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# The use of Rouse Equation to Predict Transversal Profiles of Suspended-Sediment Concentration in Open-Channel Bends: Case Study of Mataram Irrigation Channel, Indonesia

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**Abstract:** Among several equations to predict suspended sediment concentration profiles, Rouse equation can be considered as the most popular one. Rouse equation is based on logarithmic velocity distribution of 2-Dimensional flow that relatively similar to the flow characteristics at the center of channel. This study discuss on whether the Rouse's equation can be used to predict the profiles of suspended-sediment concentration within transversal direction from inner bank to the outer bank of an open-channel bends. The study was carried out based on the measurement of field data at 3 locations in Mataram irrigation channel. The results show that the Rouse equation can satisfactorily be used to predict the profiles of suspended-sediment concentration, especially for the center of channel bend. For the other position at transversal directions need tobe evaluated.

**Key words:** Rouse equation, suspended sediment, concentrations, transversal direction, satisfactorily, Mataram

## INTRODUCTION

In irrigation channel design, reservoir design and river improvement, the information of suspended sediment profiles is often required. The information of suspended sediment load transport can be obtained through measurement or sampling of suspended sediments in the field or by predicting with the equations found in literatures. In literatures, many equations can be used to determine the suspended sediment concentration distribution such as Rouse's equation in 1937, Lane and Kalinske's equation in 1941, Einstein's in 1955 equation, etc. (Graf, 1984). Among the equations mentioned above, the Rouse's equation might be considered as the most popular one because of its reliability and widely used in literatures.

The equations of suspended sediment concentration distributions are generally developed in 2D-open channel flow which have similar characteristics to that at the center of channel. In certain conditions, the information about the profile of suspended sediment concentration at different positions in transversal direction from center to the edge of channel are often required for example for predicting the amount of suspended sediment discharge in channel for studying the spread of pollutant in river flows, etc. Whether the Rouse's equation can be used or not to predict the profiles of suspended sediment concentration in transversal direction from center to the edge of the channel, still needs to be examined and will be investigated in this study. The study was carried out based on the measurement data of suspended sediment concentration, measured at different positions, from innerbank to outerbank of channel bends for field data (in Mataram Irrigation channel, Yogyakarta).

**Theoretical background:** Rouse's equation was derived from the 2 dimensional of logarithmic velocity distribution of turbulent flow with the assumption that the diffusion coefficient of suspended sediments, $\varepsilon_s$ can be approached with the momentum transfer coefficient, $\varepsilon_m$ and can be written in a general form as:

$$\varepsilon_s = \beta\varepsilon_m \tag{1}$$

Based on the assumption given above, Rouse's equation got an equation of suspended sediment concentration distribution as follows (Kironoto, 2016):

$$\frac{C}{C_a} = \left[\frac{D-y}{y}\,\frac{a}{D-y}\right]^z \tag{2}$$

With:

$$Z = \frac{w_s}{\beta k u_*} \tag{3}$$

Where:

C = The suspended sediment concentration at a point of a distance y from the reference point
$C_a$ = The concentration of the reference point at a distance of a from reference point
D = A flow depth
$w_s$ = Settling velocity of suspended sediment particles
Z = A Rouse's parameter
$\kappa$ = Von-Karman constant and $\beta$ = 1

From Eq. 3, it is known that for certain value of friction velocity, $u_*$, the value of Z is proportional to the settling velocity, $w_s$ and so, the smaller of the size of sediment particles (which means that the velocity to be smaller), the value of Z become smaller and vice versa. According to Eq. 2, for the smaller value of Z, the distribution of suspended sediment concentration, C, become more uniform and for the greater value of Z, the distribution of suspended sediment concentration, C become more non-uniform. Graf (1984) found that the value of $\beta$ in Eq. 1 approaching to $\beta = 1$, for fine sediment particles and tend to be smaller, $\beta<1$ with the increasing value of sediment particles. Settling velocity of suspended sediment particle can be calculated according to Eq. 1 (Bogardi, 1978):

$$W_s = \frac{1}{18}\frac{\gamma_s\text{-}\gamma}{\gamma}g\frac{d_s^2}{v} \qquad (4)$$

Where:

$d_s$ = A representative diameter of suspended sediment particles

$w_s$ = Settling velocity of suspended sediment particle

$\gamma_s$ and $\gamma$ = Density of sediment and water

## MATERIALS AND METHODS

**Data:** Collected data were analyzed in this study, i.e., field measurements at 1 location in Mataram Irrigation Channels, Yogyakarta. Suspended sediment concentration profiles of field data were measured by using Opcon probe-set. Channel dimensions vary between 4.2-4.5 m with roughness values, $k_s = 0.04$ cm. For each flows at certain cross section, 3 profiles of suspended sediment were measured at different positions in transversal direction, from inner bank to outerbank of bend channel, i.e., at R = 1/6B, 2/6B, 1/2B, 2/3B and 5/6B, where B is the width of channel. Detail measurement locations in transversal direction for field measurements are given in Fig. 1.

From profiles were conducted in bend channel flow the profiles were measured from different cross sections in Mataram Irigation Channel in Yogyakarta. For main flow parameters of field data are given in Table 1.

Table 1: The main flow parameters of field data

| Locations | Q (m/sec) | D (m) | B/D (-) | $u_*$ (m/sec) | $\overline{C}_v$ (g/lt) | Fr (-) | $w_S$ (cm/sec) | $\overline{C}_v$ (g/lt) |
|---|---|---|---|---|---|---|---|---|
| L1SIR1 | | 0.71 | 5.92 | 0.0752 | | 0.221 | $1.64\times10^{-3}$ | 1.752 |
| L1SIR2 | | 0.73 | 5.75 | 0.1193 | | 0.218 | $1.64\times10^{-3}$ | 1.791 |
| L1SIR3 | 1.816 | 0.75 | 5.60 | 0.1483 | 1.666 | 0.215 | $1.64\times10^{-3}$ | 1.678 |
| L1SIR4 | | 0.77 | 5.45 | 0.1311 | | 0.212 | $1.64\times10^{-3}$ | 1.605 |
| L1SIR5 | | 0.78 | 5.38 | 0.1436 | | 0.211 | $1.64\times10^{-3}$ | 1.544 |
| L1S2R1 | | 0.70 | 6.00 | 0.1166 | | 0.215 | $1.64\times10^{-3}$ | 1.697 |
| L1S2R2 | | 0.78 | 5.38 | 0.1071 | | 0.204 | $1.64\times10^{-3}$ | 1.655 |
| L1S2R3 | 1.858 | 0.80 | 5.25 | 0.1230 | 1.624 | 0.201 | $1.64\times10^{-3}$ | 1.608 |
| L1S2R4 | | 0.83 | 5.06 | 0.1175 | | 0.198 | $1.64\times10^{-3}$ | 1.596 |
| L1S2R5 | | 0.85 | 4.94 | 0.1056 | | 0.195 | $1.64\times10^{-3}$ | 1.575 |
| L1S3R1 | | 0.65 | 6.46 | 0.0809 | | 0.218 | $1.64\times10^{-3}$ | 1.636 |
| L1S3R2 | | 0.70 | 6.00 | 0.0853 | | 0.210 | $1.64\times10^{-3}$ | 1.608 |
| L1S3R3 | 1.732 | 0.75 | 5.60 | 0.1168 | 1.558 | 0.203 | $1.64\times10^{-3}$ | 1.560 |
| L1S3R4 | | 0.80 | 5.25 | 0.1008 | | 0.197 | $1.64\times10^{-3}$ | 1.542 |
| L1S3R5 | | 0.84 | 5.00 | 0.1082 | | 0.192 | $1.64\times10^{-3}$ | 1.478 |
| L2SIR1 | | 0.68 | 6.18 | 0.0722 | | 0.133 | $1.12\times10^{-3}$ | 1.365 |
| L2SIR2 | | 0.74 | 5.68 | 0.0624 | | 0.127 | $1.12\times10^{-3}$ | 1.291 |
| L2SIR3 | 1.213 | 0.78 | 5.38 | 0.0598 | 1.264 | 0.124 | $1.12\times10^{-3}$ | 1.248 |
| L2SIR4 | | 0.79 | 5.32 | 0.0871 | | 0.123 | $1.12\times10^{-3}$ | 1.224 |
| L2SIR5 | | 0.81 | 5.19 | 0.0684 | | 0.122 | $1.12\times10^{-3}$ | 1.202 |
| L2S2R1 | | 0.65 | 6.46 | 0.0924 | | 0.166 | $1.12\times10^{-3}$ | 1.274 |
| L2S2R2 | | 0.70 | 6.00 | 0.1081 | | 0.160 | $1.12\times10^{-3}$ | 1.232 |
| L2S2R3 | 1.321 | 0.78 | 5.38 | 0.1018 | 1.196 | 0.152 | $1.12\times10^{-3}$ | 1.198 |
| L2S2R4 | | 0.82 | 5.12 | 0.1092 | | 0.148 | $1.12\times10^{-3}$ | 1.159 |
| L2S2R5 | | 0.85 | 4.94 | 0.1064 | | 0.145 | $1.12\times10^{-3}$ | 1.139 |
| L2S3R1 | | 0.65 | 6.46 | 0.0838 | | 0.203 | $1.12\times10^{-3}$ | 1.216 |
| L2S3R2 | | 0.70 | 6.00 | 0.1066 | | 0.196 | $1.12\times10^{-3}$ | 1.213 |
| L2S3R3 | 1.619 | 0.75 | 5.60 | 0.1114 | 1.156 | 0.189 | $1.12\times10^{-3}$ | 1.181 |
| L2S3R4 | | 0.80 | 5.25 | 0.0896 | | 0.183 | $1.12\times10^{-3}$ | 1.104 |
| L2S3R5 | | 0.85 | 4.94 | 0.0876 | | 0.178 | $1.12\times10^{-3}$ | 1.098 |
| L3SIR1 | | 0.75 | 5.60 | 0.0948 | | 0.161 | $1.13\times10^{-3}$ | 1.403 |
| L3SIR2 | | 0.90 | 4.67 | 0.0915 | | 0.147 | $1.13\times10^{-3}$ | 1.366 |
| L3SIR3 | 1.580 | 0.91 | 4.62 | 0.0990 | 1.278 | 0.146 | $1.13\times10^{-3}$ | 1.266 |
| L3SIR4 | | 0.92 | 4.57 | 0.1005 | | 0.145 | $1.13\times10^{-3}$ | 1.218 |
| L3SIR5 | | 0.93 | 4.52 | 0.1040 | | 0.143 | $1.13\times10^{-3}$ | 1.173 |
| L3S2R1 | | 0.60 | 7.00 | 0.0852 | | 0.153 | $1.13\times10^{-3}$ | 1.263 |

