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Experimental Investigations to Determine the Distribution of Longitudinal Velocity in River Bends

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ABSTRACT

Presence of strong secondary currents and their interaction with the topography of the channel bed in river bends have significant effects on the distribution of longitudinal and transverse velocity and consequently the shear stress across the width and length of a bend. Flow in river bends has been investigated by several researchers, resulted in introducing a variety of different equations for identifying the parameters of flow in river bends. However, the proposed equations do not provide a good solution especially in sharp bends. In this research, we carried out a set of laboratory tests to investigate the distribution of the longitudinal velocity in sharp river bends. The tests were performed in the laboratory of hydraulics department of EPFL University in Switzerland, with discharges of 63, 89 and 104 L sec^{-1} on a developed topography. Based on the test results, we presented an experimental equation includes two, a power and a sinuous, segments to estimate the longitudinal velocity in sharp river bends. Having determined the longitudinal velocity profile using the new model and also some available models, we calculated the Standard Error of the predicted against the observed results from laboratory experiments. We found that the Standard Error of the new model is considerably lower than the Standard Error of the other models, confirming the high accuracy of the new equation on predicting the longitudinal velocity profile in sharp bends.

Key words: Natural rivers, sharp bend, longitudinal velocity, shear stress, secondary currents, maximum velocity

INTRODUCTION

In nature, many rivers follow a winding, sinuous course and are classified as meandering (Thorne, 1997). In meandering rivers, it is well known that bed scour occurs at the outer banks and that deposition takes place along the inner banks. As a result, it is frequently necessary to protect the outer banks against failure to avoid undesirable land loss, damage to adjoining properties and sedimentation problems downstream. From the perspective of river engineering, the process of flow and bed topography in meandering rivers are considered as important subjects for investigation and it is not surprising that river meandering has been studied intensively by hydraulic engineers.

Nevertheless, the mutual interaction between the flow and movable channel boundaries makes prediction of flow and bed topography in meander bends very complex, even for the simplified case of non-migrating bends. Knowledge of river meandering has progressed rapidly in the last 40 years and numerous studies concerning various aspects of the problem have now been published. However, most of published models necessarily make some assumptions to facilitate solution of the basic governing mass and momentum conservation equations. Consequently, some disagreements between model predictions and observed data in the field are to be expected. So, considerable experimental researches, both in the field and in the laboratory have been carried out to better understanding the flow behavior within bends. Apmann (1972), Bathurst *et al.* (1979), Anwar (1986) and Javaheri *et al.* (2008) among others carried out field investigation while Rozovskii (1961), Blanckaert (2002), Nayshabori and Eghbalzadeh (2003) and Abdesharif (2006) among others performed laboratorial investigation. Moreover, considering the presence of three dimensional flow in river bends, several attempts have been also conducted to analyze the 3D flow; e.g., Ruther and Olsen (2005), Abolghasemi (2006), Zeng *et al.* (2008) and Khosronejad *et al.* (2007) among others.

Regarding longitudinal velocity, as one of the most important parameters of flow in river bends, Rozovskii (1961), Kikkawa *et al.* (1976), Johannesson and Parker (1989a) and Bridge (1992), among others, introduced relationships to estimate the distribution of this velocity within uniform bends. All of the above introduced models to estimate longitudinal velocity (except Johannesson and Parker (1989a, b), used the logarithmic velocity distribution along with the Prantle's mixing length theorem for 2D flow. So, when they applied for 3D flow, it result in considerable error on estimation the velocity profiles. Abdesharif (2006) showed that the measured velocity profiles are flatter than those estimated using the above models; i.e., measurements show that from an specific depth, the velocity tends to decrease toward the flow surface while the above models predict a gradually increase of velocity toward the flow surface. As a result, there are disagreements between the prediction and observed values of longitudinal velocities when the above modes are employed. In this research, using laboratory experiment we introduced a new relationship to predict the distribution of longitudinal velocity within the bend.

MATERIALS AND METHODS

In order to develop a new experimental relationship to predict the distribution of longitudinal velocity within the river bend, we used a channel which had been installed, within the hydraulic laboratory of EPFL University in Switzerland. The channel has a wide of 1.3 m and curvature of 193 degrees. In Fig. 1 a schematic plan of the channel is shown. To measure the velocity in different locations of the channels and different depths, we used ADVP (Acoustic Doppler Velocimeter Profiler) machine. ADVP has a central emitter and four receivers which are located in a water-filled housing.

In order to conduct the experiments, started from January 2009 and finished in September 2009, first we made a horizontal bed using the sediment over the channel bottom and then we put the discharge of 63 L sec^{-1} inside the channel. The sediments entered to the channel from a sediment feeder installed upstream and after transferring into downstream by flow, they were poured into the basin which is used for trapping sediments at the channel outlet. Then, they collected manually in order to turn back into the feeder tank.

The flow over bed continued for three weeks in order to achieve equilibrium in bed topography and to make a balance between input and output sediments while a point bar is fully developed in inner bank side.

