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Mean flow characteristics in a flat and eroded bed curved channel

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Abstract: The mean flow characteristics in a curved channel are really different from those in a straight channel. The main cause is the existence of secondary flow within the flow in the curved channel. This paper will discuss the differences in mean flow characteristics due to changes in the bed topography in the curved channel. Acoustic Doppler Velocimetry (ADV) measurements have helped to analyse characteristics of the mean flow on flat and eroded beds in a 180° curved channel. Sand (mean diameter d_{50} = 0.001 m and specific gravity Gs = 2.65) was selected as the bed material. The condition of flow in the approach section was steady and uniform with 0.159 m depth. One of the mean flow characteristics in the curved channel is the free surface superelevation due to the presence of centrifugal force. The second is the circular motion toward the inner-bank region at the lower layer and toward the upper layer outer-bank region. The cause of the circulation is the difference in centrifugal forces between the two layers. The magnitude of velocity near the bed surface is more significant than the flow near the water surface. This causes erosion in the outer bank region and deposition in the inner bank region. In general, tangential velocity v_θ in flat bed is greater than its tangential velocity in eroded bed. The maximum velocity path in a flat and eroded bed of the curved channel resembles a sinusoidal curve, where the minimum value is located at 90° and 120° of the curve.

Keywords: curved channel, eroded bed, flat bed, mean flow

INTRODUCTION

Characteristics of the flow in a curved channel are quite different from those in a straight channel. Centrifugal force produces a number of effects, such as superelevation of the water surface and helicoidal flow, which in turn lead to a redistribution of velocity and shear stress. These flow characteristics have a pronounced effect on erosion, deposition, and sediment transport in a natural channel. ODGAARG [1984] research into an alluvial curved channel show that the layer topography develops and decays at much shorter distances than the velocity profile.

The classic research of the flow in a curved channel was preceded by ROZOVSKII [1957]. Further, he studied a variety of bend angles, aspect ratio, and used research instruments and variables to obtain more valid measurement results. In the last ten years, BLANCKAERT [2003] conducted research by reviewing components of tangential, radial, and vertical velocities on the cross 60° from the inlet. PATRA [2004] stated that the flow and velocity distributions in meandering compound channels are strongly governed by interaction between flow in the main channel and that in the floodplain.

Research on flow characteristics in the curved channel was originally done by ROZOVSKII [1957]. In addition to finding the role of the secondary flow caused by a centrifugal force, Rozovskii also developed the equation of radial velocity distribution. The radial velocity causes the upper side flows moving to the outer bank instead of the lower side flow to the inner bank. KIKKAWA [1973] states that the logarithmic velocity distribution equation does not apply to the longitudinal main flow direction or tangential velocity, v_θ in a curved channel flow. The Boussinesq's parabolic velocity distribution of quadratic equation gives good results, as:

$$\frac{v_\theta}{U} = \frac{r}{R}\frac{1 - K_1\left(1 - \frac{z}{h}\right)^2}{1 - \frac{K_1}{3}} \tag{1}$$

where: K_1 = parameter calculated by the equation: $K_1 = 3(1 - U/v_{\theta1})$, $v_{\theta1}$ = tangential velocity at the surface of the water and centerline (m·s^{-1}), U = average velocity (m·s^{-1}), r = distance from the center of the bend (m), R = radius of curved channel (m), z = vertical distance from the bed (m), h = flow depth (m).

While secondary flow velocity components of the radial velocity (v_r) and vertical velocity (v_z) are formulated by KIKKAWA [1973]:

$$v_r = \frac{1}{R_i + \zeta}\frac{\partial\psi}{\partial z} \tag{2}$$

$$v_z = \frac{1}{R_i + \zeta}\frac{\partial\psi}{\partial r} \tag{3}$$

where: R_i = radius in the curved channel (m), ζ = distance from inner bank (m), ψ = flow parameter are defined as:

$$\psi = \sum_{i,j=1}^{\infty} A_{ij}\sin\left(\frac{i\pi z}{h}\right)\cdot\sin\left(\frac{j\pi\zeta}{h}\right) \tag{4}$$

and

$$A_{ij} = -\frac{8}{conhB\pi^4}\frac{\int_0^B\int_0^h v\frac{\partial v}{\partial z}\cdot\sin\left(\frac{i\pi z}{h}\right)\cdot\sin\left(\frac{j\pi\zeta}{h}\right)\cdot dz\cdot d\zeta}{\left[\left(\frac{i}{h}\right)^2+\left(\frac{j}{B}\right)^2\right]^2} \tag{5}$$

