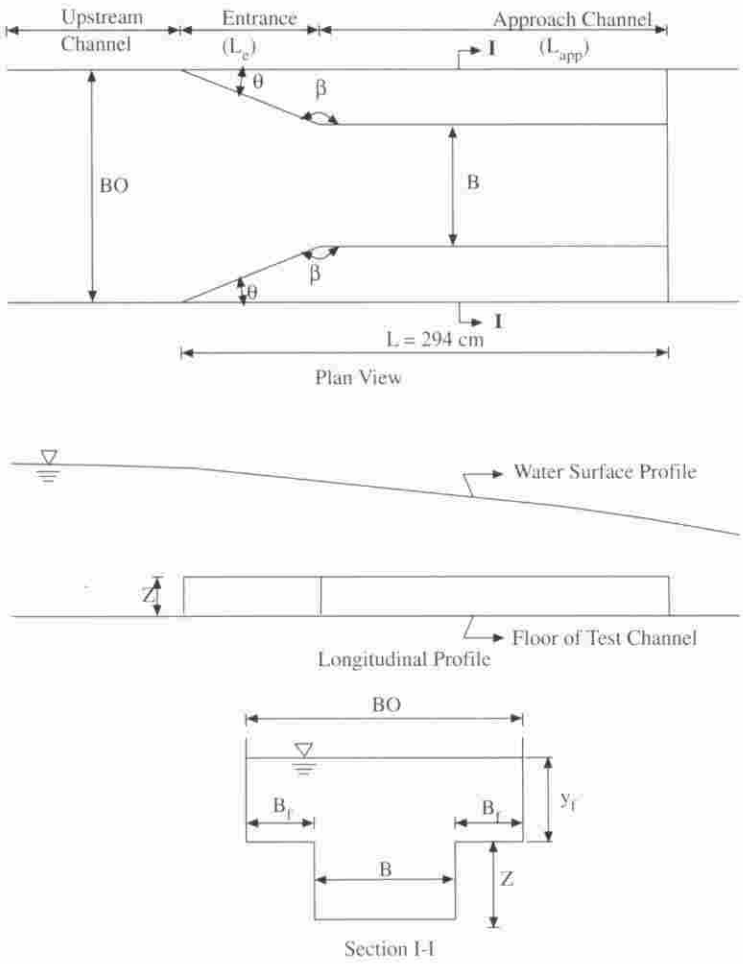


Figure 1. Definition sketch of the flume used in shear stress measurements.

The experiments were first conducted using the models associated with smallest main channel width (B = 20 cm) and varying the main channel step height (Z = 5, and 10 cm). Then, the main channel width (B) was increased to 30 cm at the specified step heights of 5 and 10 cm. Finally, the main channel width was increased to 45 cm using the same 2 specified main channel step heights of 5 and 10 cm. The compound cross-section models were constructed on a horizontal channel. Figure 2 shows the location of shear stress measurement points at the bottom boundary of the rectangular compound cross-section.

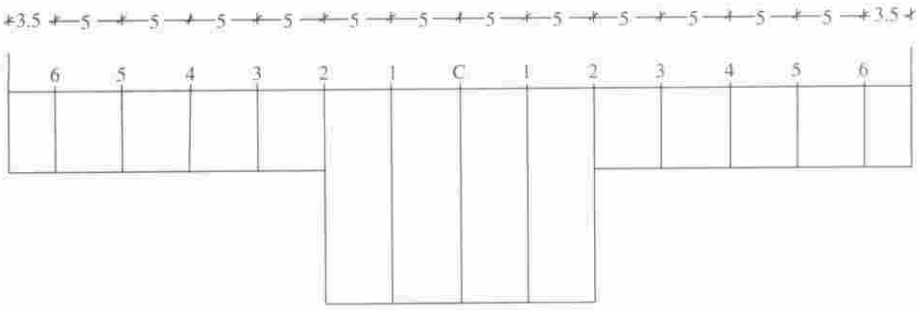
Preston (1954) developed a simple technique for measuring local shear on smooth boundaries in a turbulent boundary layer using a pitot tube (or Preston tube) placed in contact with the surface. The method is based on the assumption of an inner law (law of the wall), which relates the boundary shear stress to the velocity distribution near the wall. Assessment of the near wall velocity distribution is empirically inferred from the differential pressure between the pitot tube and static wall pressure tapping. Patel (1965) undertook further experiments to produce a reliable and definitive calibration curve to replace that developed by Preston. Patel's calibration curve, which has been shown to be reliable, may be summarized as follows (Isaacs and Macintosh, 1990):

