Bathymetry and three dimensional flow dynamics in a bend channel with parabolic bed

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***Abstract*— Three dimensional turbulent flow fields and scour in a 180° bend with parabolic non-cohesive bed have been investigated experimentally. This paper aims at improving our understanding of the flow and turbulence in bends close to natural river bed with respect to scour by incorporating intense flow data. Acoustic Doppler Velocimeter was used to measure the three components of fluctuated velocities at multiple cross sections in bend for scoured bed. Experimental results of the flow field in accordance with turbulence and Reynolds stress characteristics with respect to erosion in a model channel bend are presented. It shows that the turbulence is more close to the parabolic bed and plays an important role with respect to bend scour and bank erosion. From the experimental results it is observed that scour mainly occurs along the outer bank of bend and Reynolds stresses are relatively more in the downstream of the bend. Data obtained from present investigation are valuable for validation of analytical works and protections at bends.**

Keyword- open channel bend, three dimensional flow, bathymetry, parabolic bed

I. INTRODUCTION

The pattern of flow and turbulence structure in bends is extremely complex due to unsteadiness of vertical velocity profile with respect to scour and deposition in different parts of the bends. Scour at bend in a meandering channel is mainly due to secondary flow or change of momentum of the flowing water. Basically secondary flow creates from the disparity between the centrifugal force and transverse water surface gradient over the depth due to the primary flow velocity variation. Thompson [1] was the first who investigated and found the secondary flow in a channel bend. Numerous studies have been conducted on flow at bends [2-4]. Mainly spiral or secondary flow in open-channel bends is caused by streamline curvature [5-8]. According to Odgaard [9], in alluvial bends, the cross-stream flow transports sediment from the outer to the inner part of the cross section and significantly scours near the outer bank. Barbhuiya and Talukdar [10] conducted laboratory experiments in a channel of 90° horizontal bend to study the scour and flow pattern at particular bend. They found that the maximum scour depth occurs around the 30° azimuthal section and maximum flow velocity was observed near the outer bank. Recently Jamieson et al. [11] performed laboratory experiments in a 135° bend flume with various barb configurations in an erodible trapezoidal channel and presented the equilibrium bathymetry and mean velocity field observed in the various cases. The mechanisms underlying distributions of the velocity in open-channel bends and turbulence with respect to erosion are yet to be understood fully. Moreover detailed data on the three-dimensional patterns of flow and turbulence is scarce in the literature. Most of the previous studies of flow fields and scour at bend were restricted to mobile horizontal (flat) beds with rigid vertical side walls. This paper aims at improving our understanding of the flow and turbulence in bends with parabolic bed which is close to natural channel section. Laboratory tests are presented to describe the flow field and scour at bend. Acoustic Doppler velocimeter (ADV) was used to measure the three components of fluctuated velocities at multiple cross sections in a 180° channel bend for scoured bed condition. It was reasonable to plot the changes in the different flow parameters with measurements at multiple cross sections through the bend. Experimental results of the flow field in accordance with turbulence and Reynolds stress characteristics with respect to erosion in a model channel bend are presented. Data obtained from present investigation can be used for validation of analytical works and also help in the design of protection works at bends.

II. EXPERIMENTAL SETUP AND PROCEDURE

Experiments were conducted at 180° horizontal forced laboratory bend in the Hydraulics Engineering Laboratory of NIT, Silchar. The dimensions of the flume were 20 m long, 0.8 m wide, 0.8 m deep and the outer radius of 2.28 m. The top view of experimental setup is shown in Fig. 1. The flume was connected to the water supply system in the laboratory. An adjustable tailgate was installed at the downstream end of the flume to manage the desired flow depth (*h*) = 28.8 cm. The discharges and water level were measured using a calibrated V-notch weir and by a vernier point gauge, with an accuracy of ±0.1mm, placed at the inlet tank. The water level was measured. The bed was covered by sand characterized by mean diameter d_{50} equal to 0.34 mm having non-uniformity co-efficient 2.28. Then a trapezoidal shaped cross-section was dug on the bed. The side slope of the trapezoidal section was made in such a way that the slope angle becomes almost equal to the angle of repose of the bed sediments. Parabolic shaped cross-section was achieved by allowing water to flow on a trapezoidal channel very slowly so that the side slopes and the bed attain a cross-section which is close to the natural channel bed. To reach the dynamic equilibrium of scour depth, the pump was allowed to run around 10 hours (assessed in trial experiments) maintaining predetermined shear velocity ratio (u_*/u_{*c}=1.04). This shear velocity ratio was planned to represents the flood condition which is critical for bank erosion. Here u_* is the approaching shear velocity; and u_{*c} is the critical shear velocity of bed sediments. After draining out the water very slowly, the scoured bed profile was measured with the help of a vernier point gauge along different azimuthal sections. The bed was then stabilized and detailed velocity measurements were obtained following resumption of flow maintaining the same flow conditions. The Acoustic Doppler Velocimeter (ADV) readings were taken along several vertical lines at different azimuthal sections in stabilized scoured bed from inner to outer.