YEN [1995] stated that scour and deposition of the branch channel are influenced by the tangential flow and radial flow. Radial flow causes the movement of sediments to deviate from the tangential direction in general. At the same time, JEONG, and YOON [1998] stated that the trajectory of the maximum tangential velocity shifts toward the bend in inner banks in the entrance zone and then moves to the outer bank region. BLANCKAERT [2003] used the Acoustic Doppler Velocity Profiler (ADVP) for measuring the flow velocity. On analysis using the Acoustic Doppler Velocimeters (ADV), data present specific requirements compared to traditional current-metering equipment. Due to the types of data obtained, the analyses that are possible to ensure that technical limitations of ADV's do not adversely affect the quality of results, according to WAHL [2000]. According to GARCÍA's *et al.* [2004], the ability of the ADV to overcome flow turbulence was analysed with a new tool called ADV Performance Curves (APCs). Results showed that the value of flow kinetic energy (K) reached a maximum in the central region while turbulent kinetic energy (k) reaches a minimum value at the outer-bank region; the value of turbulent kinetic energy (k) on cornering lines do not follow the exponential function $k = 4.78u_*^2\ e^{-2(z/h)}$, which applies to a straight line but is directly proportional to the depth in the area of the outer region ($0.2 \le z/h \le 1$) and inversely proportional to the depth in the inner region ($z/h < 0.2$).

Transversal water surface slope can be calculated by the Equation (6):

$$\alpha = \mathrm{atan}\left(\frac{\Delta h}{B}\right) \tag{6}$$

where: Δh = difference of the surface water level between an outer bank and inner bank, while B = width of the channel.

Flow in the curved channel is also important for the design of unarmoured channels, such as irrigation canals, which must often incorporate bends. Secondary circulation has a significant effect on the erosion along the outer bank region, as well as on the potential scour at the toe of the bank.

Velocity magnitude at any point is calculated from the three measured components:

$$v = \sqrt{v_\theta{}^2 + v_r{}^2 + v_z{}^2} \tag{7}$$

where: v_θ, v_r and v_z = tangential, radial, and vertical velocities, respectively.

So maximum velocity in any cross-section is:

$$v_{\max} = \max\left(\sqrt{v_\theta{}^2 + v_r{}^2 + v_z{}^2}\right) \tag{8}$$

METHODS

EXPERIMENTAL SET-UP

Experiments were performed in a B = 0.5 m wide and H = 0.4 m high laboratory acrylic flume consisting of an 8 m long straight approach section followed by a 180° bend section with a constant radius of curvature of R = 1.25 m and 6 m downstream section. The plan view of the experimental set-up is shown in Figure 1. Initially, a horizontal bottom of nearly uniform sand, d_{50} = 0.001 m, was installed. Two types of beds, namely flat bed and eroded bed, have been installed. The flat bed is a base with sand material that is distributed evenly along the channel. Meanwhile, the eroded bed was formed by a process of erosion and sedimentation in a curved channel with a steady flow for 30 h. As a result, the bottom in the straight approach channel remained stable, but a typical bar pool bottom topography developed in the bend. Ultimately, after running discharge for 30 h, the bed topography stabilised, and there was no active sediment transport along the flume. This condition is further referred to as equilibrium. The resulting bed topography is shown in Figure 2.

