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Technical note

INVESTIGATION OF SHEAR STRESS DISTRIBUTION IN A 90 DEGREE CHANNEL BEND

Seung Kyu LEE
Sustainable Management of Natural Resources and Environment Research Group
Faculty of Environment and Labour Safety
Ton Duc Thang University Ho Chi Minh City, Vietnam
19, Nguyen Huu Tho Str., Tan Phong Ward, Dist. 7, Ho Chi Minh City, VIETNAM
E-mail: leeseungkyu@tdtu.edu.vn

Truong An, DANG*
VNU-HCM, University of Science
227 Nguyen Van Cu Str., 5 Dist., Ho Chi Minh City, VIETNAM
E-mail: dtan@hcmus.edu.vn

Van Tuan, LE
Institute of Coastal and offshore Engineering (ICOE)
658 Vo Van Kiet Boulevard, Dist. 5, HCM City, VIETNAM
E-mail: levantuan.vktb@gmail.com

Shear stress is a key parameter that plays an important role in sediment transport mechanisms; therefore, understanding shear stress distribution in rivers, and especially in river bends, is necessary to predict erosion, deposition mechanisms and lateral channel migration. The aim of this study is to analyze the shear stress distribution near a river bed at 90-degree channel bend using a depth-average method based on experimental measurement data. Bed shear stress distribution is calculated using the depth-averaged method based on velocity components data has been collected from a 3D-ADV device (three-dimensional acoustic doppler velocity) at different locations of a meandering channel. Laboratory experiments have been made at the hydraulic laboratory of the RCRFIDF (Research Center for River Flow Impingement and Debris Flow), Gangneung-Wonju National University, South Korea to provide data for simulating the incipient motion of the riverbed materials and then predicting the river morphological changes in the curved rivers. The calculated results show that the maximum value of shear stress distribution near the riverbed in the different cross sections of the surveyed channel occurs in a 70-degree cross section and occurs near the outer bank. From the beginning of a 40-degree curved channel section, the maximum value of the shear stress occurs near the outer bank at the end of the channel.

Key words: experimental channel, *90*° bend, shear stress, erosion, deposition.

1. Introduction

Natural channels never stop changing their geomorphic characteristics, especially with regard to the flow in meandering channels, which results in geomorphic changes such as bank erosion and deposition. Bed shear stress is a key parameter to estimate bed load sediment transport in open channel flow problems. According to [1, 2, 3] bed shear stress is one of the most difficult parameters to analyze from a purely

* To whom correspondence should be addressed

theoretical point of view, even for the simplest cases. To understand the shear stress distribution mechanism for meandering channels in detail, physical models in detail are useful.

In recent decades, many studies have been conducted to calculate the shear stress distribution. Schlichting [4] suggested a bed shear stress calculation method by applying a linear regression between the logarithmic profiles of the flow depth and velocity. Sin *et al*. [3] concluded that when the hydraulic radius / width of a channel is more than 3.5, the shear stress distribution at the entrance of a channel bend is almost constant; their study results also indicate that maximum shear stress occurs at the end of a channel bend, near the outer bank. Montes [5] suggested a linear extrapolation of the linear portion of a Reynolds shear stress profile as a method for calculating bed shear stress. According to [6, 7, 8], the maximum dimensionless shear stress occurs at the beginning of the bend, near the inner wall.

To determine the shear stress distribution in the meandering channels, many studies have been carried out based on the physical model. Ippen and Drinker [9] performed laboratory experiments to correlate the impacts of shear stress on meandering channel bank erosion using a Preston tube. Heintz [10] used a Preston tube to measure shear stress in a curved channel constructed at Colorado State University. Naji *et al*. (2010) [11] made experiments on the flow pattern in a 90-degree bend and also calculated the bed shear stress. In 2014, Vaghefi *et al*. [7] conducted an experimental investigation on the bed shear stress distribution at 180-degree sharp bends. They concluded that the maximum dimensions of the shear stress occur at the beginning of a bend, near the inner wall. Baird [12] suggested a linear extrapolation of a Reynolds shear stress profile to obtain bed shear stress using 3D-ADV data. According to Sin *et al.* [3] measurement of flow velocity from the ADV device is one of the good parameters for calculating the distribution of shear stress.