The time averaged three-dimensional velocity components were measured by a 5 cm downlooking Sontek micro Acoustic Doppler Velocimeter (ADV) with acoustical frequency of 16 MHz. The ADV operated on a pulse-to-pulse coherent Doppler shift to provide instantaneous three-dimensional velocity components. In the present experiment, the velocity range setting was ±50 cm/s. A minimum of 90-s sampling time was used at each point. Despiking of the original recorded data was done using WinADV version 2.0. The improvement of the data after despiking was not significant as the signal to noise ratio and correlation coefficients for all the three components during experiments were more than 30 dB and 97% respectively. Although, efforts were made to maintain constant depth and velocity during the scour experiments and also during measurements of velocity, there might be some deviations and errors. The reasons for deviations and errors may be due to variation of discharge caused by fluctuation of electric voltage, the interference of echoes from bed affecting receiving signal and inaccurate orientation of vertical stem and receivers of ADV probe.

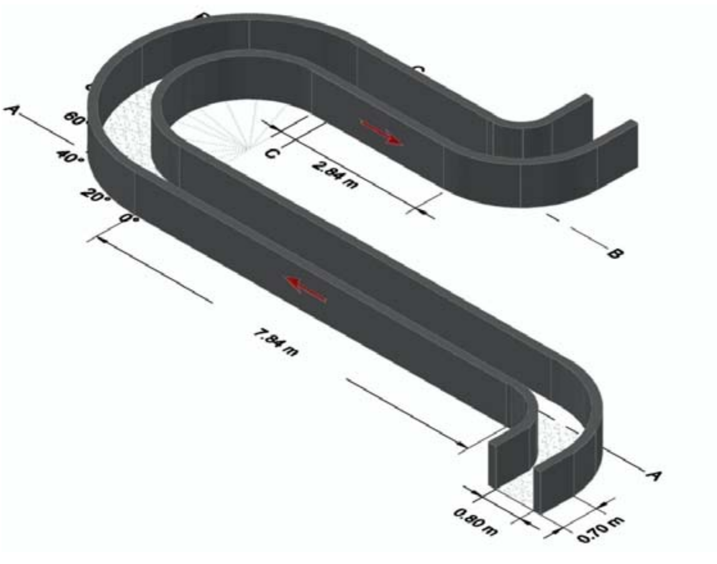


Fig. 1. Top view of 180° bend channel

A. Co-Ordinate System and Sections of Measurement

The bed profile of the initial and scoured bed was measured along different azimuthal sections using a vernier point gauge with an accuracy of ± 0.1 mm. The Acoustic Doppler Velocimeter (ADV) readings were taken along several vertical lines at different azimuthal sections in stabilized scoured bed. All the measurements are done starting from inner to outer bank and in the presented data graphs; left side represents the inner bank. At each cross section, velocity measurements were made at 5 lateral positions at stabilized scoured bed (5 cm. 20 cm, 40 cm, 60 cm and 75 cm from inner wall). The measurement at different vertical positions was in the order of 0.5 cm, 1 cm, 2 cm, 3 cm, 5 cm, 8 cm, 10 cm, 15 cm etc. from the bed upto maximum possible point. The time averaged velocity components (*u, v, w*) are presented in cylindrical polar coordinates (*θ, r, z*), where *u, v, w* represents three dimensional velocities along *θ* (streamwise), *r* (radial) and *z* (vertical) directions respectively. All linear dimensions and velocity components are normalized by the average approach flow depth (*h*) or width (*b*) of the channel and average approaching flow velocity, *U* respectively.