$$X^* = \log_{10}\left[\frac{\Delta P d^2}{4\rho\nu^2}\right] \tag{1}$$

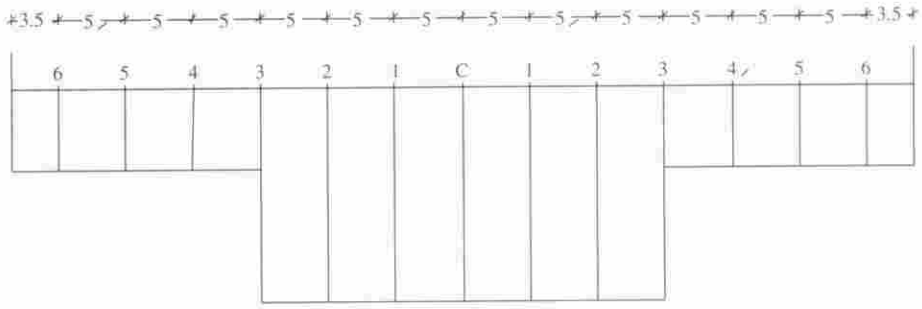
and

$$Y^* = \log_{10}\left[\frac{\tau_0 d^2}{4\rho\nu^2}\right] \tag{2}$$

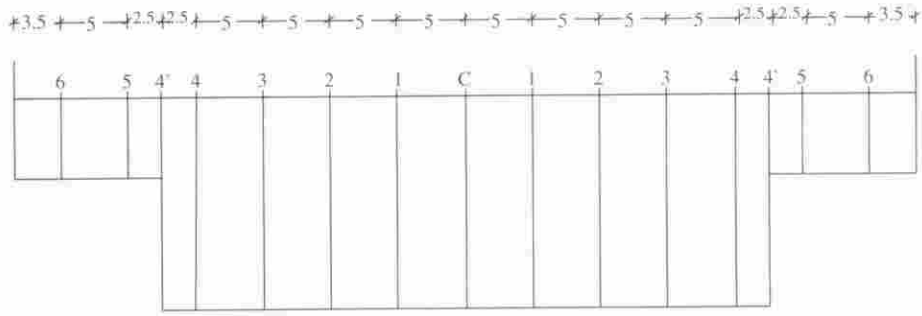
where ΔP= is the Preston tube pressure difference;



(a) Rectangular Compound Cross-Section Types 1 and 2



(b) Rectangular Compound Cross-Section Types 3 and 4



(c) Rectangular Compound Cross-Section Types 5 and 6

Figure 2. Definition sketch of point locations used in shear stress measurements (All location spacings are in centimeters).

d = is the probe outside diameter,

ρ = is the fluid density,

υ = is the kinematic viscosity of the fluid,

τ_0 = is the boundary shear stress,

X^* = is the log of dimensionless differential pressure,

Y^* = is the log of dimensionless shear stress.

Patel (1965) produced 3 equations covering the range $0.0 < Y^* < 5.3$:

$$Y^* = 0.5X^* + 0.037 \tag{3}$$

$$Y^* = 0.8287 - 0.1381X^* + 0.1437X^{*2} - 0.0060X^{*2} \tag{4}$$

$$X^* = Y^* + 2log_{10}(1.95Y^* + 4.10) \tag{5}$$

where Eq. (3) is applicable for $0.0 < Y^* < 1.5$,

Eq. (4) is applicable for $1.5 < Y^* < 3.5$,

Eq. (5) is applicable for $3.5 < Y^* < 5.3$

As can be seen, the Preston-tube method of obtaining wall shear stress is much simpler than the Clauser plot, which requires detailed velocity measurements. The technique has been widely used

for measurement of boundary shear stresses in both smooth and rough open channels. Recent research utilizing the technique includes Knight and Lai (1985), Mc Kee *et al.* (1985), Knight and Demetriou (1984), Baird and Ervine (1984), Knight (1981), and Knight and Macdonald (1979).

To determine the wall shear stress at the bottom of the main channel and along the floodplain bottom, the measurements were taken by the Preston tube at successive points. Following the analysis of measured data and then using Eqs. (3)-(5), the shear stress distributions at the main channel bottom and floodplain bottom were calculated for each experiment.

Presentation and Discussion of Results

Shear stress patterns were obtained for 11 different depths of flow (h), each corresponding to a certain discharge value. Some of these depths were within the main channel step height only, while the others were within the full compound cross-section depth as defined by the specific geometry of each model. The following notations are used to define 5 different types of shear stresses that are obtained from the measurements at corresponding point locations:

T_1 = average shear stress at the bottom of the main channel obtained by averaging the calculated shear stress values as measured at specified points along the main channel cross-section.