Table 1: Continue

| Locations | Q (m/sec) | D (m) | B/D (-) | u* (m/sec) | $\overline{C}_y$ (g/lt) | Fr (-) | $w_S$ (cm/sec) | $\overline{C}_y$ (g/lt) |
|---|---|---|---|---|---|---|---|---|
| L3S2R2 | | 0.75 | 5.60 | 0.0886 | | 0.137 | $1.13\times10^{-3}$ | 1.228 |
| L3S2R3 | 1.347 | 0.90 | 4.67 | 0.0956 | 1.170 | 0.125 | $1.13\times10^{-3}$ | 1.191 |
| L3S2R4 | | 1.00 | 4.20 | 0.0862 | | 0.119 | $1.13\times10^{-3}$ | 1.141 |
| L3S2R5 | | 1.06 | 3.96 | 0.0862 | | 0.115 | $1.13\times10^{-3}$ | 1.096 |
| L3S3R1 | | 0.65 | 6.46 | 0.0639 | | 0.133 | $1.13\times10^{-3}$ | 1.173 |
| L3S3R2 | | 0.77 | 5.45 | 0.0712 | | 0.123 | $1.13\times10^{-3}$ | 1.123 |
| L3S3R3 | 1.219 | 0.82 | 5.12 | 0.0785 | 1.094 | 0.119 | $1.13\times10^{-3}$ | 1.079 |
| L3S3R4 | | 0.88 | 4.77 | 0.0948 | | 0.115 | $1.13\times10^{-3}$ | 1.070 |
| L3S3R5 | | 0.95 | 4.42 | 0.1060 | | 0.110 | $1.13\times10^{-3}$ | 1.052 |

Q = flow discharged; D = flow depth; B/D = aspect ratio; u* = friction velocity; $\overline{C}$ = cross-section average suspended; sediment concentration; Fr = froude number; B = channel wide; $w_S$ = settling velocity; $\overline{C}_y$ = depth average suspended sediment concentration (Kironoto, 2016)