III. RESULTS AND DISCUSSIONS

A. Bathymetry

The experiment was conducted to simulate the flow and scour pattern in a river bend during flood flow condition. The contour of the scoured bed and normalized equilibrium bed topography for some of the azimuthal sections are shown in the Fig. 2 and Fig. 3 respectively. It is found that at 0°, small scour occurred along the top edge of the inner bank slope and small deposition was observed at the outer bank slope. At 40° section, scour took place on both the inner and outer bank but magnitude of scour was very less at the inner bank. At 40° section, deposition was noticed on the inner bank slope and on the bed and scour took place on the entire outer bank. On moving towards downstream at 60° section, the magnitude of scour increases at outer bank and some scour was observed on the upper part of inner bank with very little deposition at the bed. At 90° section, the scour magnitude increases further at the outer bank and some amount of deposition took place along the bed and lower slope of the inner bank. Small scour was also observed near the inner bank. Further downstream at 130° and 150° sections, the outer bank was completely eroded forming an almost sloped bed starting from the top of the inner bank and passing through the toe of the outer bank forming a right angled triangular section of the channel. But, little undulation throughout the bed was seen due to ripple formation. A close examination of the bed topography reveals that the area of maximum scour and deposition occurred at around outer bank of 130° section and inner bank of 100° section respectively. The value of maximum scour in the present experiment was 0.69h and maximum deposition was 0.19h.