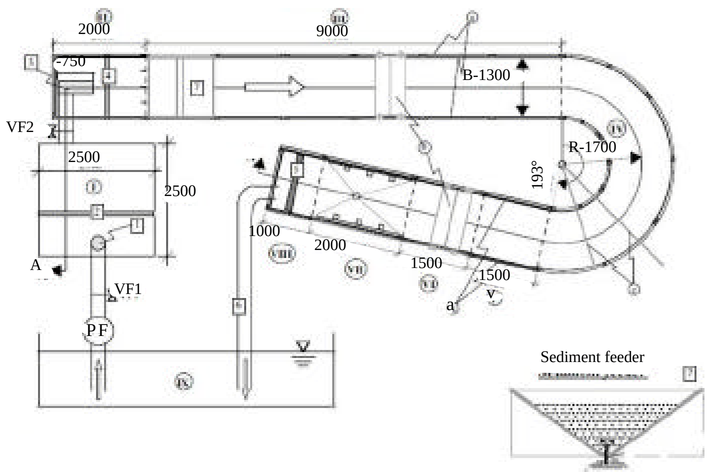

Fig. 1: A view of the experiment channel (Blanckaert, 2002). I: The water tank before entering into the channel, II: The inlet basin, III: The straight segment of the channel (length of 9 m), IV: The fixed bend with radius of 1.7 m, V: The downstream straight section with length of 3 m, VI: The downstream straight section with length of 2 m, VII: The basin for depositing sediments and VIII: Outlet basin

Table 1: Properties of flow in the channel

Q (L sec^{-1})	H (m)	U (m sec^{-1})	u_* (m sec^{-1})	S_f (-)	Re (-)	Fr (-)	R/B (-)	R/H (-)	B/H (-)
63	0.098	0.49	0.056	0.004	43000	0.5	1.31	17	13
89	0.12	0.54	0.063	0.0037	58000	0.5	1.31	14.1	10.8
104	0.13	0.63	0.065	0.0043	73000	0.56	1.31	13	10

Q: Discharge, H: Flow depth, U: Flow velocity, u_*: Shear velocity, S_f: Hydraulic slope, R_e: Reynolds number, Fr: Froud number, R: Radius of curvature, B: Channel width. (-): Non-dimensional value

Considering the required time for measuring the velocity along the channel and because of the rapid changes in the position of the dunes, it was impossible to carry out the measurements over the moving bed. Therefore, the sediments in the bed were frozen with a special material, named Dakfill, in order to make possible to carry out the measurements in a fixed bed. Table 1 represents the properties of the flow in a channel with the discharge of 63 L sec^{-1}. Furthermore, the discharges of 89 and 104 L sec^{-1} were also run on the developed topography which has been used for the discharge of 63 L sec^{-1}, in order to examine the applications of the new model in different discharges. The properties for discharges of 89 and 104 L sec^{-1} are also shown in Table 1.

It needs to be pointed out that the discharge of 63 L sec^{-1} was measured in thirteen cross sections and the discharges of 89 and 104 L sec^{-1} were measured in six cross sections. The network of measurements in cross sections is illustrated in Fig. 2 in which Δn is the transverse distance between the measured profiles. The time of measurement for each vertical velocity profile was 180 seconds. After measuring the velocity by ADVP, we used MATLAB program to draw the flow patterns to see the overall results. Then using the obtained data, we developed a new relationship to predict the longitudinal velocity in bends.

In order to quantitatively compare the results obtained from different models with those obtained from laboratory tests, we used the Standard Error (SE) which defines as the square

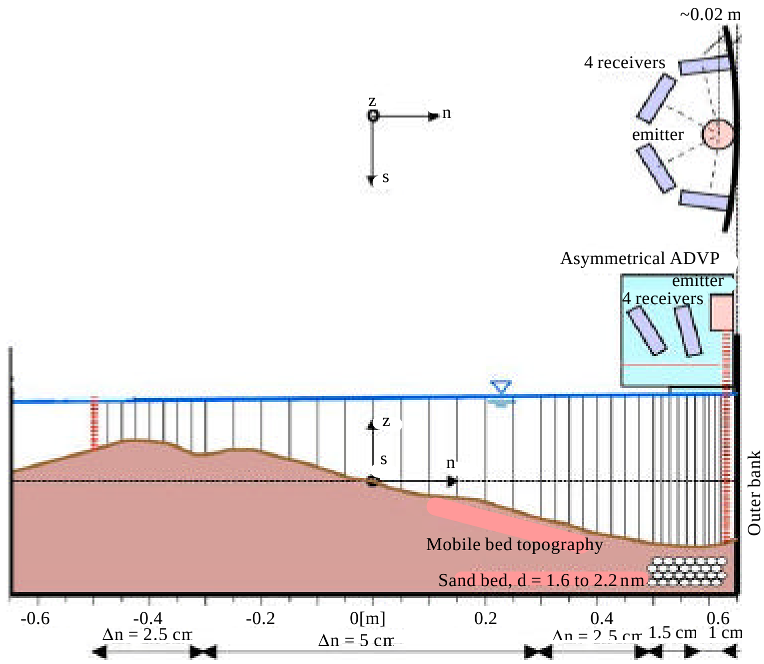

Fig. 2: The network of measurement in cross sections

amount of the estimated errors with respect to the observed values. Standard Error may be estimated using:

$$S.E = \frac{\sqrt{\overline{e_i^2}}}{\bar{o}} \qquad \overline{e_i^2} = \frac{\sum_{i=1}^{n}(o_i - e_i)^2}{n} \tag{1}$$

where, o is the observed value, e is the predicted value and n is the number of data. Standard Error indicates the relative value of estimated error of the model. Therefore, the less the amount of this parameter is, the more accurate the prediction of the model will be.

RESULTS AND DISCUSSION

Figure 3 shows the equilibrium bed topography for the discharge of 63 L sec^{-1} after full development while dunes are visible in the outer bank. From Fig. 3 it can be seen that in the entrance to the bend, the inner side of the cross section is deeper, perhaps because of the uneven distribution of the sediments come from the sediment feeder which makes the central core of the velocity in the bend inlet deviate from the center of the cross section. Six dunes are visible inside the bend while the deepest part in the cross section; i.e., the basin which covers about half of the cross section, is seen in cross section of 70 degrees with respect to the bend entrance. At this cross section, the maximum height of the point bar can also be observable.

Figure 3 also is a typical topography which includes both basin and point bar. In this sharp bend, the maximum depth of flow was about 3.5 times as big as the mean depth of the flow in the

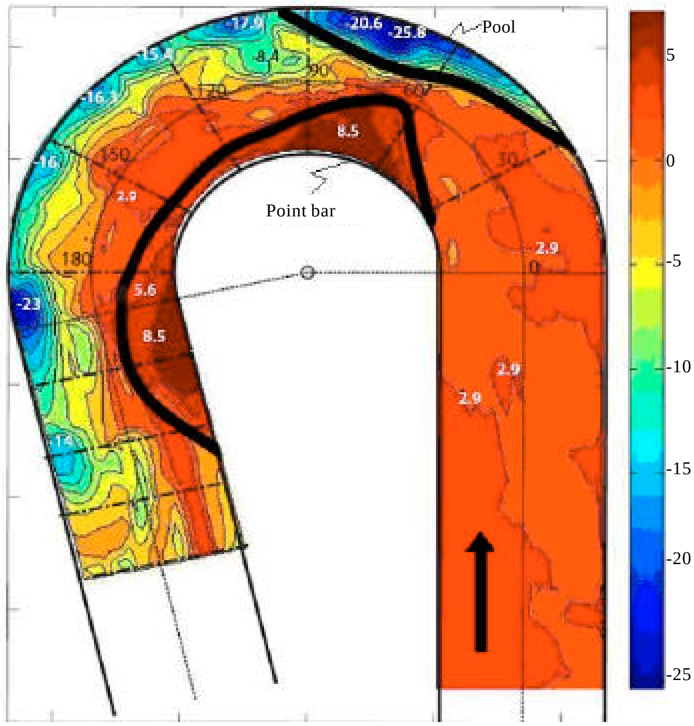

Fig. 3: Developed topography for the flow of 63 L sec^{-1}

channel. A point bar and a basin have been developed in the inner and outer banks, respectively. The transverse slope in this cross section is 31 degrees, greater than the sediment angle of repose, indicating that there is a strong transverse force toward the inner bank. In downstream of cross section of 90 degrees, the transverse bed slop displays little changes in the cross section and the shape of cross sections tends to be linear.

Figure 4 and 5 indicate two examples of the measured longitudinal velocity on the developed topography expressed in Fig. 3 which are compared with those predicted by different models. As it is shown in Fig. 4 and 5, the velocity profile in bends has two major characteristics which make it different from the velocity profile in straight channels. The first indicative characteristic of longitudinal velocity profile in bends is that the maximum velocity occurs near the bed; e.g., around 0.2d (d is the depth of flow) above the bed in the station close to the outer bank and around 0.3d above the bed in the station located in channel centerline while in straight channels the maximum velocity appears near the water surface.

As the second indicative, the velocity profiles in bends are flatter than logarithmic profiles of the velocity. This point is shown in Fig. 4 in which the measured and logarithmic velocity profiles in cross section of 180 degrees for the flow discharge of 63 L sec^{-1} are indicated. De Vriend (1981) and Blanckaert (2002) have pointed out that the flatness of the velocity profile is the result of the impact of secondary flow cell on longitudinal velocity profiles which in turn results in a weak secondary flow cell inside the bend.