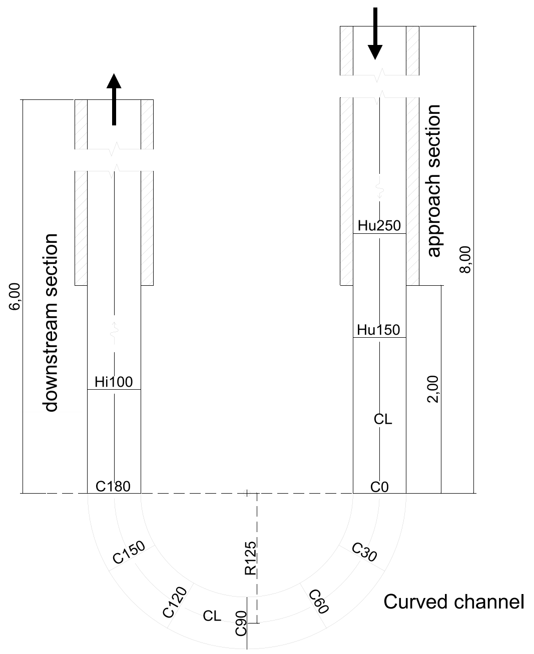

Fig. 1. Plan view of the experimental set-up; source: own elaboration

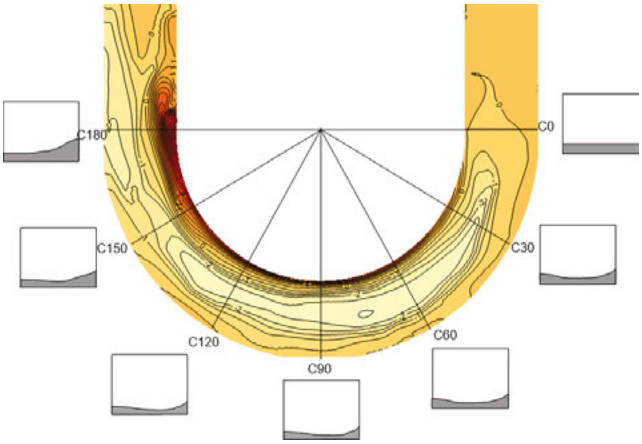

Fig. 2. Bed topography in equilibrium for each radius of curved channel C0–C180 (section 0°–180°); source: source: own elaboration

CALIBRATION OF RESEARCH INSTRUMENTS

Prior to data collection, calibration of research instruments was performed by comparing measurement results of the Acoustic Doppler Velocimetry (ADV) with the Acoustic Doppler Current Profilers (ADCP) conducted by GONZALEZ [1996]. According SONG'S [1996] research, from acoustic Doppler velocity profiler (ADVP) measurements, using the Fourier components method, the mean velocities, turbulence intensities, and the Reynolds-stress profile are obtained. The data compared are 3 data series of velocity measurements in the approach section (R115, R125 and R135) in the form of non-dimensional velocity (u/u_*) and relative depth (z/h). The comparison results are shown in Figure 3. Based on Figure 3, it can be concluded that the measurement data with ADV is not much different from the measurement with ADCP. The measurement results with ADV can be considered valid.

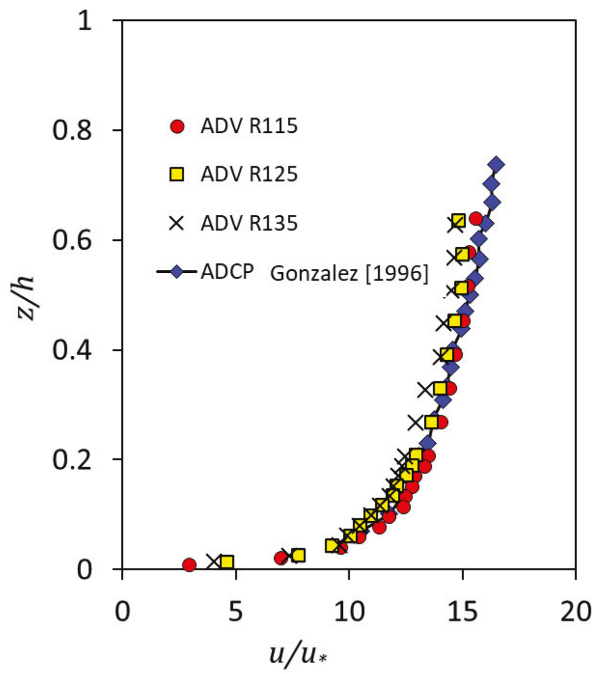

Fig. 3. Comparison of non-dimensional velocity (u/u_*) profile taken by Acoustic Doppler Velocimetry (ADV) vs. Acoustic Doppler Current Profilers (ADCP); z = vertical distance from the bed, h = flow depth; source: own elaboration