T_2 = average shear stress at the bed of floodplains obtained by averaging the calculated shear stress values as measured at specified points along the floodplain cross-section.

T_3 = maximum shear stress at the bottom of the main channel obtained by selecting the maximum calculated shear stress as measured at specified points along the main channel cross-section.

T_4 = maximum shear stress at the bed of floodplains obtained by the selecting the maximum calculated shear stress as measured at specified points along the floodplain cross-section.

T_5 = shear stress at the bottom of main channel centerline, location "c" in Figure 2.

The above 5 shear stress types have been plotted against the relative depth parameter (Y_r) for each of the 6 manufactured compound rectangular cross-sections. Relative depth is defined as the ratio of the depth above floodplain bed (Y_f) to the total depth associated with the compound cross-section (h). Figures 3-8 depict the general trend of the interaction mechanism between the 5 types of shear stress and models of different geometry. All curves shown in these figures reveal one basic trend between the various shear stress types and relative depth, which is of an exponential form. This exponential trend has strongly dominated the general format of all derived prediction models, as will be seen in the following sections delegating the generalization of shear stress distribution by statistical regression.

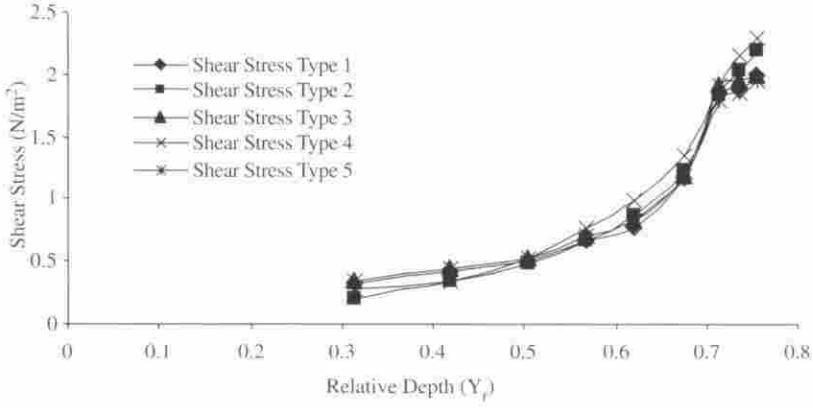


Figure 3. Shear stress data for compound cross-section type 1.

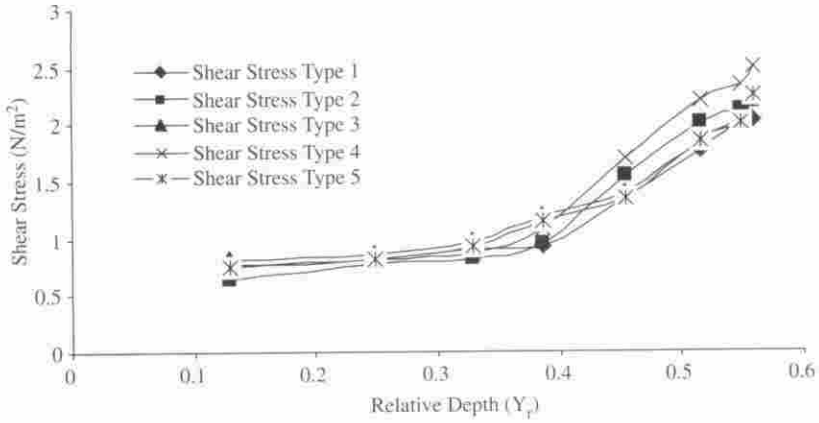


Figure 4. Shear stress for compound cross-section type 2.

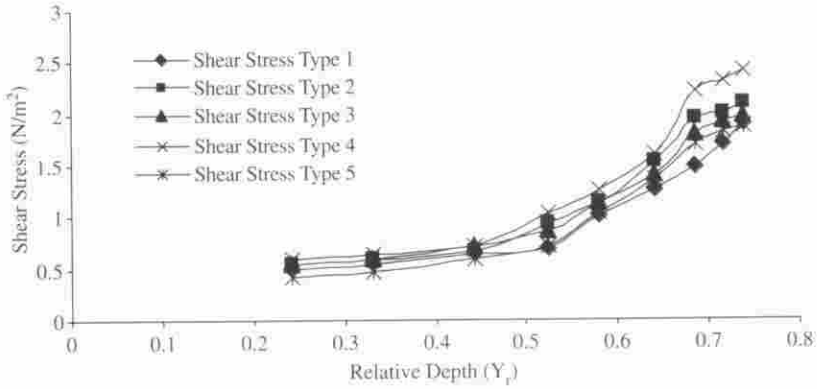


Figure 5. Shear stress data for compound cross-section Type 3.