The study examines the bed shear stress distribution for the control of the bed aggradation and degradation process in curved open channel which was constructed in the same shape as a natural river bend using the depth-average method based on the measurement data of the three components of velocity (Vx, Vy, Vz) from the 3D-ADV device. The calculated results of this work can be considered as an effective method to determine position of maximum shear stress and help professional agencies find out the places which are facing the problem of erosion in a natural river bend.

2. Material and methodology

2.1. Material

In this study, in order to calculate the shear stress distribution near the bed in a curved open channel, the experimental flume was constructed by the RCRFIDF (Fig.1) which has the same shape as a natural river bend.

Fig.1. Illustrations of the 90-degree channel bend (Dang and Park [13]).

The experimental flume was *12.0 m* long and *1.5 m* wide, and the rotation angle consisted of 90-degree central bend with a *2.5 m* external radius that connects the two inflow and outflow straight channel of sections reaching *4.5 m* (Fig.2). The bed and side walls of the experimental flume were constructed cement. The bed slope and the Manning's roughness coefficient (*n*) were *1.5*% and *0.015*, respectively. The water depth and flow discharge were established as being *15 cm* and *290 l/s* which were equivalent to the incipient motion condition of the median grain size during the experiment at the entrance to the channel, the median diameter of the particles at the bottom was $d_{50}=3.4$ *cm* and the roughness of side walls was not considered in this work. Flow velocity components were measured by the 3D-ADV device having an accuracy of ±*1*%. For the adjustment of flow depth at the curve entrance, a sluice gate was established at the end of the experimental flume to control the depth of downstream flow.

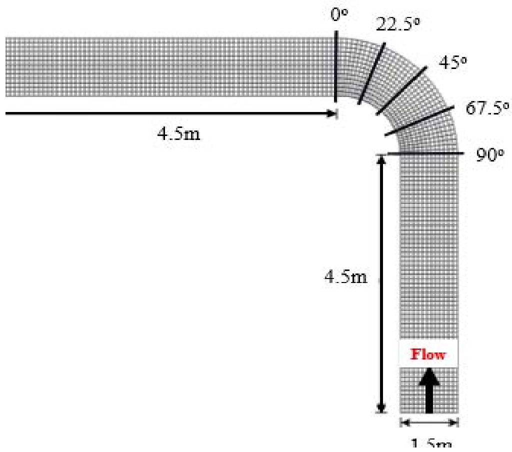

Fig.2. The schematic plan and specifications of the experimental flume.

2.2. Methodology

The ADV is high-resolution equipment used to measure 3D velocity components (V_x, V_y, V_z). Different probes of this device are seen in Fig.3. The 3D-ADV is an accurate solution for high-precision, 3D velocity measurements in a wide variety of settings from laboratory to ocean conditions. In addition, the ADV is extremely simple to set up and use. The velocity range is from ±*0.001- 4.5 m/s*, and is adjustable for the user with ±*1*% of measured velocity accuracy (±*0.001 m/s*). The experiments can be carried out at a *25* Hz frequency in 1.0 minutes. Therefore, the device can record up to 1,500 data of the flow velocity per second in the V_x, V_y and V_z directions [14, 5].

Fig.3. Illustrations of the 3D-ADV device (Dang and Park [14]).

Figure 4 shows an experimental survey to measure the flow velocity components. In this work, the 3D-ADV device (Fig.4) was used to measure the two velocity components (V_x, V_y) in the longitudinal and lateral directions of velocity and the measuring points were installed on the data collection cart. The measured data related to the two flow velocity components were recorded at five different cross sections in the longitudinal direction and 15 points in each cross section along the width of the experimental flume (Fig.2) at a distance of *5.0 mm* from the bed in order to determine shear stress near the bed. In order to measure the water depth and flow velocity components near the bed of the experimental flume, five cross sections (Fig.2) (corresponding to bending sections 0^o, 22.5^o, 45^o, 67.5^o and 90^o) from the beginning to the end of the flume were established. Flow depth was defined by subtracting the bed level from the water surface elevation and each vertical point 90 seconds flow velocity readings are taken. Flow velocities were measured directly at five cross sections with 15 points in each cross section.