HYDRAULIC CONDITION IN THE APPROACH SECTION

Hydraulic condition of flow in the approach section is a steady uniform flow with h = 0.159 m depth and Q = 0.0242 $m^3 \cdot s^{-1}$ discharge. $U = Q/(Bh)$ = 0.304 $m^3 \cdot s^{-1}$ is the averaged velocity, and $S = 7 \cdot 10^{-4}$ is the averaged water-surface slope on the centerline. The boundary shear stress calculated by $\tau_0 = \rho u_*^2$ = 0.28 $N \cdot m^{-2}$, where shear velocity u_* = 1.66·10^{-2} $m \cdot s^{-1}$ calculated from the Clauser method corresponds well to the critical shear stress for the sediment according to Shields' diagram. The Chezy friction factor can be estimated by $C = U/\sqrt{R_h S}$ = 37 $m^{0.5} \cdot s^{-1}$. The flow Reynolds numbers, Re = Uh/ν = 54,000 (with ν = the kinematic viscosity) show that the flow is rough turbulent, and the Froude number, $\mathrm{Fr} = U/\sqrt{gh}$ = 0.24, indicates a subcritical flow.

RESULTS AND DISCUSSION

BED TOPOGRAPHY

Measurements of the maximum scour depth occur at 60° of the bend and the depth is equal to 2.9 cm, and the maximum deposition occurs at 180° of the bend and it is equal to 8.1 cm (Fig. 4). Furthermore, the path of maximum scouring along the eroded bed of the curved channel occurs in the centerline; furthermore, it moves to the outer bank region at the end of the bend. At the same time, the path of maximum deposition occurs in the inner bank along the curved channel (Fig. 4). The bed topography shown in this study is slightly different from the results of BLANCKAERT'S [2003] study where maximum scouring along the curved channel occurs in the outer bank region along the curved channel. This happens because BLANCKAERT [2003] uses a larger discharge per unit width so that equilibrium conditions last longer and consequently the erosion and sedimentation processes take longer too.

SUPERELEVATION

One of the specific phenomena that occur in the curved channel flow is the difference of water level between the inner bank and the outer bank, which is called superelevation. This is due to the centrifugal force on the flow that drives the flow to the outer bank; consequently, the water level in the outer bank is higher than in the inner bank.

By increasing the bend angle, the angle of the transversal water surface slope also increases (Fig. 5). This occurs due to the growth of the secondary flow, which is triggered by the circulation flow by increasing the bend angle, the growth of secondary flow, especially radial velocity component, also increases. It contributes to the increase of the water surface level on the outer bank. In general, the angle of the transversal water surface slope decreases in the 90° of the bend and remains relatively stable until 120° of the bend. Then, it increases again until it reaches a maximum value at 150° of the bend. This phenomenon is also in line with the results of research by BLANCKAERT [2003]. The difference is only in the maximum value, which is 45° and 75° of the bend. This difference is possible because the study was conducted on a flume with a 90° curve. Furthermore, the angle of the transversal water surface slope gradually decreases in the outlet section. Finally, the flow depth becomes uniform in the downstream section.