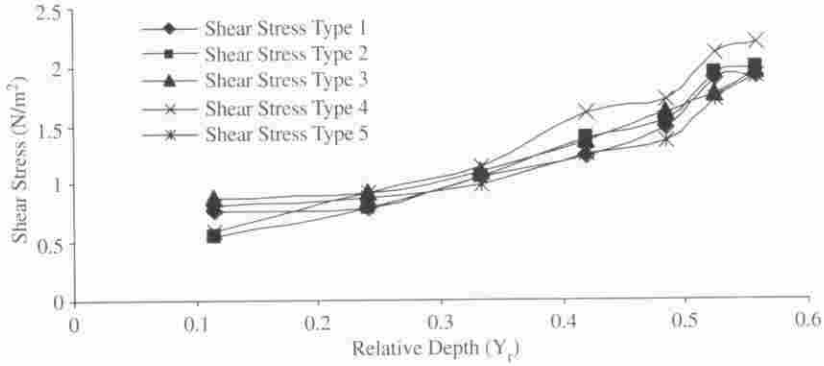


Figure 6. Shear stress data for compound cross-section type 4.

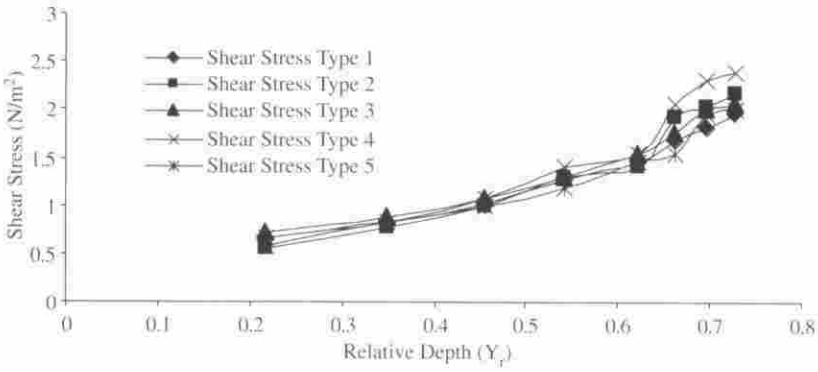


Figure 7. Shear stress data for compound cross-section type 5.

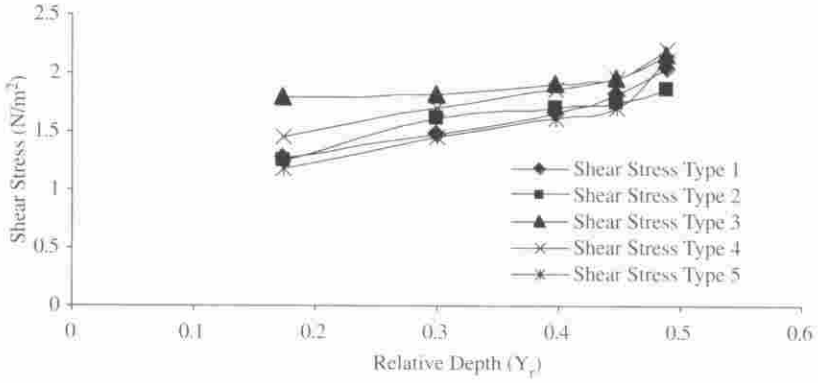


Figure 8. Shear stress data for compound cross-section type 6.

The average shear stresses (T_1 and T_2) are calculated as weighted averages by assuming a step-function with step width (ΔX_k). For interior points along the main channel and floodplains, the shear stress measured at the kth point (T_k) is assumed to be constant along a step width that is equal to half the distance between points (k-1) and (k+1). For points located at the 2 ends of the main channel and floodplains, the measured shear stress is assumed to be constant along a step width that is equal to half the distance between the end point and the adjacent one located in the same channel (i.e. main channel or floodplain channel). The step width is obtained from the point spacings along the wetted perimeter of the channel bottom shown in Figure 2. Equation (6) is used to calculate the average shear stress.

$$T_1 or T_2 = \frac{\sum_k \Delta X_k \times T_k}{\sum_k \Delta X_k} \tag{6}$$

It must be emphasized that shear stresses were measured at the bottom boundary of the main channel and floodplains with no measurements taken at the channel walls as indicated by the point locations shown in Figure 2. Sample calculated average shear stresses are compared against the corresponding values estimated from the generalized regression model as provided in a subsequent section.