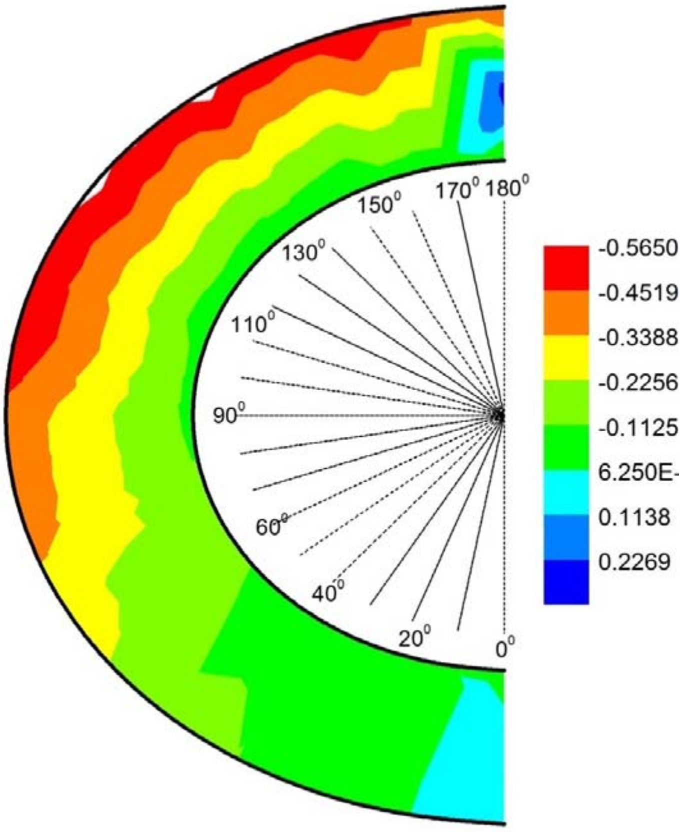


Fig. 2. Contour of the normalized scour magnitude

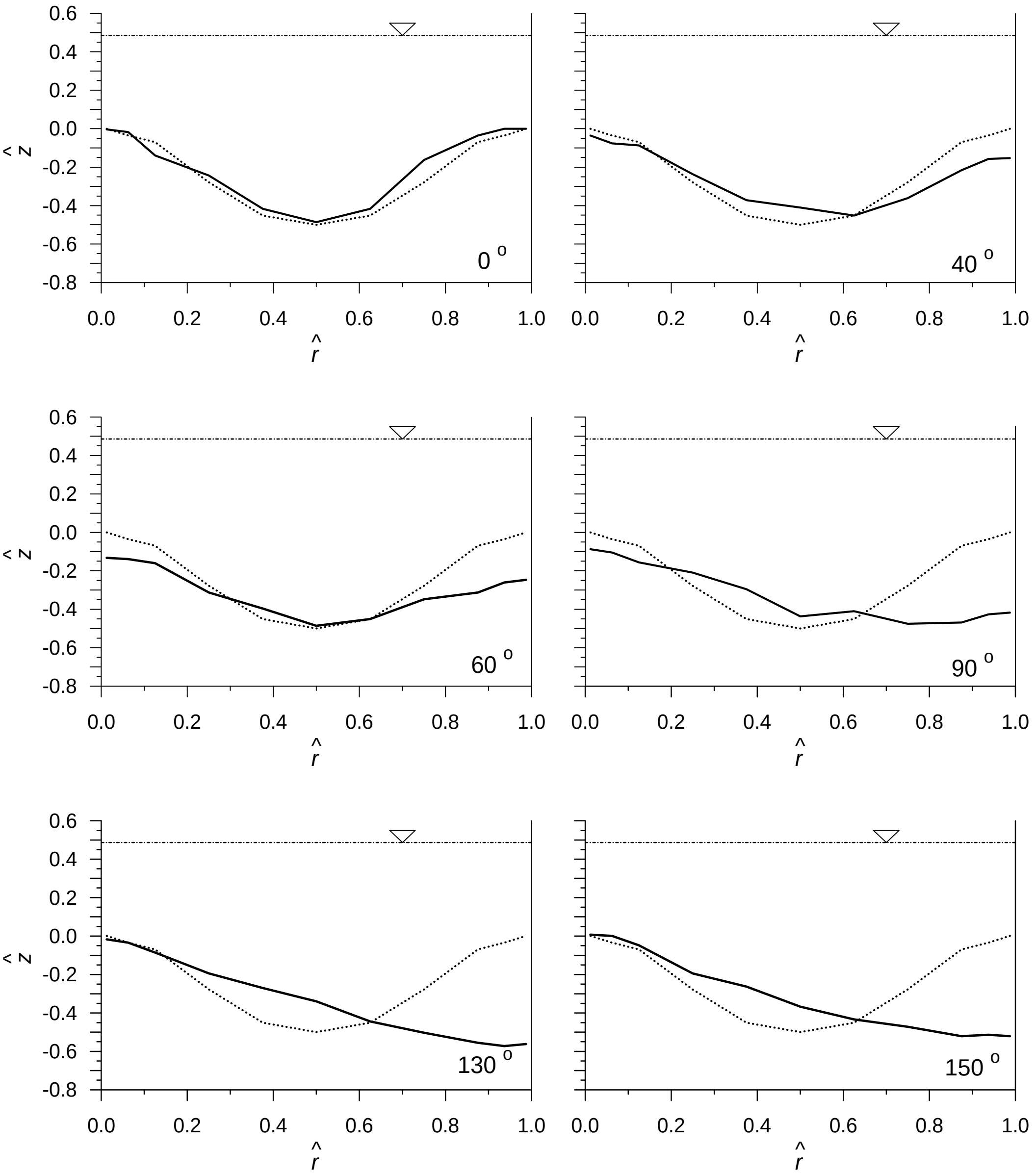


Fig. 3. Normalized equilibrium bed profile of 180° bend at: θ= 0°, θ = 40°, θ =60°, θ = 90°, θ = 130° and θ = 150°, dotted line and solid lines indicate the initial bed and scoured bed profile, and the outer bank is to the right

B. 3D Flow Dynamics

The experimental data shows that the turbulence and Reynolds stress plays a significant role with respect to bend scour and bank erosion. Turbulent intensity component in stream wise u^+ [= $(\overline{u'^2})^{0.5}/U$, where u' is the fluctuation of u], radial v^+ [= $(\overline{v'^2})^{0.5}/U$, where v' is the fluctuation of v] and vertical w^+ [= $(\overline{w'^2})^{0.5}/U$, where w' is the fluctuation of w] direction were analyzed. The normalized contour of three turbulent intensity component are exhibited in Fig. 4, Fig. 5 and Fig. 6 respectively to understand the flow pattern for scoured bed. From the graphs it is clear that, the magnitude of fluctuation is more in the vicinity of the bed of 130° and 150° azimuthal section and reduces towards the surface. Generally close to the convex zone, the intensity of turbulence u^+ (Fig. 4) is very strong at 150° azimuthal section. The distributions for all the azimuthal section of v^+ and w^+ are almost similar nature to that of u^+. However it is observed from the contours that w^+ (Fig. 6) is weaker than u^+ and v^+ and its magnitude near the bed is comparatively less.