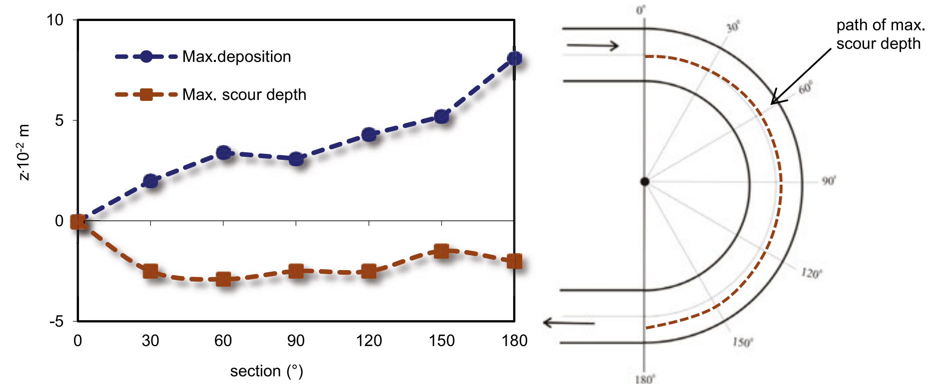

Fig. 4. Maximum deposition and scour depth in equilibrium condition; z = vertical distance from the bed; source: own study

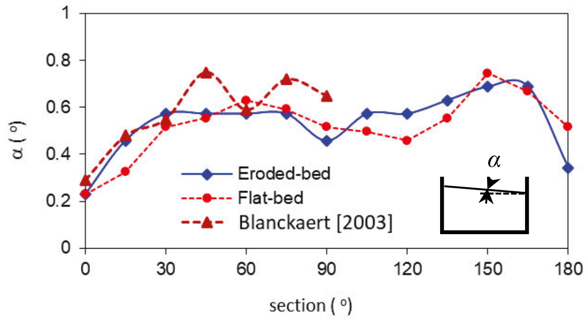

Fig. 5. Transversal water surface slope (α); source: own study

TIME-AVERAGE VELOCITIES

The second characteristic of the flow in a curved channels is circulation, which moves toward the inner-bank region at the lower layer and toward the outer-bank region at the upper layer. Near the bed surface area, closer to the inner bank, the magnitude of velocity also increases. It is able to move the bed material from the outer bank and centerline to the inner bank. As a result, the maximum deposition occurs at the inner bank region (Fig. 6).

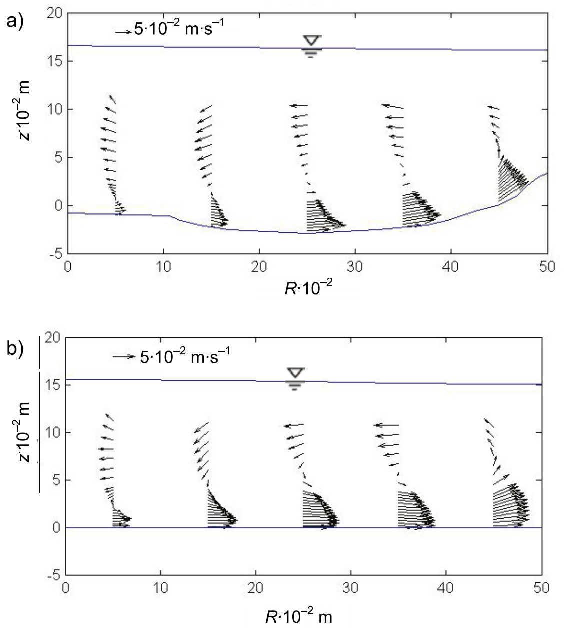

Fig. 6. Velocity vector $v_r v_z$ in the curved channel: a) eroded-bed, b) flat bed; source: own study

In general, the tangential velocity v_θ in a curved channel with a flat bed is greater than its tangential velocity in an eroded bed. The maximum tangential velocity is recorded near to the bed surface. Tangential velocity in the outer bank region is also greater than its tangential velocity in the inner bank region. Because of the deposition and erosion process, the cross-sectional flow area in the eroded bed is greater than its cross-sectional flow area in the flat bed, resulting in reduced tangential velocity (Fig. 7).