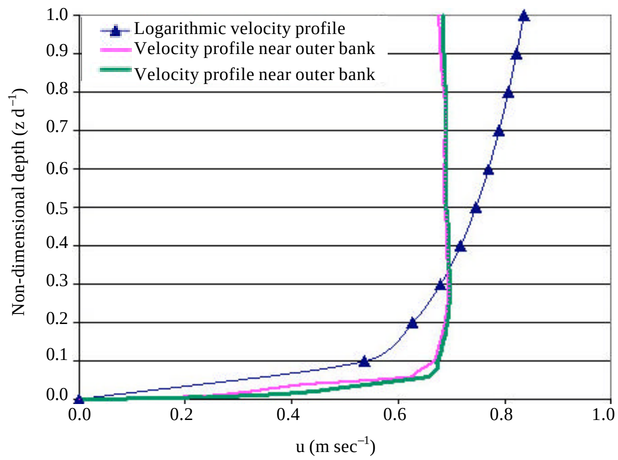

Fig. 4: The measured (close to outer bank) and logarithmic velocity profiles in cross section of 180 degrees for the flow discharge of 63 L sec^{-1}

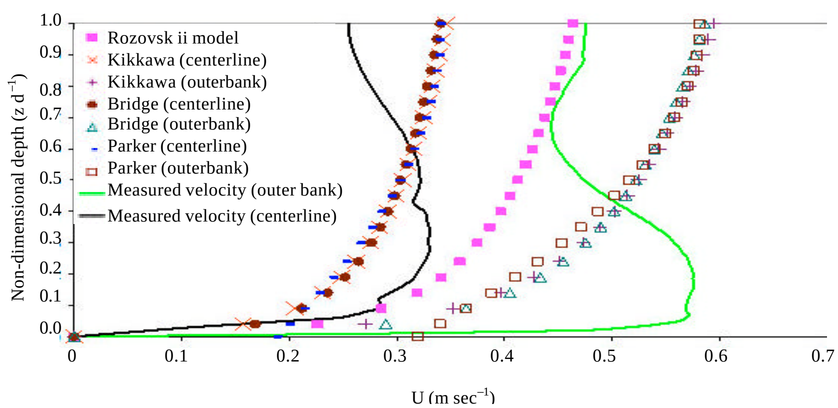

Fig. 5: Predicted velocity profiles using introduced models in Table 2 and the observed profiles for the discharge of 63 L sec^{-1}.

To determine the accuracy of some of the models introduced in the second section, in Table 2 we introduced four models to investigate their accuracy on predicting the velocity profile in river bends.

In Fig. 5 the predicted velocity profiles using introduced models in Table 2 are compared to the observed profiles in our experiments. The predicted velocity profiles show that the velocity increases from the channel bed and reaches to its maximum value on water surface which are different from the observed velocity profile.

Moreover, Fig. 5 shows a common point in that, in all mentioned models except Rozovskii's model, there is a difference between the predicted velocity profile obtained close to the outer bank and the one obtained in central region. The predicted profiles in the regions of outer bank and the channel center are the same in the Rozovskii (1961) model because there is no parameter defining the location of the profile inside the cross section in this model.

Table 2: Models to estimate longitudinal velocity

Author	Relationship	Comments
Rozovskii (1961)	$\frac{U_s}{U_a} = 1 + \frac{g^{0.5}}{\kappa C}(1 + \ln \eta)$	$\eta = \frac{z}{d}$
Kikkawa *et al*. (1976)	$\frac{U_s}{\overline{U_*}} = \frac{\overline{U_s}}{U_a}\left(\frac{U_a}{\overline{U_*}} + \frac{1}{\kappa}(1 + \ln \eta)\right)$	
Johannesson and Parker (1989b)	$U_s = \frac{\sqrt{C_f}}{0.077}\overline{U_s}\left[\chi + \frac{z}{d} - 0.5\left(\frac{z}{d}\right)^2\right]$	$\chi = \frac{0.077}{\sqrt{C_f}} - \frac{1}{3}, C_f = \left(\frac{\overline{U_*}}{U_a}\right)^2$
Bridge (1992)	$\frac{U_s}{\overline{U_s}} = 1 + \frac{U_{*_o}}{\overline{U_{so}}}\left[\frac{1}{\kappa}(1 + \ln \eta)\right]$	For steady flow in a uniform bend

U_s: Longitudinal velocity, U_a: Cross-sectionally averaged longitudinal velocity, κ: Von Karman constant, C: Chezy coefficient, $\overline{U_*}$: Cross - sectionally averaged shear velocity, $\overline{U_s}$: The vertically averaged longitudinal velocity, d: Depth of flow, z: The height above the bed, $\overline{U_{so}}$: The value of U_s at channel centere line, U_{*_o} : The shear velocity at channel center line

Table 3: The value of standard error for different models for the discharge of 63 L sec^{-1}