The shear stresses measured in the presented rectangular compound channels, and used in this paper to develop generalized regression models, were compared against measured values obtained by other investigators in a separate published research paper (Al-Khatib and Dmadi, 1999).

Single Variable Regression Prediction Models

A generalized single variable regression model has been derived to predict each of the 5 experimentally measured shear stresses as a function of relative depth (Y_r). The prediction model is exponential in form as indicated by Eq. (7).

$$Ln(T_{i,j}) = a + bY_r^n, \quad Y_r = \left(\frac{Y_f}{h}\right) \tag{7}$$

where Ln = natural logarithm function,

$T_{i,j}$= i^{th} shear stress type for the jth compound cross-section type (i = 1, 2, ... ,5; j = 1, 2, ... ,6).

a = regression constant,

b = regression coefficient associated with independent variable Y_r,

n = regression power for independent variable Y_r, and

Y_r = independent variable representing relative depth.

Table 2 provides the derived numerical values of the regression parameters (a, b, n) for a total of 30 different models representing 5 types of shear stress for each of the 6 different compound cross-section cases. The derivation of the generalized model provided in Eq. (7) has been accomplished based on the optimization of 3 main regression statistics. The first main statistic is the standard error ($S_{T_{i,j}}$) associated with the dependent variable ($T_{i,j}$) that has been minimized to the lowest possible values as provided in Table 3. The second main statistic is the model coefficient of determination (R^2), which has been maximized to very high values. The third main statistic is the Student t-value associated with independent variable coefficient (b), which has been maximized to reflect high significance at over 99.7% confidence level. Table 3 also provides for each model the coefficient of variation for the dependent variable with the corresponding value being generally low. The coefficient of variation ($CV_{i,j}$) is defined as the ratio of the standard error ($S_{T_{i,j}}$) to the mean shear stress value ($\bar{T}_{i,j}$) in a percentage. Generally, all presented statistics are related to each other for the same model, which means that any improvement in any one of them would result in an improvement in all others.

All the obtained statistics indicate that the derived regression models are very powerful and can effectively be used to estimate shear stresses with a high degree of reliability for constructed compound cross-sections based only on relative depth. Therefore, the derived general exponential model presented in Eq. (7) is the appropriate model to be used in estimating shear stresses in open channels of rectangular compound cross-sections. The model regression parameters (a, b, n) need to be estimated for any particular cross-section geometry since Table 2 indicates that these coefficients are different for each compound cross-section type. Alternatively, typical regression parameters can be obtained from Table 2 for each shear stress type by averaging the corresponding values from the 6 cross-section types.

Table 2. Regression Coefficients for Single–Variable Prediction Models.

Shear Stress Type (i)	Regression Parameters	Compound Cross–Section Type (j)					
		1	2	3	4	5	6
1	a	0.309	0.758	0.460	0.719	0.541	1.207
	b	5.086	7.548	3.466	3.665	2.083	2.309
	n	3.4	3.4	2.8	2.2	1.5	2.1
2	a	0.099	0.607	0.467	0.392	0.388	0.040
	b	5.021	5.432	3.296	2.940	2.617	4.130
	n	1.7	2.4	2.4	1.0	1.3	0.1
3	a	0.315	0.792	0.526	0.831	0.563	1.237
	b	4.787	5.297	3.554	3.133	2.115	2.849
	n	3.2	2.8	3.0	2.2	1.5	2.3
4	a	0.198	0.695	0.519	0.305	0.433	0.085
	b	4.779	6.029	3.563	2.964	2.697	3.383
	n	2.3	2.6	2.6	0.8	1.4	0.1
5	a	0.313	0.730	0.354	0.805	0.565	1.131
	b	4.560	5.354	3.531	4.409	2.251	2.557
	n	3.1	2.7	2.2	2.8	1.8	2.1

Table 3. Regression statistics for single–variable prediction models.