The calculation of Reynolds shear stress gives an indication of the stress on the fluid due to shear from turbulent fluctuations [12]. The datas of normalized Reynolds stresses $uv^+(=-\overline{u'v'}/u_*^2)$, $vw^+(=-\overline{v'w'}/u_*^2)$, $wu^+(=-\overline{w'u'}/u_*^2)$, shows that the magnitudes are very small in the upper zone but near the bed its magnitude is relatively more. Contours of normalized Reynolds stresses near the bed (Fig. 7) confirm that the magnitude of vw^+ is highest at the bend.

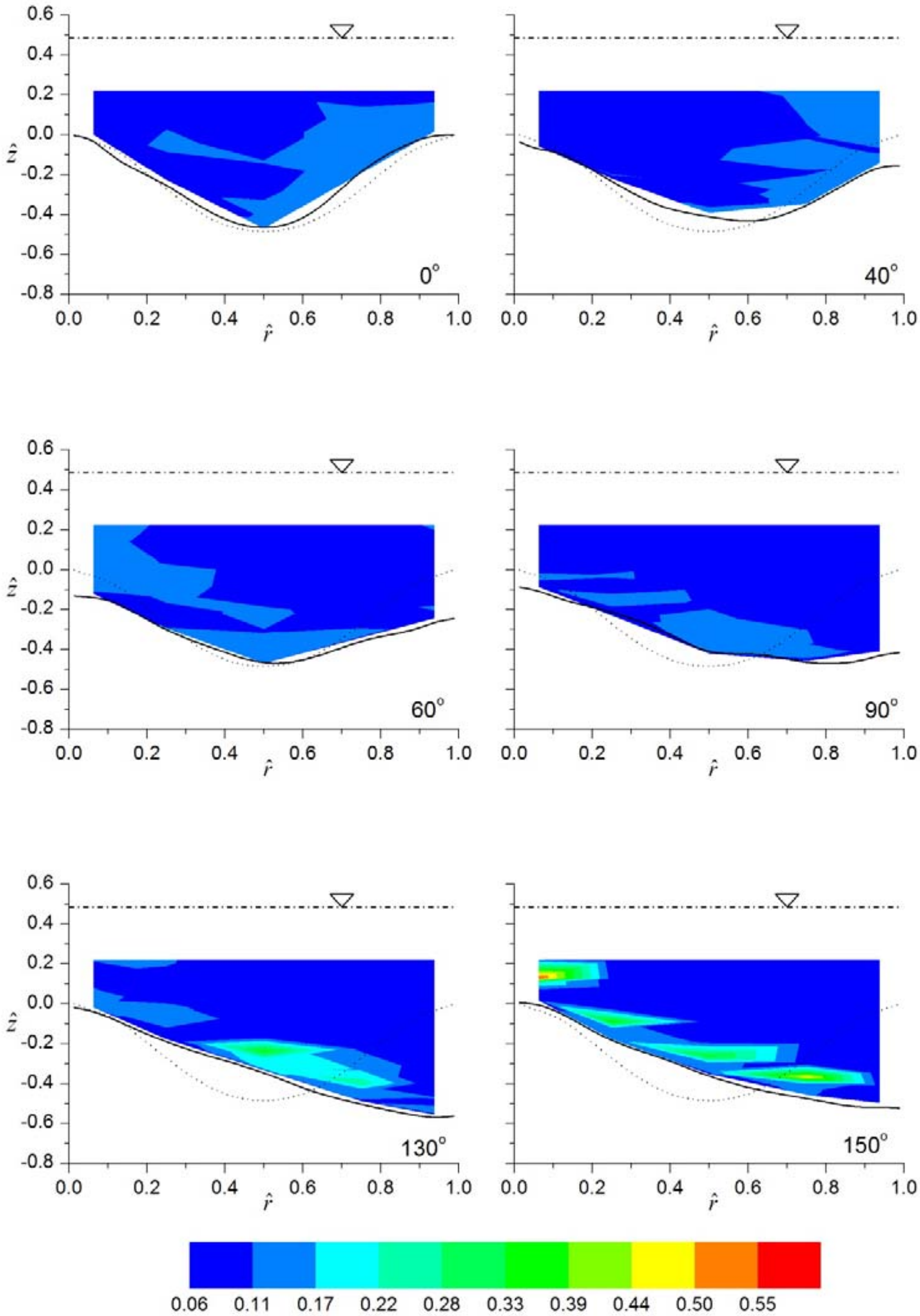


Fig. 4. Normalized contours of u^+ for scoured bed at azimuthal sections: θ= 0°, θ = 40°, θ =60°, θ = 90°, θ = 130° and θ = 150°