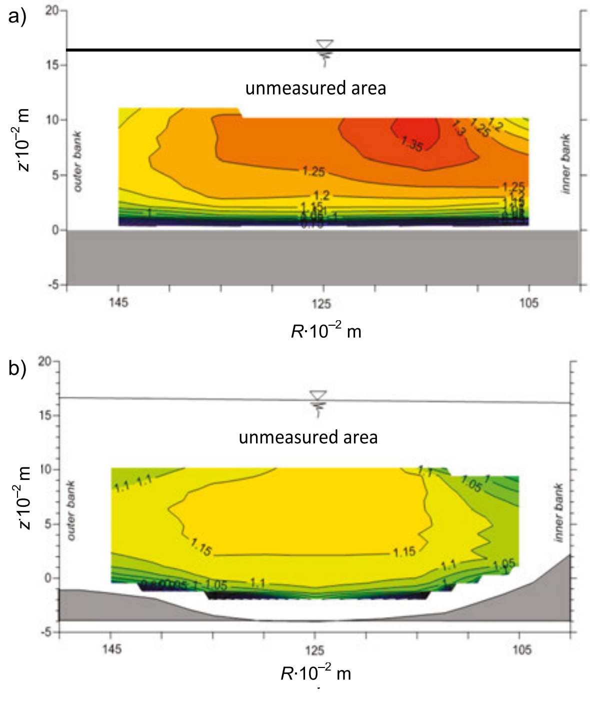

Fig. 7. Normalised tangential velocity (v/U) contours in curved channel with: a) flat bed, b) eroded-bed; z = vertical distance from the bed; source: own study

While the longitudinal velocity in the downstream section is divided into vertical layers with the maximum value located in the outer bank region (Fig. 8). This indicates that the flow in the downstream section can not immediately return to a steady uniform flow as the flow in the approach section. It requires a certain distance from the bend outlet. Unfortunately, in this study, the distance needed for the flow to return to a steady uniform flow cannot be determined because of the insufficient length of the downstream section.

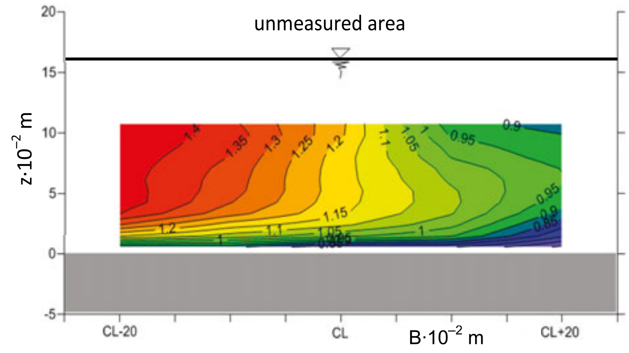

Fig. 8. Normalised longitudinal velocity (u/U) contours in downstream section; z = vertical distance from the bed; B = width of the channel; source: own study

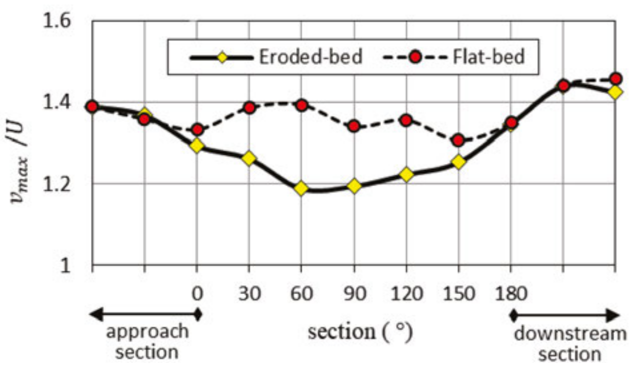

Fig. 9. The difference of normalised maximum velocity (v_{max}/U) in curved channel between flat bed and eroded-bed; source: own study

