Flow and Bed Topography in a 180° Curved Channel

Jae Wook Jung¹, Sei Eui Yoon²

Abstract

The characteristics of flow and bed topography have been analyzed by changing the bed materials in a 180-degree, with constant-radius curved experimental channel. Sand (D₅₀ = 0.56mm, S=2.65) and anthracite (D₅₀ = 0.26mm, S=1.54) were selected as the experimental bed materials. The measured maximum scour depth was about two times for mean flow depth at the outer bank of bend angle 30°~60° section. The location occurred maximum scour depth in the case of anthracite bed was found the upper part of bend angle 5°~15° than that of sand bed. Regardless of bed materials the path of maximum streamwise velocity is skewed inwards in the upper part of the bend, the maximum velocity shifts outwards, and it lagged downward as bed roughness increases. The maximum skewed angle of flow grows faster in the smooth bed than in the rough one, and its value also increases. The secondary flow in anthracite bed was appeared to be larger than that of sand one. Analyzing the flow characteristics and bed topography in a curved channel, the equation of mass and momentum, the vertical distribution of secondary flow, and the transverse slope were used. The application results of this model to the sand bed and the anthracites bed accorded well with the observed ones in the experiments. The predicted the path of maximum streamwise velocity and bed topography in channel bend with the model showed a good agreement with observed ones.

1 Introduction

Under the natural conditions, the rivers rarely take a rectilinear outline in plane. Flow characteristics and bed topography in a river bend are so complicated that they prevent one from complete understanding. The mechanics of flow in a curved alluvial channel has some distinct characteristics are absent in a straight alluvial channel. It is generally assumed that the governing forces in a bend flow are the centrifugal forces due to the vertical nonuniformity of the velocity profile combined with the flow curvature, the shear stresses, and the transverse pressure gradients caused by the transverse inclination of the water surface. The balance between the governing forces tends to produce a helical flow pattern.

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in the bend and a tilting of the channel bed, with an increase in depth near the outer (concave) bank. As a result, the bank is often undermined and eroded. The grain size of bed material in channel bend tends to vary throughout the transverse bed. Many investigations of flow and bed topography in curved channel have been made on a descriptive basis since the early observations of Thomson (Chow, 1959). The evolution of mathematical modeling of flow in alluvial channel bends can be traced back to the classical work of Rozovskii (1961). Yen (1970) studied bed topography effects on flow in a meandering channel by theoretical analysis and laboratory experiments. De Vriend (1982) conducted laboratory experiments on steady turbulent flow in a rather sharply curved U-shaped flume with a shallow rectangular cross section and an artificially roughened bottom. Dietrich and Smith (1983, 1984) studied bed load transport in Muddy Creek, Wyoming, a sand-bedded meandering river with stable bottom topography. Odgaard (1984) argued that as the transverse bed slope is linearly related to both transverse bed-shear stress and transverse velocity component at the water surface, the streamwise variation of transverse bed slope should be governed by an exponential function similar to that for transverse surface velocity, as was developed by Rozovskii (1961). Parker and Andrews (1985) treated grain sorting in sinuous rivers in terms of linear analysis, in which the lateral bed load and the sediment mass balance for the mixture were used to obtain the lateral slope and the grading of sediment. Ikeda et al. (1987) developed a mathematical model for defining the bed topography and the bed material size distribution in uniformly curved bends of alluvial rivers. Bridge (1992) revised his previous model by considering the effect of bedload particle sorting on sediment transport and bed topography. His theoretical model consists of five parts. Talmon et al. (1995) conducted laboratory experiments to provide data for modeling the direction of sediment transport on a transverse sloping alluvial bed and the effect of a sloping bed on the direction of sediment transport is determined by conducting bed-levelling experiments. Many researchers had been studied the characteristics of channel bends such as Ko (1975), Song (1980, 1994), Yoon (1986, 1990), Lee (1987), Cha (1991), Jung (1998) in Korea. But we can not find the paper that analyzes flow and bed topography by changing the bed material in channel bend. In this study, experiments are conducted by changing the discharge and the bed materials in order to analyze the characteristics of flow and bed topography. A mathematical model, which can analyze the characteristics of flow and bed topography, was suggested.

2. Experimental condition and method

The experiments were conducted to analyze flow and bed topography. A curved channel with 180 degree of centroidal angle was used in this experiments. The experimental work
was undertaken in the NCRI (National Construction Research Institute). The relevant parameters of the experimental channel and properties of the bed materials are tabulated in Table 1.