No. of cross section	Johannesson and Parker (1989a)	Kikkawa *et al*. (1976)	Rozovskii (1961)	Bridge (1992)
Centerline of the channel				
30°	0.1	0.09	0.11	0.10
60°	0.28	0.24	0.28	0.24
90°	0.2	0.18	0.40	0.18
120°	0.21	0.17	0.17	0.17
180°	0.2	0.16	0.27	0.16
Mean	0.21	0.17	0.25	0.17
Outer bank of the channel				
30°	0.28	0.25	0.30	0.25
60°	0.23	0.24	0.26	0.24
90°	0.23	0.25	0.31	0.25
120°	0.19	0.15	0.17	0.15
180°	0.15	0.16	0.30	0.13
Mean	0.22	0.21	0.27	0.21

In order to quantitatively compare the results from the four predicted velocity profiles, we used the Standard Error (SE). In Table 3 the values of SE for different models in various locations within the bend are introduced. As it can be seen in Table 3, Kikkawa *et al*. (1976) model has the least error comparing the other models. Also, the amount of SE in Kikkawa *et al*. (1976) model decreases toward the end of the curve and it increases as it moves toward the outer bank. Among the above four models, the Rozovskii's model (Rozovskii, 1961) has the highest error because it does not take the changes of average velocity in transverse of cross section into consideration. As stated previously, three of the investigated models use a logarithmic distribution for longitudinal velocity in depth. Moreover, although the model of Johannesson and Parker (1989a, b) does not consider logarithmic distribution, the corresponded SE for this model is a little more than SE corresponds to the models of Kikkawa *et al*. (1976) and Bridge (1992).

As a result, it can be seen that these models are not able to predict the value and the position of the maximum velocity, correctly and it is necessary to introduce more accurate model in this regard.

A NEW MODEL FOR PREDICTION OF LONGITUDINAL VELOCITY IN BENDS

In order to propose a new model for longitudinal velocity in bends, the major characteristics of longitudinal velocity should be taken into consideration. As it was mentioned before, both the existence of maximum velocity in location close to the bed and the flatness of the profile in comparison with the logarithmic profile, are the main characteristics of longitudinal velocity in bends. These characteristics were observed in our laboratory test and also in some previous researches including Blanckaert (2002) and Abdesharif (2006) among the others.

The experimental investigations of longitudinal velocity profile in laboratory show that in most cases the velocity increases from the bed toward the flow depth of 0.1-0.5 d until it reaches its maximum value and after that it begins to decrease. We measured 241 longitudinal velocity profiles, classified the flow depth to 10 separate classes and found the depth in which the maximum velocity is recorded. Table 4 shows the number of experiments in which the maximum velocity was observed in each depth categories for 241 longitudinal velocity profiles. As it can be seen in Table 4, in 66% of the experiments, the maximum velocity occurs between the depths of 0.1 to 0.5 d.

As stated previously, in most laboratory experiments, it is seen that the longitudinal velocity decreased when it approached to the flow surface; i.e., there is a flatter profile rather than logarithmic one. So, in order to flatten the longitudinal velocity profile and also to move the location of the maximum velocity to a lower position along the flow depth, we defined following Equation:

$$u = A\bar{u}\left(1 + \frac{1}{\kappa}\frac{\bar{u}_*}{\bar{u}}\left(\frac{z}{d} - 0.1\right)^{0.5}\right) + \frac{\bar{U}}{B}\sin^2\left(\frac{3\pi}{4}\left(1 - \frac{z}{d}\right)\right) \qquad (2)$$

in which $\bar{u}$ is the depth averaged velocity, $\bar{u}*$ is the depth averaged shear velocity, $\bar{U}$ is the cross sectional average velocity and coefficients A and B have to be determined from experiments. Using fifty velocity profiles for the discharge of 63 L sec^{-1} and by taking several values for A and B, we calculated the mean standard error for those fifty velocity profiles. In Fig. 6 curves to optimize the coefficients A and B are shown. From Fig. 6 it can be seen that the minimum mean error of those velocity profile is provided when B = 8.0 and A= 0.9.

It can be shown that in Eq. 2 the first paragraph is considered to make a flatter profile while the second paragraph, the sinuous segment, results in a lower position for maximum longitudinal

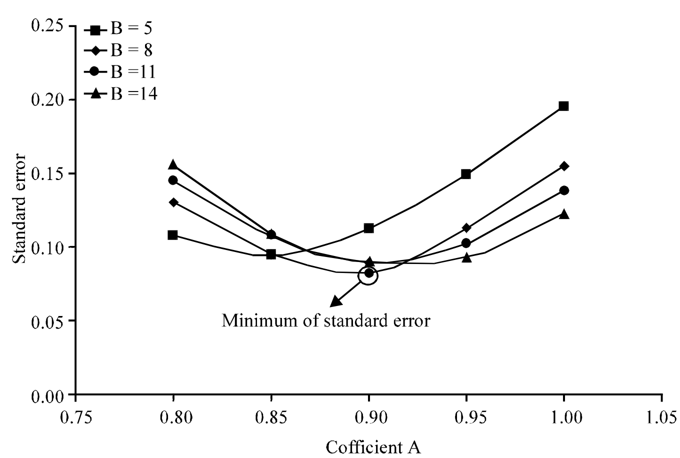

Fig. 6: Curves to find the minimum standard error to estimate the values of A and B