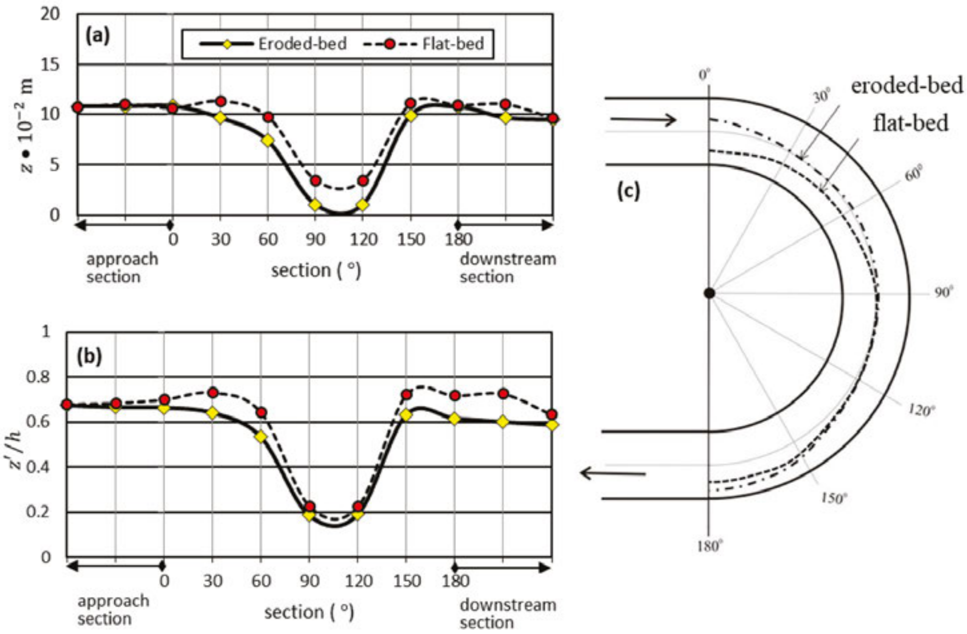

Fig. 10. Path of maximum velocity: a) based on elevation, b) based on relative distance, c) plan view; z = vertical distance from the bed, h = flow depth; source: own study

The maximum velocity, which is the result of the tangential, radial, and vertical velocity components, has been analysed at each measurement point. The analysis showed that the maximum velocity in the flat bed is larger than its maximum velocity in the eroded bed. This is caused by differences of tangential and radial velocity components in the flat bed and eroded bed, where the value of both in the flat bed tend to be larger (Fig. 9).

Furthermore, the path of maximum velocity in the curved channel resembles the tangential curve where the minimum value is located between 90 and 120° of the bend. This is in contrast to the flow in a straight channel where the maximum velocity is occurs near the water surface.

The path of maximum velocity in the flat bed is generally located at a higher elevation than the maximum velocity in the eroded bed (Fig. 10a), but maximum velocity in both of them occurs at the same distance from the bed surface (Fig. 10b). Due to changes in the bed topography, the path of maximum velocity in the eroded bed tended to be located in the centerline and shifted to the outer banks in the bend outlet region following the maximum scour location. For the flat bed, the path of maximum velocity tends toward the inner bank in the bend inlet and subsequently shifted to the centerline and toward the outer bank in the bend outlet (Fig. 10c). Meanwhile, KIKKAWA's [1973] research has showed that the maximum speed trajectory at the entrance of the bend tends to be in the direction of the inner bank. Then, it moves to the centerline and, at the outlet of the bend, it moves to the outer bank. This is more identical to the maximum velocity trajectory for the flat bed in this study which is also consistent with KIKKAWA [1973].

CONCLUSIONS

1. The maximum scour depth occurs at section 60° while the maximum deposition height occurs at section 180°. The path of the maximum scour depth was originally located at the centreline and subsequently moved to the outer bank region on the end of the bend. In contrast, the path of the maximum deposition is always located in the inner bank. On a larger discharge per unit width, the path of the maximum scour depth will shift further to the outer bank region as shown by the results of the research.