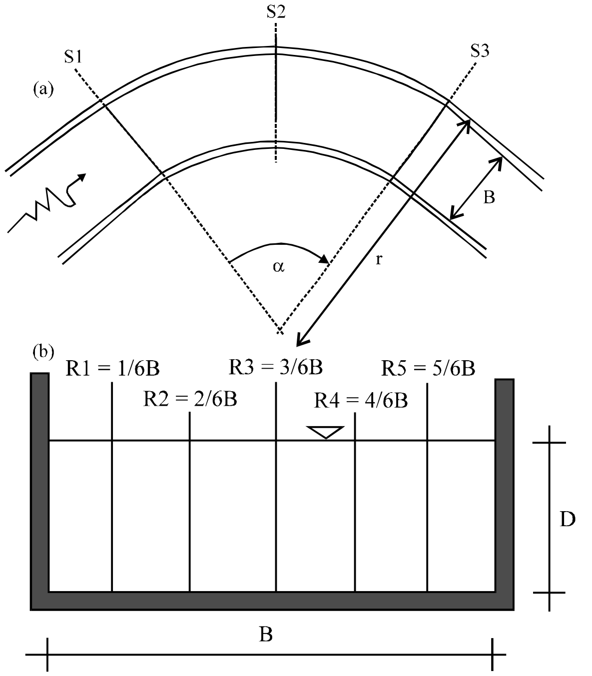

Fig. 1: a) Location of measurement at different positions and b) positions in transversal direction

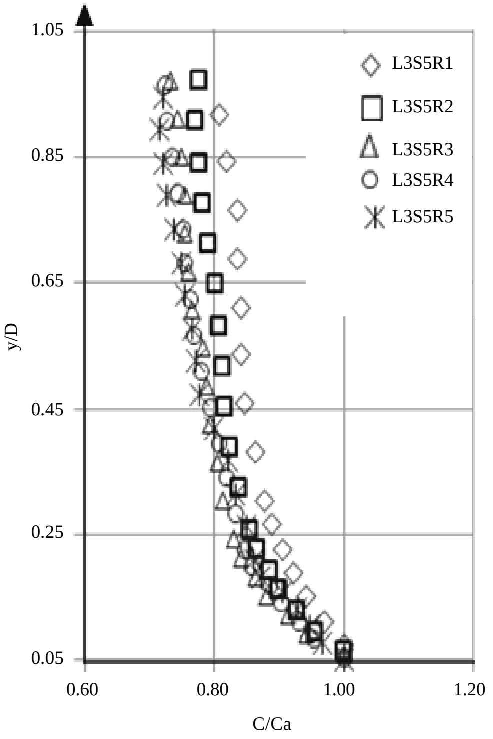

Fig. 2: Typical examples of suspended sediment profiles at different positions in transversal direction

## RESULTS AND DISCUSSION

The distribution of suspended sediment concentration in Rouse equation is influenced by the values of Rouse parameter, Z which is proportional to settling velocity, $w_s$. The smaller size of particles, the value of $w_s$ and Z become smaller which give the distributions of suspended sediment concentration ratio, $C/C_a$ become more uniform and vice versa, the greater value of Z, the distributions of suspended sediment concentration ratio, $C/C_a$ become more non-uniform while y/D is the ratio of depth. The profiles of suspended sediment concentration from center to the edge of channel are typically represented by profiles L3S2R1, L3S2R2, L3S2R3, L3S2R4 and L3S2R5. As shown in Fig. 2, the profiles of suspended sediment concentration changed from innerbank to outerbank of channel bend, however where suspended sediment concentration closer to outerbank, the suspended sediment concentration profiles become smaller and to be more non-uniform.

The variation of setting velocity, $w_s$ in the channel can be obtained through suspended sediments sampling, from the center to the edge of channel. Although, the variations of $w_s$ (and friction velocity, u*) theoretically can be determined but to determine these values (especially in the fields) are not easy. To solve these difficulties, Rouse parameter, Z was determined from the parameters such as u*, $w_s$ and β-values obtained in the center of the channel. Kironoto and Yulistiyanto (2009) but to provide a good agreement between the measurement data (inner bank or outer bank of channel bend) with Rouse equation, a correction factor that is a function of position in transversal direction should be applied. A correction factor was determined using the measured data as explined in the following.