Shear Stress Type (i)	Regression Statistics	Compound Cross–Section Type (j)					
		1	2	3	4	5	6
1	$S_{Ti,j}$	0.088	0.058	0.053	0.055	0.012	0.020
	R^2	0.985	0.983	0.991	0.982	0.999	0.991
	t_b	21.76	18.69	27.22	16.68	81.5	18.30
	$CV_{i,j}$	8.05%	4.20%	4.19%	4.17%	0.86%	1.21%
2	$S_{Ti,j}$	0.062	0.088	0.066	0.038	0.063	0.035
	R^2	0.995	0.974	0.987	0.994	0.986	0.962
	t_b	38.64	14.93	22.96	30.21	20.5	8.72
	$CV_{i,j}$	5.25%	5.80%	4.78%	2.59%	4.13%	1.96%
3	$S_{Ti,j}$	0.084	0.025	0.067	0.022	0.020	0.016
	R^2	0.986	0.996	0.985	0.996	0.998	0.995
	t_b	22.36	41.31	21.39	34.80	51.61	25.74
	$CV_{i,j}$	7.89%	1.89%	6.22%	1.70%	1.49%	0.96%
4	$S_{Ti,j}$	0.048	0.087	0.073	0.063	0.054	0.011
	R^2	0.997	0.974	0.985	0.986	0.990	0.994
	t_b	46.06	15.17	21.58	18.56	24.86	22.10
	$CV_{i,j}$	4.36%	6.21%	6.03%	4.62%	3.81%	0.64%
5	$S_{Ti,j}$	0.069	0.034	0.076	0.039	0.038	0.054
	R^2	0.990	0.994	0.986	0.988	0.992	0.949
	t_b	26.58	32.93	21.87	20.45	28.13	7.49
	$CV_{i,j}$	5.79%	2.08%	3.08%	2.16%	1.56%	2.54%
Sample Size		9	8	9	7	8	5

Multiple-Variable Regression Prediction Models

A generalized multiple variable regression model has been derived to predict each of the 5 experimentally measured shear stresses as a function of 3 dimensionless parameters. The 2 additional dimensionless parameters take into consideration the horizontal dimensions (B_f and B) of the constructed compound cross-section types. The prediction model is also exponential in form as indicated by Eq. (8)

$$Ln(T_i) = a_1 + b_1 B_1 + c_1 B_2^{n_1} Y_r^{n_2} \qquad (8)$$

where $B_1 = \left(\frac{B_f}{Z}\right); B_2 = \left(\frac{B_f}{B}\right); Y_r = \left(\frac{Y_f}{h}\right)$ and Ln = natural logarithm function.

$T_i = i^{th}$ shear stress type (i = 1, 2, . . . , 5) in Newton per square meter,

a_1 = regression constant,

b_1 & c_1 = regression coefficients, and

n_1 & n_2 = regression powers associated with independent variables.

Other variables defining the 3 dimensionless parameters (independent variables) are as defined earlier. Table 4 provides the derived regression parameters (a_1, b_1, c_1, n_1, n_2) for the 5 shear stress types. These regression parameters are relatively close to each other when compared to the regression parameters obtained for the single variable regression models. The negative sign associated with regression coefficient (b_1) has an accurate physical interpretation indicating that the shear stress decreases with the increase in the first dimensionless parameter (B_1). The explanation for this is that as the floodplain width (B_f) increases and reaches its maximum (i.e. B = 0.0), it results in the elimination of main channel depth (Z) and shear stress becomes minimum as the wetted perimeter becomes minimum for the same floodplain depth (Y_f). Similarly, the positive sign associated with the second regression coefficient (c_1) indicates that there is a direct relation between shear stress and the product of the 2 other remaining dimensionless parameters (B_2 and Y_r).

Table 4. Regression Coefficients and Statistics for Multiple-Variable Prediction Models.

T_i	a_1	b_1	c_1	n_1	n_2	S_{T_i}	t_{b_1}	t_{c_1}	R^2	$\frac{S_{T_i}}{T_i}(\%)$
T_1	0.678	−0.448	3.984	0.39	2.4	0.088	−31.98	33.53	0.969	7.14%
T_2	0.566	−0.484	4.267	0.32	2.0	0.151	−20.52	23.22	0.934	11.67%
T_3	0.788	−0.449	3.844	0.38	2.5	0.105	−27.24	27.50	0.956	7.87%
T_4	0.642	−0.474	4.149	0.31	2.0	0.143	−21.16	23.92	0.937	10.02%
T_5	0.606	−0.450	3.854	0.38	2.1	0.083	−33.95	36.57	0.973	6.70%

Table 4 also provides the regression statistics associated with the 5 derived models representing the 5 shear stress types. A total of 46 data points have been used in the generation of each model representing the sum of measurements obtained from the 6 constructed compound cross-section types. The first statistic is the standard error (S_{T_i}) associated with the dependent variable (T_i) representing the shear stress type. The obtained values of this statistic are relatively low but are higher than the values obtained for the single variable regression models. This can be attributed to an increase in the number of independent variables. The second statistic is the Student t-values (t_{b_1} and t_{c_1}) associated with the regression coefficients (b_1 and c_1). The obtained Student t-values indicate that the derived regression models are all significant at over 99.7% confidence level. The third statistic is the model coefficient of determination (R^2), which ranges from 93.4% to 97.3%. The fourth statistic is the coefficient of variation, which ranges from 6.7% to 11.67%.