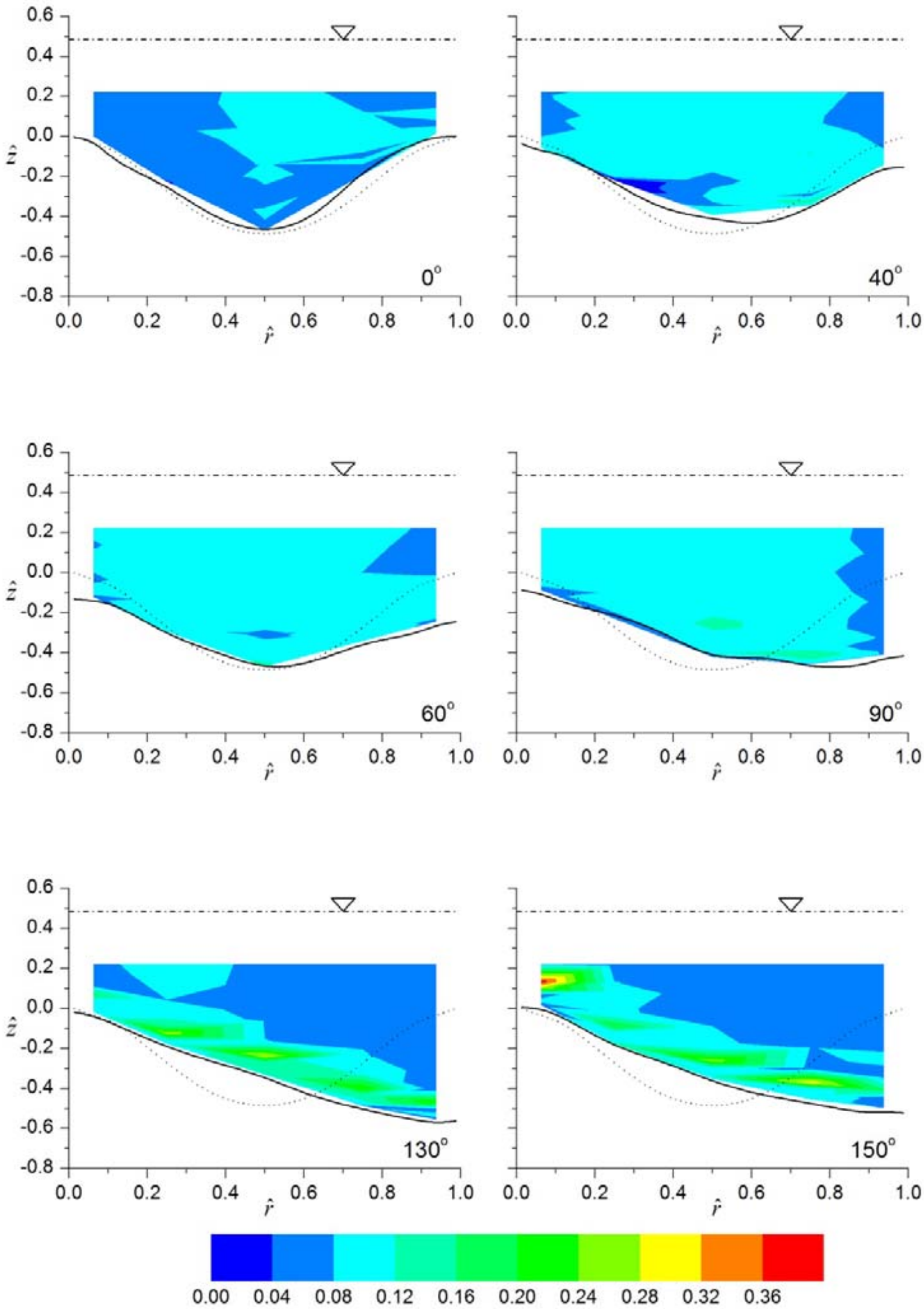


Fig. 5. Normalized contours of v^+ for scoured bed at azimuthal sections: θ= 0°, θ = 40°, θ =60°, θ = 90°, θ = 130° and θ = 150°