Table 1. Parameters used in the experiments

<table>
<thead>
<tr>
<th>parameter</th>
<th>length (m)</th>
<th>width (m)</th>
<th>discharge (l/s)</th>
<th>bend angle(°)</th>
<th>radius (m)</th>
<th>slope</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>34</td>
<td>1.5</td>
<td>80, 110</td>
<td>180</td>
<td>5.5</td>
<td>1/750</td>
<td>D(_{50})(mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.56</td>
</tr>
<tr>
<td>anthracite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.26</td>
<td>1.54</td>
</tr>
</tbody>
</table>

The flume is consisted of three segments as shown in Figure 1: (1) 12m straight channel, (2) 180 degree curved channel with radius of 5.5m, and (3) 8m-straight channel. Sand and anthracite were selected as the bed materials in the movable bed experiment. The median diameter(D\(_{50}\)) of sand is about 0.56mm and anthracite is about 0.26mm. The geometric standard deviations(σ) of sand and anthracite are 1.65 and 2.73, respectively. The depth of bed material in the movable bed experiments was about 20cm. The discharges measured in the weir were 80l/s and 110l/s.

Figure 1. Flume geometry

The magnitude and the direction of the time-mean horizontal velocity vector were measured in the nodal points of three-dimensional grid, using the combined current-velocity meter (Model: VM-201, ACM-300). Water depth, velocity, and bed elevation were measured at 18 sections; in bend 13 sections in every 15° and three sections at the upstream and two sections at the downstream in straight channel, with each section 1m
apart. Further details about the experiments were described elsewhere (Jung and Yoon, 1998). Measurements of bed elevation were made after flow and bed appeared to have achieved steady-state conditions. The sediment moved through in the channel as bed load. It was measured by using a sampler developed in the experimental setup. The sampler was fabricated by a wooden box (150cm × 50cm × 60cm) with a fine mesh. Additional the control of water depth is provided by adjusting sluice gate located at the exit section.

3. Governing equations

In this study, a mathematical model, which was suggested using the equation of mass and momentum, secondary flow, and the transverse slope. The equations can be written (Odgaard, 1986 a: Hsu, 1988) as

\[
\frac{\partial}{\partial s} \left( \frac{u_b h}{k} \right) + \frac{1}{\gamma} \frac{\partial (v' \gamma h)}{\partial n} = 0
\]

(1)

\[
\frac{1}{2} \frac{\partial}{\partial s} \left( \frac{u_b}{k} \right)^2 + \frac{\kappa^2}{m^2} \left( \frac{u_b}{k} \right)^2 = g \frac{S_c \gamma_v}{\gamma}
\]

(2)

\[
\frac{\partial v'_s}{\partial s} + \frac{\partial V}{\partial s} + A v'_s = F
\]

(3)

\[
S'_c = \frac{\partial h}{\partial n}
\]

(4)

where \( u_b \) is the near-bed streamwise velocity, \( h \) is the depth, \( k \) is the streamwise velocity coefficient, \( \gamma \) is the radius of curvature, \( V \) is the depth-averaged transverse velocity component, \( \kappa \) is von Karman's constant, \( m \) is the velocity-profile exponent, \( S_c \) is the streamwise slope of water surface along the centerline, \( v'_s \) is the centrifugally induced transverse velocity component at the surface, and \( A \) and \( F \) are the substitution variables.

4. Results and discussion

4.1. Flow characteristics

Figure 2 shows the path of the maximum streamwise velocity. The distributions of maximum streamwise velocity are compared with the fixed bed and the movable bed (sand and anthracite). The tendency of the maximum streamwise velocity to shift towards the inner bank in bend inlet is represented in all the experiments, and the thread of maximum
Regardless of bed materials the path of maximum streamwise velocity is skewed inwards in the upper part of the bend, the maximum velocity shifts outward, and it lagged downward as bed roughness increases.

The vertical distributions of secondary flow have been plotted in Figure 3. The secondary flow in the anthracite bed was measured larger than that of sand one, and two cells of secondary flow were found in this experiment. Near the outer wall, the secondary flow profiles are strongly deviant from the ones elsewhere. This cell, which exists even in the
upper part of the bend and persists in the downstream straight reach, extends from the outer wall to about one and half times of mean depth further inwards and from the water surface to about half-mean depth.

Figure 4 shows the measured longitudinal distributions of the flow depth along inside and outside point with fixed bed, sand bed, and anthracite bed. It is supposed that the maximum scour depth is especially influenced on the bed friction. When the bed material is anthracite, the shifting of the maximum scour depth upward was observed. Thus anthracite bed was affected by bed shear stress much larger than the sand one, and the maximum scour depth in anthracite bed was found in the upper part of bend angle $5^\circ \sim 15^\circ$ than that of sand.