All obtained regression statistics indicate the high reliability of the derived regression model in estimating presented shear stress types in an open channel of rectangular compound cross-section. The values for each of the 5 derived regression parameters (a_1, b_1, c_1, n_1, n_2) are relatively close to each other, and the experimentally measured values of the 5 shear stress types are also within a close range to each other as indicated by Figures. 3-8. Therefore, a single multi-variable regression model for estimating mean shear stress (T_e) at the bottom of the main channel and floodplains of a rectangular compound cross-section can be formulated using average values of obtained regression parameters. The resulting model is demonstrated by Eq. (9).

$$Ln(T_e) = 0.662 - 0.466\left(\frac{B_f}{Z}\right) + 4.12\left(\frac{B_f}{B}\right)^{0.36}\left(\frac{Y_f}{h}\right)^{2.2} \quad (9)$$

Equation (9) can only be used to estimate mean shear stress at the bottom of a rectangular compound cross-section using dimensionless parameter values within the ranges used in the experimentally constructed cross-section types as provided in Table 1.

The measured shear stresses (T_k) and the calculated mean shear stresses for main channel and floodplains (T_1 and T_2) are plotted in relation to the bottom boundary of the compound channel for 4 selected cross-sections (types 3-6) as shown in Figures 9-12. The sample calculated mean shear stresses associated with the floodplains are generally higher than the mean shear stresses associated with the main channel as demonstrated by the plotted values in 3 selected cross-sections (Figures 9-11). This trend is not generally true, but rather depends on the geometry of the compound channel and the channel flow discharge. The estimated mean shear stresses (T_e) associated with the 4 selected compound channel cross-sections are obtained from Eq. (9) and plotted in Figures 9-12. The estimated values generally fall between the calculated main channel mean shear stress (T_1) and the calculated floodplain mean shear stress (T_2), as might be expected, an indication of the effectiveness of the derived regression model in estimating the mean shear stress in a compound rectangular channel. The flow discharge used in the presented sample mean shear stresses is about 80 l/s.

Conclusions

Shear stress distributions at the bottom of main channel and floodplains for 6 different rectangular compound cross-section types have been presented. Numerical values of the regression parameters (a, b, n) for a total of 30 different single variable prediction models, representing 5 types of shear stress for each of the 6 cross-sections, have been derived. All the obtained statistics have indicated that the derived prediction models are quite good, and can effectively be used to estimate shear stresses with a

high degree of reliability for the constructed compound cross-sections based only on relative depth.

A generalized multiple variable regression model has also been derived to predict each of the 5 experimentally measured shear stresses as a function of 3 dimensionless parameters. All the obtained regression statistics have indicated the high confidence level associated with the derived regression models in estimating presented shear stress types in an open channel of rectangular compound cross-section. A single multi-variable regression model for estimating mean shear stress at the bottom of a rectangular compound cross-section has been formulated using average values of obtained regression parameters of the multi-variable regression models.

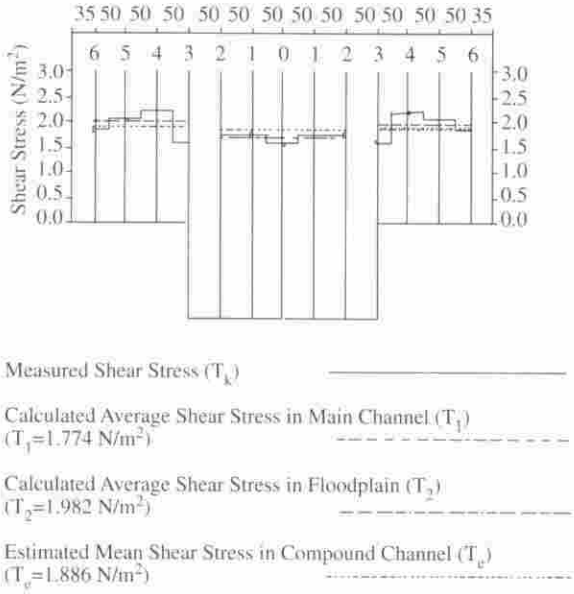


Figure 9. Calculated and estimated mean shear stresses for channel cross-section type 3.