Secondary flow in a bend is the combination of cross stream and vertical velocity components. In general, uw^+ and vw^+ are relatively strong because which are each a function of cross stream turbulent velocity fluctuations and associated momentum flux for bend flow. The most interesting observation found from the contour (Fig. 7a) is that near-bed maximum positive streamwise-radial (uv^+) Reynolds stress found at the outer bank of 150° azimuthal section and it is somehow associated with location of scour. For sloping bed (uv^+) is a streamwise stress that acts on bed and this had direct impact on sediment transport. Therefore, its positive value associated with the location of outer bank scour and negative value associated with deposition at channel bend. This is consistent with previous finding in bend flows [12]. It is also evident from Fig. 7 that maximum radial-vertical Reynolds stress (in combination with high negative streamwise-radial Reynolds stress near the bend apex) found at the inner bank bar.

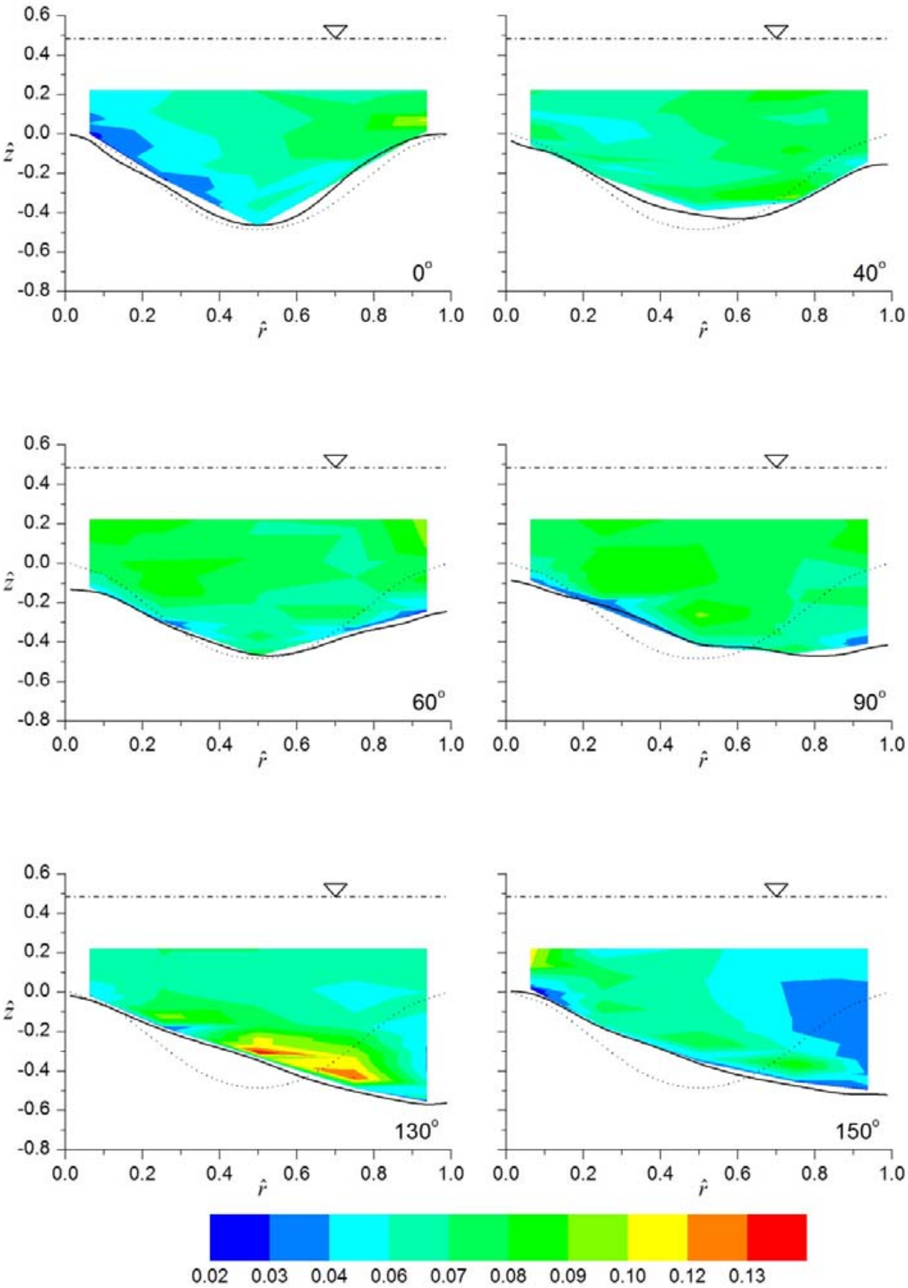
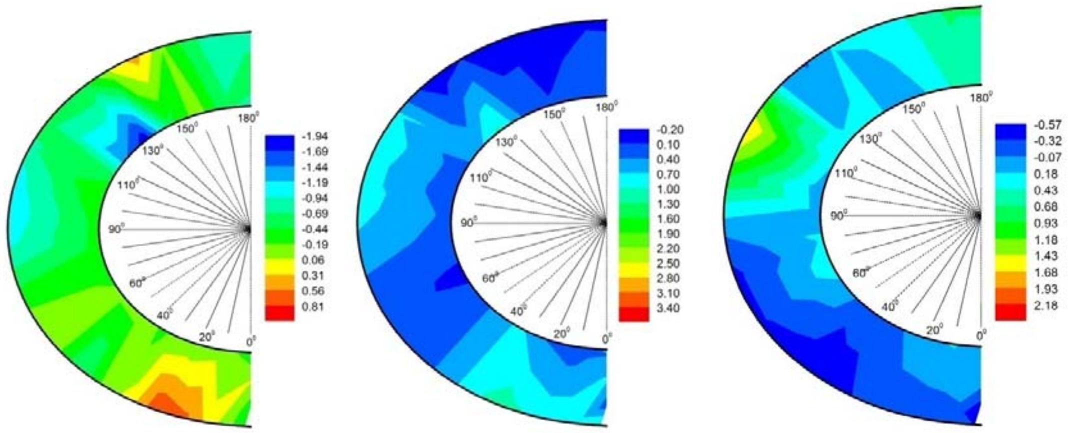