Table 4: The distribution of occurrence of the maximum velocity in various depths

	Depth from the bed (d)								
Description	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1.0
No. of occurrence for each depth	41	48	45	23	18	13	13	6	34
Percentage	17	20	19	10	8	5	5	2	14
Accumulative percentage	17	37	56	66	74	79	84	86	100

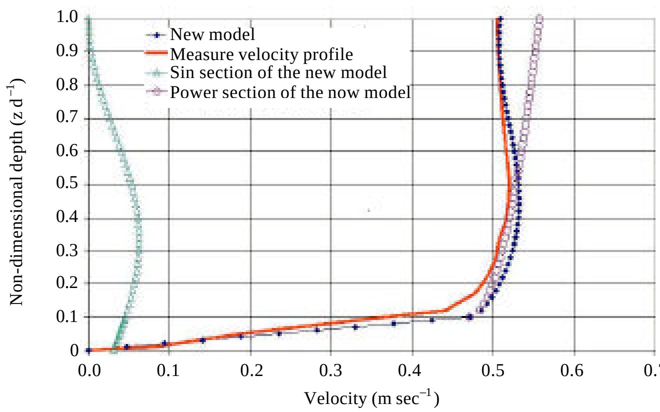

Fig. 7: Indicating the two parts of the predicted profile by the new equation

velocity; i.e., around 0.4 d that is the average depth of the maximum velocity which obtained from 564 velocity profiles with the discharges of 63, 89 and 104 L sec^{-1}.

To show the ability and also the accuracy of the new equation, we used it to estimate the longitudinal velocity profile in cross section located in 60 degrees for the discharge of 63 L sec^{-1} and compared it with the related profile observed in laboratory (Fig. 7). The two parts of the new model are also illustrated separately in Fig. 7.

Moreover, in Fig. 8 some measured longitudinal velocity profiles along with those predicted by Eq. 2 with the discharges 63, 89 and 104 L sec^{-1} are shown.

It should be noted that Figs. 4, 5, 7 and 8, provide some examples of the measured velocity profile in bends, all of which show that the longitudinal velocity profile is nearly linear from the bed toward the 0.1d from the bed. Hence, the power segment of the model is only valid for distance between water surface and above 0.1 d from the bed.

In order to examine the value of error of the new model, we determined the Standard Error for the results of the new model. Table 5 represents the values of SE for discharges of 63, 89 and 104 L sec^{-1} in both outer bank and the centerline of the channel. These values indicated the accurate prediction of the new model in sharp bends.

To compare the accuracy of the new model with those models mentioned previously, in Table 6 the values of SE for all models in different cross sections are shown.

Comparing SE values for the new model with those for other models shows that there is a significant difference between the predicted error of the new model with those of the other models. So, the new model seems to be more appropriate for prediction of longitudinal velocity in sharp bends. We also tested Eq. 2 with data provided by three other researchers as:

Table 5: The values of SE of the new model for various discharges in outer bank and channel centerline

	63 L sec^{-1}		89 L sec^{-1}		104 L sec^{-1}	
No. of cross section	Outer bank	Centerline	Outer bank	Centerline	Outer bank	Centerline
30	0.16	0.12	0.09	0.05	0.06	0.06
60	0.13	0.05	0.09	0.04	0.10	0.06
70	0.08	0.07	-	-	-	-
80	0.04	0.06	-	-	-	-
90	0.05	0.11	0.17	0.10	0.06	0.07
100	0.12	0.08	-	-	-	-
110	0.10	0.09	-	-	-	-
120	0.05	0.11	0.07	0.07	0.06	0.07
135	0.06	0.08	-	-	-	-
150	0.09	0.05	0.09	0.04	0.08	0.07
165	0.07	0.12	-	-	-	-
180	0.08	0.09	0.04	0.05	0.07	0.06
193	0.07	0.09	-	-	-	-
Mean	0.087	0.084	0.09	0.06	0.07	0.07