2. The superelevation phenomenon has been investigated where the water surface level in the outer bank is higher than in the inner bank. As a result, the flow in the curved channel became non-uniform. Experimental results also indicate that the curve of the transverse water surface slope angle resembles a sinusoidal curve with two peaks located at sections 60° and 150°.
3. In general, the tangential velocity in the flat bed is greater than the tangential velocity in the eroded bed. This occurs because the cross-sectional flow area in the eroded bed curved channel is greater than the cross-sectional flow area in the flat bed, resulting in a reduced tangential velocity.
4. The maximum velocity in the flat bed curved channel is greater than its maximum velocity in the eroded bed. In contrast, the path of maximum velocity formed a sinusoidal curve where the lowest point is located at sections 90° and 120°. The path of the maximum velocity in the flat bed under the study is identical with the results of previous research.

REFERENCES

Blanckaert K. 2003. Flow and turbulence in sharp open-channel bends. PhD Thesis. No. 2545. Lausanne. Switzerland Ecole Polytechnique Federale pp. 286. DOI 10.5075/epfl-thesis-2545.

García C.M., Cantero M.I., Niño Y. García M.H. 2004. Acoustic Doppler Velocimeters (ADV) Performance Curves (APCs) sampling the flow turbulence. World Water and Environmental Resources Congress. DOI 10.1061/40737(2004)294.

Gonzalez J.A., Melching Ch., Oberg K.A. 1996. Analysis of open-channel velocity measurements collected with an Acoustic Doppler Current Profiler. Proceedings from the 1st International Conference on New/Emerging Concepts for Rivers. 22–26.09.1996 Chicago. DOI 10.1061/40517(2000)308.

Jeong J.W., Yoon S.E. 1998. An experimental study on the characteristics of flow and bed topography with changing bed material in a curved channel. Journal of Korea Water Resources Association. Vol. 31. Iss. 3 p. 291–301.

Kikkawa H., Ikeda S., Ohkawa H., Kawamura Y. 1973. Secondary flow in a bend of turbulent stream. Proceedings of the Japan Society of Civil Engineers. No. 219 p. 107–114.

Odgaarg A.J., 1984. Flow and bed topography in alluvial channel bend. Journal of Hydraulic Engineering. Vol. 110(4) p. 521–532. DOI 10.1061/(ASCE)0733-9429(1984)110:4(521).

Patra K.C., Kar S.K., Bhattacharya A.K. 2004. Flow and velocity distribution in meandering compound channels. Journal of Hydraulic Engineering. Vol. 130(5) p. 398–411. DOI 10.1061/(ASCE)0733-9429(2004)130:5(398).

Rozovskii I.L. 1957. Flow of water in bends of open channels. Kiev. Academy of Sciences of the Ukrainian SSR, Israel Program for Scientific Translations. ISBN 0706501586 pp. 233.

Song T., Graf W.H. 1996. Velocity and turbulence distribution in unsteady open-channel flow. Journal of Hydraulic Engineering. Vol. 122(3) p. 141–154. DOI 10.1061/(ASCE)0733-9429(1996)122:3(141).

Song T., Chiew Y.M. 2001. Turbulent measurement in non-uniform open-channel flow using Acoustic Doppler Velocimeter (ADV). Journal of Engineering Mechanic. Vol. 127(3) p. 219–232. DOI 10.1061/(ASCE)0733-9399(2001)127:3(219).

Sumiadi S., Istiarto, Kironoto B.A., Legono D. 2011. Developing laboratory experiment on flow in an erodible curved channel. Proceedings of the 4th ASEAN Civil Engineering Conference. 22–23.11.2011. Yogyakarta p. 223–226.

Tominaga A., Nagao M. 1998. Secondary flow structures in bends of narrow open channels with various cross section. Nagoya, Japan. Nagoya Institute of Technology.

Wahl T.L. 2000. Analyzing ADV data using WinADV. Joint Conference on Water Resources Engineering and Water Resources Planning and Management. 30.07–2.08.2000. Minneapolis, Minnesota, United States p. 1–10. DOI http://dx.doi.org/10.1061/40517(2000)300.

Yen C-L., Lee K.T. 1995. Bed topography and sediment sorting in channel bend with unsteady flow. Journal of Hydraulic Engineering. Vol. 121(8) p. 168–179.