Fig. 6. Normalized contours of w^+ for scoured bed at azimuthal sections: θ= 0°, θ = 40°, θ =60°, θ = 90°, θ = 130° and θ = 150°

It is also observed that, streamwise-vertical Reynolds stress remains highest in the straight-approach section, but less than radial-vertical Reynolds stress through the bend. Moreover, from the experimental results it is found that for the present experimental condition also turbulences are more close to the bed and Reynolds stresses are more in the downstream of the bend. This flow phenomenon may be explained by the fact that, the lower reach of the bend receives the elevated water surface at outer bank from the upstream reach. In addition, by increasing curve degree, field of low velocity was transmitted from the surface to bellow across the inner wall which basically formed the secondary flow at the bend. The scour phenomenon for the present condition at the bend can be explained with the help of this observed secondary flow pattern. The accelerated flow along the outer bank in combination with turbulence along the outer slope dislodges the materials, part of it is carried away towards downstream, and a small part is deposited on the inner slopping bank.



(a) **(b)** **(c)**

Fig. 7. Normalized contours of three components of Reynolds stresses for scoured bed (a) uv^+ (b) vw^+ (c) uw^+ at 0.5 cm from bed

IV. CONCLUSION

From the present study we can conclude that scour mainly occurs along the outer bank of 180° horizontal bend. Maximum scour at bend occurred at between section 130° and 140°. Deposition at 180° bend was confined mainly at the bed and inner bank slope of 60° and 130° sections. The value of maximum scour in the present experiment was 0.69*h* and maximum deposition was 0.19*h*. From the detail 3D velocity data, we can see that the the magnitude of fluctuation is more in the vicinity of the bed of 130° and 150° azimuthal section and reduces towards the surface. For the present study, turbulent intensity component in vertical direction (w^+) was found weaker than streamwise (u^+) and cross-stream (v^+) direction. The Reynolds stresses are more in the downstream of the bend. For the present experimental condition we can also see that the Streamwise-vertical (uw^+) and radial-vertical(vw^+) Reynolds stresses are relatively strong. Near-bed maximum positive streamwise-cross stream (uv^+) Reynolds stress found at the outer bank of 150° azimuthal section and it is associated with location of scour. The main scouring agent is identified as the onset of secondary flow which is mainly the combination of cross stream and vertical velocity components along with turbulences. Experimental data provided in the present study will help for validation of 3D morphodynamical numerical codes, which in turn will be useful to design perfect protection at bend. The next step in this research will be to design perfect protection work mainly considering parabolic bed at bend.

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