By using the flow parameters as well as the suspended sediment parameters obtained at the center of the channel (R/B = 0.5), Rouse parameter. Z, Eq. 3 Kironoto and Yulistiyanto (2009) can be written as:

$$Z_{ct} = \frac{W_{s_{ct}}}{\beta_{ct}\, k_{*ct}} \tag{5}$$

For the others positions in transversal direction, i.e., R/B<0.5 and R/B<0.5, correction factors which consider the variation of $w_s$ and $u_*$ in transversal direction should be applied to Rouse parameter as:

$$Z_{R/B} = \frac{\bar{C}_{y/R/B.}\, w_{sct}}{\beta_{R/B}\, \bar{C}_{y^2R/B.}\, u_{*ct} k} \tag{6}$$

Or:

$$Z_{R/B} = \frac{W_{s_{ct}}}{\beta'_{R/B}\, u_{*_{ct}}\, k} \tag{7}$$

Where:

$$\frac{1}{\beta'_{R/B}} = \frac{\bar{C}_{y^1 z/B}}{\beta_{R/B}\, \bar{C}_{y^2R/B}}$$

Or:

$$\beta'_{R/B} = \frac{\beta_{R/B}\, \bar{C}_{y^2R/B}}{\bar{C}_{y^1R/B}} \tag{8}$$

Equation 7, $Z_{R/B}$ is Rouse parameter which is a function of R/B (positions in transversal direction), $w_{sct}$ is settling velocity of suspended sediment particle obtained from suspended sediment sampling taken at the center of the channel and is friction velocity $u_*$ at the center of the channel which can be calculated with the energy gradient method, $u_* = \sqrt{g.h.s_0}$ or from the measured data of velocity profiles (with the Clauser method, Kironoto *et al.* (2007). $\beta'_{R/B}$ is a correction factor of Rouse parameter, expressed as a function of R/B. In Fig. 3, it is shown examples of determining the value of for data L1S1R3 and L1S1R5.

As shown in Fig. 3, Rouse equation shows a good agreement with the data measured at the center of the channel (profile L1S1R 3) where $\beta' = \beta \approx 1$. However, closer to the wall in the outerbank region of the channel bend, the best fit of Rouse equation to the data, obtained for $\beta' < 1$, i.e., $\beta' = 0.59$, respectively for profile L1S1R5. These results mean that Rouse equation can still be used to predict the suspended sediment concentration in the edge region inner bank and outer bank of the channelbend, however, the β-value of Rouse parameter in Eq. 3 should be corrected as a function of R/B, i.e., $\beta = \beta' = f\,(R/B)$.

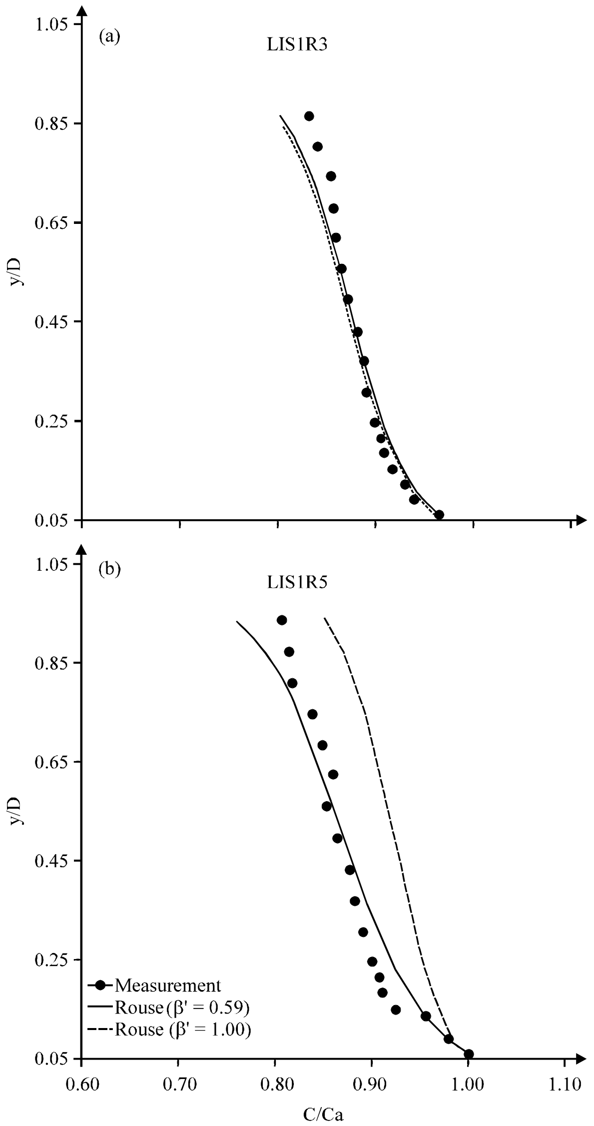

Fig. 3: a, b) Comparation between measured data of suspended sediment concentration profiles and Rouse equation at location 1