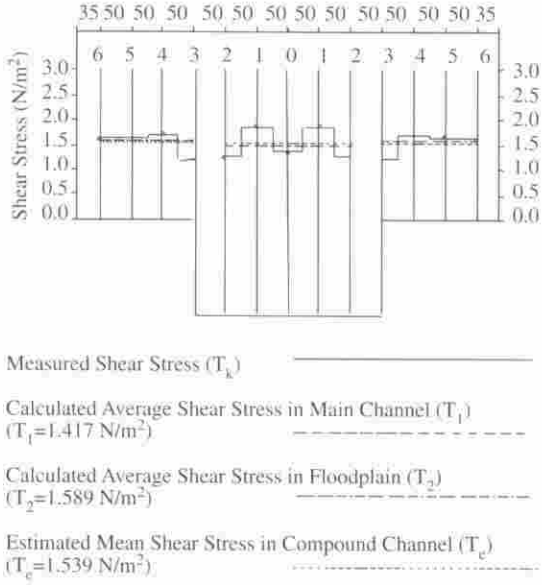


Figure 10. Calculated and estimated mean shear stresses for channel cross-section type 4.

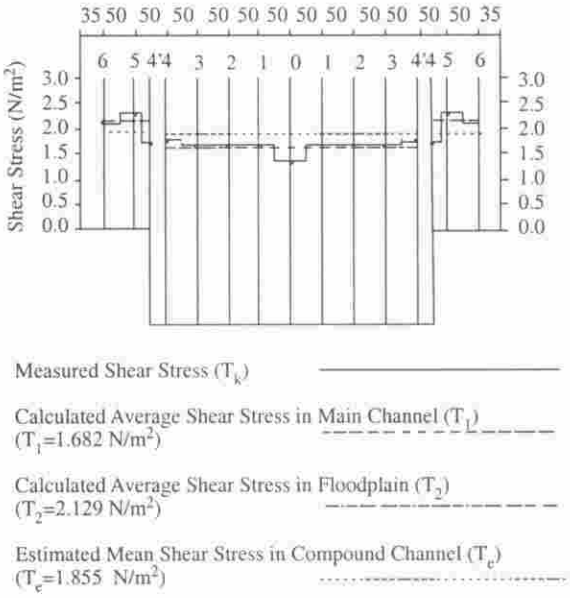


Figure 11. Calculated and estimated mean shear stresses for channel cross-section type 5.

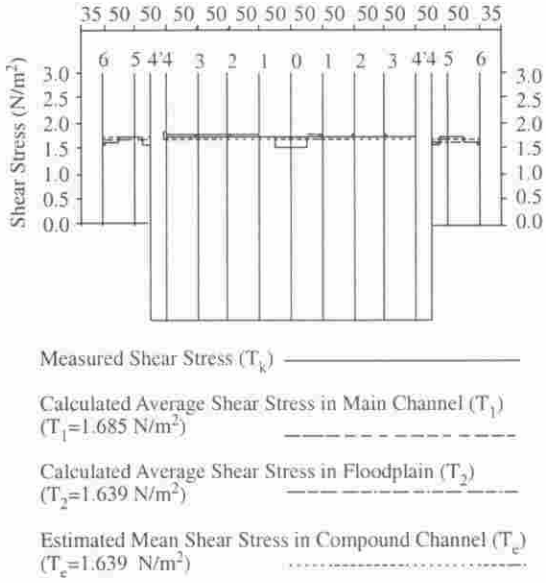


Figure 12. Calculated and estimated mean shear stresses for channel cross-section type 6.

Nomenclature

B bottom width of the approach channel.
BO bottom width of the upstream channel.
g gravitational acceleration.
d probe outside diameter.
Q volume rate of flow.
ΔP Preston tube pressure difference.
ρ fluid density.
υ the kinematic viscosity of the fluid.
τ_0 boundary shear stress.
X^* log of dimensionless differential pressure.
Y^* log of dimensionless shear stress.
Y_f floodplain water depth.
h total depth of compound cross-section.
B_f floodplain width.
Z depth of main channel (step height).
$Y_r = \left(\frac{Y_f}{h}\right)$, $B_1 = \left(\frac{B_f}{z}\right)$, $B_2 = \left(\frac{B_f}{B}\right)$
T_k measured shear stress at the kth point.
T_1 average shear stress at the bottom of main channel.

T_2 average shear stress at the bed of floodplains.
T_3 maximum shear stress at the bottom of main channel.
T_4 maximum shear stress at the bed of floodplains.
T_5 shear stress at the bottom of main channel centerline.
$T_{i,j}$ the ith shear stress type for the jth compound cross-section type.
T_e estimated mean shear stress at the bottom of the compound cross-section.

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