Fig.4. Measuring the 3D flow velocity using the ADV device.

As mentioned above, shear stress plays an important role in sediment transport mechanisms. Therefore, calculating the shear stress distribution in meandering channels to predict bank erosion is necessary. So far, various methods have been developed to define the shear stress distribution, such as the Reynolds shear stress method [5] the Preston tube method [15, 16], the linear regression method [12, 5], the depth-averaged method [17, 18, 7]. The depth-averaged method is used by [2, 18, 10, 3] to calculate the bed shear stress distribution along the *x* and *y*-directions and the resultant bed shear stress.

In this study, the depth-averaged method is selected to calculate the bed shear stress distribution along the *x* and *y*-directions and the resultant bed shear stress through the following relations.

$$\tau_{bx} = C_f \rho \bar{u} \sqrt{\bar{u}^2 + \bar{v}^2} \, , \tag{2.1}$$

$$\tau_{by} = C_f \rho \bar{v} \sqrt{\bar{u}^2 + \bar{v}^2} \, , \tag{2.2}$$

$$\tau_b = C_f \rho \sqrt{\bar{u}^2 + \bar{v}^2} \, , \tag{2.3}$$

$$C_f = \frac{n^2 g}{y^{\frac{1}{3}}} \, , \tag{2.4}$$

$$n = \frac{d_{50}^{\frac{1}{6}}}{21.1} \tag{2.5}$$

where τ_x, τ_y are shear stresses along the length and the width of the channel, respectively;

τ_b is the resultant shear stress respectively;

$\overline{u}, \overline{v}$ are measured velocities in the depths along the x and y- directions;

n is Manning's coefficient; y is the flow depth; g is the acceleration of gravity.

3. Results and discussion

Figures 5 and 6 show the shear stress distribution near the bed in the 90-degree channel bend. The calculated results of the bed shear stress distribution at different locations in the 90-degree channel bend have been recorded using the depth-averaged method.

The results calculated show that the maximum shear stress value near the channel bed occurs at the beginning of the channel bend and near the inner bank (Fig.5). After, from the beginning of the channel to the 40-degree curved channel section, the maximum value of shear stress occurs near the outer bank to the end of the channel bend (Fig.6). The calculated results are quite consistent with studies of Atashi and Bejestan [17], and Vaghefi *et al*. [7].

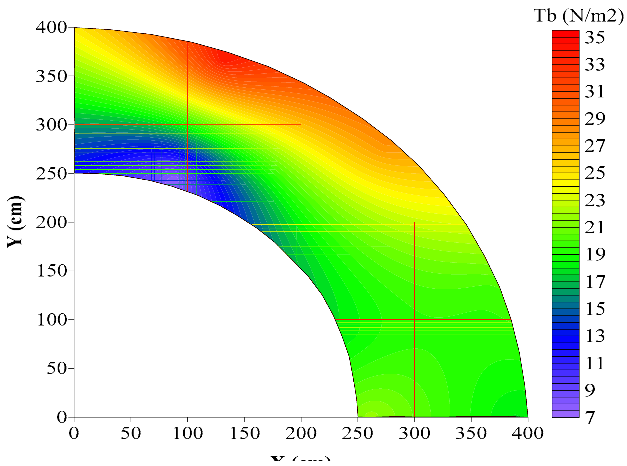

Fig.5. Illustrations of the shear stress distribution in the 90-degree channel bend.

As seen in Fig.6, the distribution of shear stresses throughout a channel bend has been calculated and the maximum shear stress value occurs in the 70-degree cross section and it is about 3.5 times the minimum value of the shear stress. Then, the maximum shear stress value decreases from 70-degree cross section to the end of the channel bend.

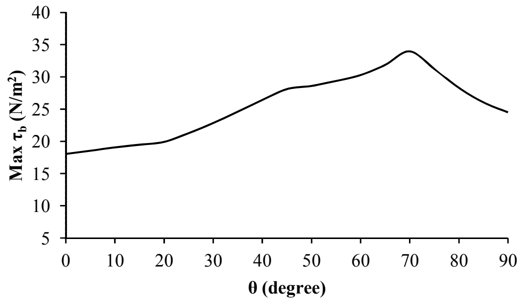

Fig.6. Maximum shear stress values at different cross sections of the channel studied.