Considering the measured data of suspended sediment concentration profiles in the edge region of channel which are more uniform compared with the distribution in the center of the channel and considering the characteristic of Rouse equation and Rouse parameter,

Table 2: Correction factor of Rouse parameter $\beta'$

| | $\beta'$ value for different positions | | | | |
|---|---|---|---|---|---|
| | Innerbank | | Centre | Outerbank | |
| Location | R1(1/6B) | R2 (2/6B) | R3 (3/6B) | R4 (4/6B) | R5 (5/6B) |
| L1S1 | 1.28 | 1.20 | 1.00 | 0.82 | 0.78 |
| L1S2 | 0.98 | 0.95 | 0.85 | 0.83 | 0.81 |
| L1S3 | 1.02 | 0.98 | 0.71 | 0.78 | 0.75 |
| L2S1 | 1.32 | 1.10 | 1.00 | 0.74 | 0.88 |
| L2S2 | 0.73 | 0.67 | 0.58 | 0.53 | 0.51 |
| L2S3 | 0.63 | 0.55 | 0.61 | 0.73 | 0.82 |
| L3S1 | 0.64 | 0.81 | 1.00 | 0.51 | 0.53 |
| L3S2 | 0.82 | 0.61 | 0.55 | 0.43 | 0.40 |
| L3S3 | 0.73 | 0.53 | 0.45 | 0.37 | 0.33 |

Z, one can conclude that closer to the edge (side wall) ragion of the channel, the value of Rouse parameter, Z, become smaller.

The smaller value of Z from the center to the edge of channel, especially due to the smaller value of settling velocity, $w_s$. The settling velocity, $w_s$ that is a function of the size of suspended sediment particle as well as the suspended sediment concentration, theoritically also variate from the center to the edge of channel. Fugate and Friedrich (2001) showed that the settling velocity of suspended sediment particles increase with the increasing value of suspended sediment concentration. This means that the settling velocity of particle, $w_s$ in the edge region of channel is smaller compared with that in the center of the channel.

With the least square method, the value of correction factor, $\beta'_{R/B}$ can be obtained by finding the best fit between the measurement data with Rouse equation. For position at the center of the channel, namely at the position of R/B = 0.5, it is obtained $\beta'_{R/B} \approx 1$. The complete results of $\beta'_{R/B}$ analyzed in this study are given in Table 2.

Although, the plot of $\beta' = f(R/B)$ rather scattered, however tend of data analyzed in this study clearly appear, i.e., closer to the inner bank region, $\beta'$ tend to increase; at the center of the channel, $\beta' \approx 1$ while closer to the outerbank, $\beta' < 1$. The regression equation for all data used in this study is given as following:

$$\beta' = -0.415\ln(R/B) + 0.7342 \tag{9}$$

where, according to Eq. 9 for R/B = 0.5, $\beta' = 1.021 \approx 1$.

## CONCLUSION

From the results of analysis to the data used in this study, some conclusions might be drawn as the following: by comparing the measured data used in this study with Rouse equation, it can be concluded that Rouse equation can predict the profiles of suspended sediment concentration satisfactorily only at the center of channel, especially at the beginning of entering the bend while to another region of the channel bend, the Rouse equation deviate from the measured data. In order to use the Rouse equation in the whole channel cross section, i.e., from inner bank to outer bank of bend channel cross section, a correlation factor of $\beta' = f(R/B)$ as given in Eq. 9 should be applied to Rouse parameter as given in Eq. 3 and 7.

Although, the plot of $\beta' = f(R/B)$ rather scattered, however, tend of data analyzed in this study clearly appear, i.e., closer to the inner bank region, $\beta'$ tend to increase at the center of the channel, $\beta' \approx 1$ while closer to the outerbank, $\beta' < 1$.

The conclusions drawn here are valid only in the range of data used in this study. Further, researches are necessary for the other range of the data.

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