Figure 5 shows the streamwise averaged profiles of the skewed angle along constant-radius paths. A positive angle indicates skewed toward the outer bank and negative one toward the inner bank.

Figure 5. Longitudinal distribution of the skewed angle of flow

In this experiments, the magnitudes of skewed angles were observed in the order of the fixed bed, the anthracite bed, and the sand bed. It means that the magnitude of skewed angles increases as the roughness of bed material decreases. The maximum skewed angle of the flow grows faster in the smooth bed than in the rough one. The flow direction is skewed to the inner side at the bend inlet, and skewed to the outside at the bend outlet, regardless of their bed materials. The skewed angles with the streamwise direction were measured with the range of $-5^\circ \sim 13^\circ$ in a $180^\circ$ curved channel.

4.2 Comparative analysis with numerical model

Figure 6 shows the simulated result of streamwise flow depth and main velocity by changing the grain size of bed materials from 0.5mm to 2.0mm in a 180-degree with constant-radius
curved channel. When it comes to the flow depth, it seems that the changing range of relative depths becomes broad as the diameter of bed materials gets smaller. This result is driven by the reaction that the grain size of bed is in inverse proportion to the transverse bed slope, which was applied to depth prediction in the governing equation. That is, the transverse bed slope increases in accordance with the decrease of the grain size of bed. The computed values of velocity decrease in proportion to the increase of the bed material diameter, and the fluctuation range of flow depth broadens in proportion to the decrease of the bed material diameter. Although the grain size of bed materials was not operated directly in the equation of momentum, its influence is presented by virtue of flow depth.

![Figure 6](image-url)  
**Figure 6.** Streamwise depth and velocity distribution of simulated values with variation of grain size

After all, it is confirmed that the computed results of flow depth and velocity with numerical model become different a great deal as bed materials change.

![Figure 7](image-url)  
**Figure 7.** Streamwise comparison of the computed and the measured flow depth

Figure 7 shows comparison between the measured and the computed longitudinal distribution of flow depth with the sand bed and the anthracite bed. The computed results
and the measured ones gave a relatively good agreement in Figure 7. In a computational equation, as the specific gravity of bed material was used to predict the transverse bed slope, the flow depth increases in the anthracite bed of low specific gravity and the maximum value of relative depth of anthracite bed is also turned out to be a little bigger than that of sand due to the small resistance of bed materials.

Figure 8 shows the computed results and the measured one of the main velocity distribution. In the upper part of the bend the velocity distribution is skewed inwards under the influence of the longitudinal pressure gradients, which are largest near the inner wall. Then, under the influence of secondary flow convection, the main velocity increase in the inner wall of inlet region, and the main velocity increased in the outer wall after passing the 30° section of channel bend. The low velocity region near the inner wall gradually extends its influence further outwards, until the main velocity distribution has become skewed outwards throughout the cross-section in the last part of the bend.

![Figure 8. Streamwise variations of main velocity](image)

This outward skewedness is enhanced by the longitudinal pressure gradients near the bend exit, which are largest in the outer bend. In the process of developing the secondary flow at the bend inlet, the loss of momentum happens while transverse velocity near bed is skewed to the inside and transverse velocity near water surface is skewed to the outside to recover the lost momentum. This reaction occurs due to the fact that all the processes are transmitted to downstream having effect on the neighboring fluid, that is, the redistribution of velocity over the section spreads in the direction of flow. The phase which velocity moves from the inside to the outside gets delayed to downstream when bed material is sand, and main velocity increases as flow proceeds to downstream in anthracite bed of low specific gravity.
5. Conclusion
The 180° total angle curved channel was used to analyze the characteristics of flow and bed topography by changing bed material. Sand and anthracite were selected as bed materials. In this study, following conclusions are derived:

(1) The maximum scour depth was found to be about two times as big as mean flow depth at the outer bank of bend angle 30°–60° section, and in case of the anthracite bed, the maximum scour depth was found in the upper part of bend angle 5°–15° than that of the sand one.
(2) Regardless of bed materials the paths of maximum streamwise velocity are skewed inwards in the upper part of the bend, the maximum velocity shifts outwards, and it lagged downward as bed roughness increases.
(3) The maximum skewed angle of flow grows faster in the smooth bed than in the rough one.
(4) The secondary flow in the anthracite bed was measured larger than that of the sand one, and two cells of secondary flow was found in this experiment.
(5) The application results of model to the sand bed and the anthracite one accorded well with the observed ones.

References