As seen in Fig.7, there are some variations of the maximum shear stress values throughout the different channel sections. From the beginning of the 20-degree curved channel section, the maximum shear stress value occurs near the inner bank, but thereafter, the maximum shear stress value is oriented towards the closed outer bank from the 40 degrees curved channel section to the 70-degree cross section and after passing over the 70-degree curved channel section the maximum value of shear stress started to decrease by the end of the channel bend. The analyzed results showed that scour mainly occurs along the outer bank of the curved channel.

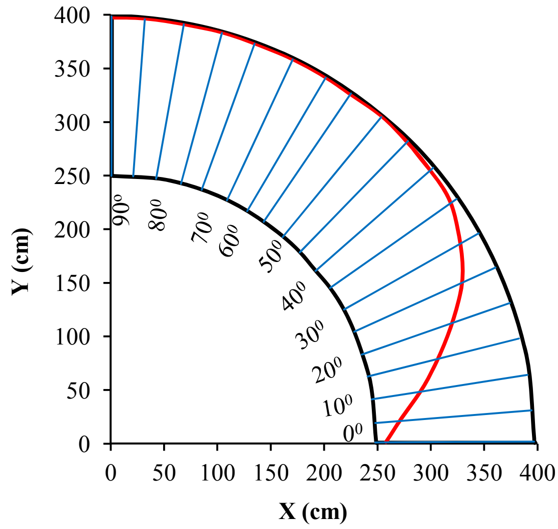

Fig.7. Maximum shear stress variations throughout the 90-degree channel bend.

Figure 8 presents the variation of bed shear stress at different distances from the inner bank (*5*%, *50*%, and *95*% compared with the width of the experimental channel) and shows that the maximum shear stress value occurs at a distance of *5*% of the width of the channel and occurs at the half ends of the channel bend section. Similarly, at a distance of *50*%, and *95*% of the width of the channel the values of shear stress are in the range *18.8-21.8* N/m^2, *7.79-21.4* N/m^2 respectively and approximately *81.1*%, and *60.08* % compared with the values of shear stress at distances of *5*%.

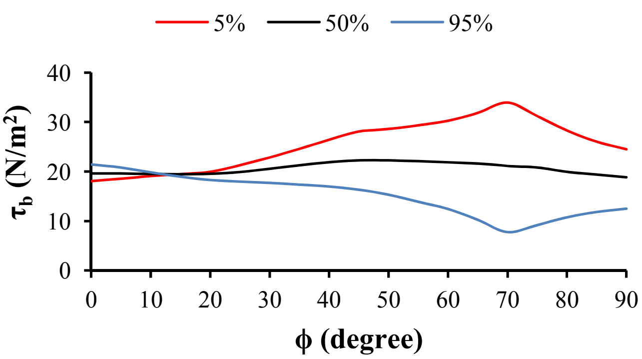

Fig.8. Shear stress variations at different distances from the inner bank.

The formation of this bar is likely related to deposition of bedload due to decreased bed shear stresses around the junction corner during formative flows. Further study of the development of this bar is needed, especially for channel-shaping flow events, as it may be critical to the long-term stability of confluent meander bends.

4. Conclusions

A physical model has been established to test the validation of the shear stress theory near the bed in a 90-degree meandering channel using the depth-averaged method, and the results of the calculations are presented as follows:

- the maximum shear stress occurs in the 70-degree channel cross section and near the outer bank,
- from the beginning to the 40 degrees curved channel, the maximum value of shear stress occurs near the outer bank at the end of the channel,
- the greatest variations of shear stress were observed near the outer bank.

The advantages of this study are:

- the shear stress distribution was calculated and the position of the maximum shear stress values and the places which must be protected from erosion in strong channel bends were easily determined.

The disadvantages of this study are:

- the 3D-ADV device has instrumentation limitations because it could not directly touch the channel bed during measurements,
- the number of data points that were collected by the 3D-ADV device in this study was eight points, which is not good enough to obtain an accurate result.

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