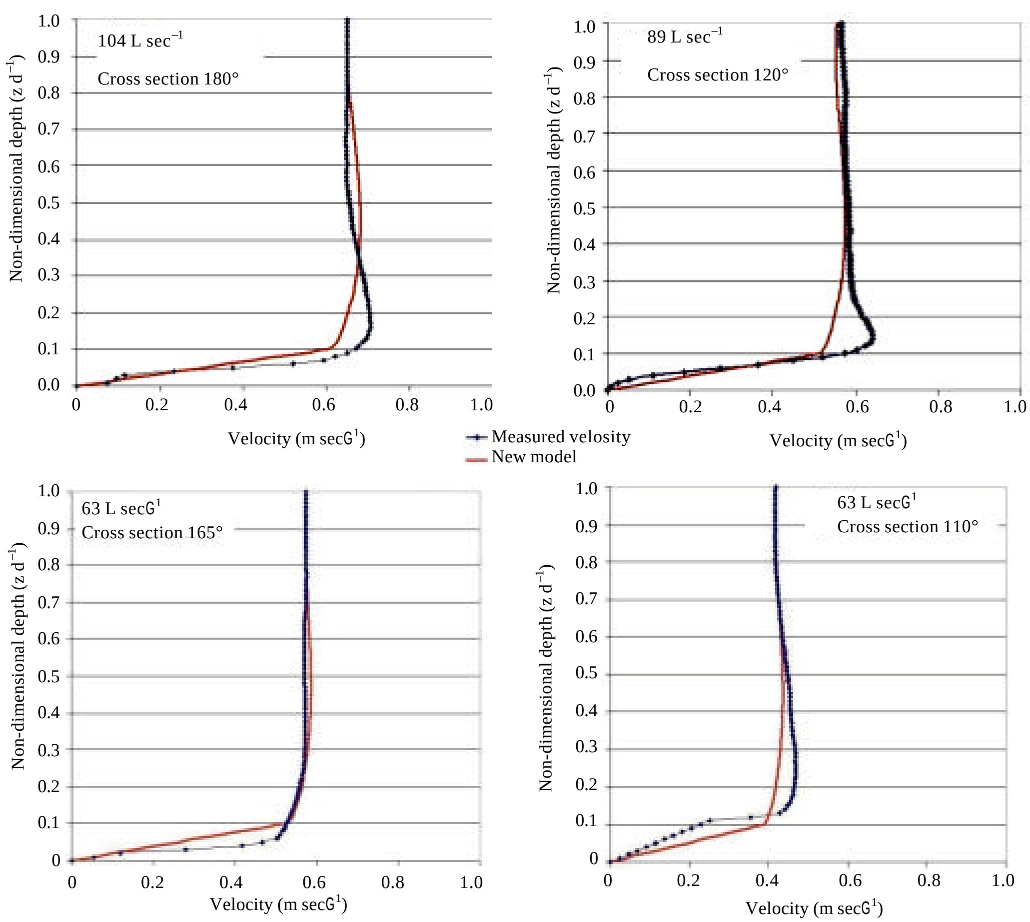

Fig. 8: Measured longitudinal velocity profiles along with those predicted by Eq. 2 with the discharges 63, 89 and 104 L sec^{-1}

Table 6: The value of standard error for different models including the new model for the discharge of 63 L sec^{-1}

No. of cross section	Johannesson and Parker (1989a)	Kikkawa *et al.* (1976)	Rozovskii (1961)	Bridge (1992)	Eq. 2
Centerline of the channel					
30°	0.10	0.09	0.11	0.10	0.12
60°	0.28	0.24	0.28	0.24	0.05
90°	0.20	0.18	0.40	0.18	0.11
120°	0.21	0.17	0.17	0.17	0.11
180°	0.20	0.16	0.27	0.16	0.09
Mean	0.21	0.17	0.25	0.17	0.10
Outer bank of the channel					
30°	0.28	0.25	0.30	0.25	0.16
60°	0.23	0.24	0.26	0.24	0.13
90°	0.23	0.25	0.31	0.25	0.11
120°	0.19	0.15	0.17	0.15	0.11
180°	0.15	0.16	0.30	0.13	0.09
Mean	0.22	0.21	0.27	0.21	0.12

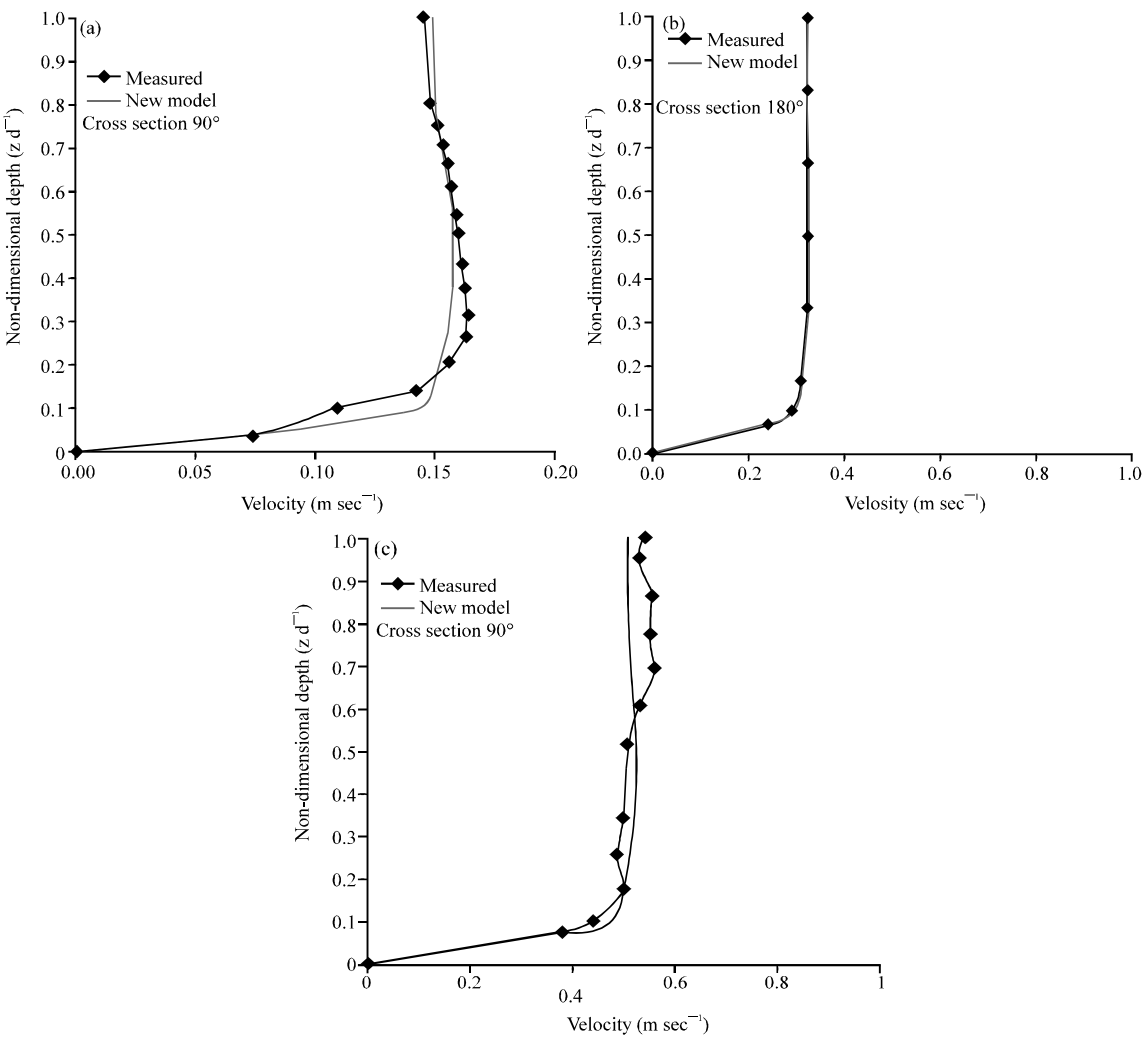

Fig. 9: The predicted and observed longitudinal velocity profiles for the experiments of (a) Abdesharif (2006) and Rozovskii (1961), (b) Rectangular flume and (c) Desna river

Table 7: The values of standard error for the new model using two sets of data provided by Rozovskii (1961) and one set of data obtained by Abdesharif (2006)

Rozovskii (1961) USSR data		Rozovskii (1961) Desna river data		Abdesharif (2006) data	
Cross section	Error (%)	Cross section	Error (%)	Cross section	Error (%)
65	7	60	9	30	7
100	6	90	8	60	7
145	6	150	10	90	6
180	5	180	10	120	5
-	-	-	-	150	6
-	-	-	-	180	7
Mean	9.3	Mean	5.8	Mean	6.3

- Data provided by Abdesharif (2006) who conducted a series of laboratory experiments in a concrete flume with the width of 1 m, flow discharge of 50 L sec^{-1} and R/B of 3.5
- Data provided by Rozovskii (1961) from experiments carried out in a rectangular flume with the discharge of 12.3 L sec^{-1}, width of 0.8 m, smooth and flat bed and R/B of 1
- Data provided by Rozovskii (1961) obtained from a sharp bend of Desna River

In Table 7, the SE values of Eq. 2 for data obtained from the above studies are presented. Moreover, in Fig. 9 the predicted and observed longitudinal velocity profiles in those three studies are indicated. Both Table 7 and Fig. 9, confirm the suitability of Eq. 2 to apply for estimating the longitudinal velocity profile even in different ratio of B/R.

CONCLUSION

Computing the distribution of longitudinal velocity in bends has been investigated by many researches and several models have been introduced. However, due to some simplifications, one expects some errors when it uses those models. In this research, by conducting a great number of experiments in the laboratory of Hydraulics Department of EPFL University, in Switzerland, we found that the observed velocity profile is different from those predicted by some available models. The comparison of the predicted velocity profiles by available models with the observed values from laboratory experiments, showed that the examined models are not capable of predicting the two major characteristics of longitudinal velocity profile in bends, that is, the position of maximum velocity is fully under water surface and the flatness of velocity profile in comparison with logarithmic profile. By considering these two properties of longitudinal velocity profile in sharp bends which make it different from the velocity profile in straight channels, we introduced a new experimental relationship to predict the velocity profile in sharp bends. Using observed data from the laboratory experiments and also the predicted velocity profiles by the new and previous models, we calculated Standard Error of the prediction in some locations of the bend. The comparison of the Standard Error of the new model with that of the previous models showed that the new model predicts longitudinal velocity much more accurately than the previous models. We also used another data set with different ratio of radius of curvature to width, to test the accuracy of the new relationships. We found a small Standard Error (less than 7%) confirming the high accuracy of the new equation on predicting the longitudinal velocity profile in different ratio of B/R in bends.

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