Impact of Spur Dike Placement on Flow Dynamics in Curved River Channels: A CFD Study on Pick Angle and River-Width-Narrowing Rate

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Abstract: The long-term effects of the centrifugal force of water flow in a curved river channel result in the scouring of the concave bank and the silting of the convex bank. This phenomenon significantly impacts the stability of bank slopes and the surrounding ecological environment. A common hydraulic structure, the spur dike, is extensively employed in river training and bank protection. Focusing on a 180° bend flume as the research subject, this study examines the effects of spur dike placement on the concave bank side of the bend. To this end, a second-order accurate computational format in computational fluid dynamics (CFD) and the RNG k-ε turbulence model were employed. Specifically, the influence mechanism of the pick angle and the river-width-narrowing rate on the flow dynamics and eddy structures within the bend were investigated. The results indicated that both the river-width-narrowing rate and pick angle significantly influence the flow structure of the bend, with the pick angle being the more dominant factor. The vortex scale generated by a positive pick angle of the spur dike is the largest, while upward and downward pick angles produce smaller vortex scales. Both upward and positive pick angles have larger areas of influence, and the maximum value of turbulent kinetic energy occurs at the back of the secondary spur dike. In contrast, the downward pick angle has a smaller area of influence for turbulent kinetic energy, resulting in a smaller vortex at the back of the spur dike and leading to smoother water flow overall. In river-training and bank-protection projects, the selection of the spur dike angle is crucial for controlling scour risk. The findings provide valuable insights for engineering design and construction activities.

Keywords: spur dike; pick angle; river-width-narrowing rate; turbulent kinetic energy; flow characteristics; numerical simulation

1. Introduction

Rivers are a crucial component of the Earth’s surface. As river water interacts with the riverbed, a complex river system is formed. Curved rivers are affected by inertia and centrifugal force during their evolution, which leads to the scouring of concave banks and siltation of convex banks [1–3]. These processes can have adverse effects on the stability of bank slopes and the surrounding ecosystems. To mitigate these effects, measures such as channel dredging, bank-protection works, soil and water conservation, and ecological restoration are usually employed [4–7]. A spur dike is a fundamental and cost-effective structure commonly utilized in water-conservancy engineering. Its primary functions include regulating water flow, enhancing navigation depth, managing sediment distribution, reducing riverbank erosion, and improving the quality of the aquatic ecosystem. With their low cost, straightforward construction process, and multiple benefits, spur dikes play a crucial role in comprehensive river management, ecological restoration projects, and flood-mitigation efforts. They have emerged as a valuable tool for promoting sustainable water resource utilization and fostering environmental harmony. The placement of spur...
dikes at river bends alters the over-water cross-section, leading to changes in the direction of mainstream water flow and the distribution of flow velocity. Specifically, the mainstream shifts from the concave bank side toward the central axis, thereby reducing the scouring of the concave bank and improving the stability of the riverbed. Concurrently, the water flow near the spur dike experiences a series of hydraulic phenomena, including separation, eddies, and undercutting. The increase in turbulent kinetic energy promotes the formation of various eddies, resulting in an enhanced mixing of the water body and an improved suspension and transport of sediments. Furthermore, the deployment of spur dikes induces changes in riverbed morphology and water-flow structure. These alterations subsequently influence the oxygen content, temperature, and sediment distribution within the water body, with significant implications for the ecological environment. Over time, the presence of spur dikes may continue to affect the evolution of the river channel, sedimentation patterns, and biological habitats. In recent years, the frequency of flood occurrences has increased globally. The unreasonable length and pick angle of spur dikes result in strong erosion of the spur dike body by the water flow. This erosion leads to the hollowing out of the foundation and the partial or complete collapse of the spur dike body, resulting in significant losses [8,9].

The flow characteristics near spur dikes are represented by the comprehensive manifestation of velocity distribution, turbulence intensity, water-surface slope, riverbed erosion, and deposition changes attributable to the installation of spur dikes. Majid [10] and Ghodsian [11] conducted flume tests and found that the size of scour pits near the head of a spur dike placed in bends is related to the Froude number and the length of the spur dike. Koken [12] found through numerical simulations that the values of shear stress and standard deviation of pressure increase with the increasing length of the spur dike. This increase occurs near the spur dike crest, below the upstream section of the main horseshoe vortex, and below the separating shear layer. By conducting experiments, Pandey [13] found that the maximum scour depth increases with the increasing length of the spur dike. Through a numerical simulation, Ning [14] investigated the effect of different rates of river width narrowing on the head of a non-inundated spur dike on a rectangular straight channel, specifically on the depth of scouring and morphology. Akbari [15] and Rashedi [16] separately conducted experiments on the effect of spur dikes on water flow in 180° open and curved flumes. Specifically, Giglou [17] focused on the deployment of T-spur dikes, whereas Choufu [18] examined a single spur dike. Both studies concluded that the maximum depth of scour occurs when the spur dike is placed at 75° in the bend. Wei [19] performed a numerical simulation to analyse the water-flow characteristics of a 60° bend after the deployment of spur dikes. The results showed that the deployment of spur dikes increased the maximum flow velocity in the bend. Additionally, the area of the maximum flow-velocity region increased, the depth of the main channel increased, and the water surface cross-drop decreased overall. These findings suggest that the deployment of spur dikes is beneficial for improving the flow pattern of water in bends. Ulu [20] placed clusters of thin-walled spur dikes at various angles on either side of a straight channel and found that dikes placed at 120° resulted in the highest energy dissipation. Numerical simulations by Granados [21] have shown that perpendicular spur dikes generate greater shear stresses in water flow.

In general, previous studies have primarily investigated the flow structure and scouring mechanism based on the deployment of double-spur dikes in straight flumes or a single spur dike in curved channels. As natural river channels are curved and have a large curvature coefficient, erosion near spur dikes is variable under the scouring action of water flow over long periods. This study investigated the effects of installing a double-spur dike at the concave bank of a 180° bend flume. The double-spur dike is used as the spur-dike group unit, and 15 different working conditions were tested through experiments and numerical simulations. Changes in the water-surface transverse-specific drop, cross-sectional flow field, planar flow field, and turbulent kinetic energy under identical flow conditions were
analysed. Furthermore, the influences of the pick angle of the spur dike and the rate of narrowing of river width on the flow structure of the bend were examined.

2. Numerical Model
2.1. Water Flow Control Equations

Continuity and momentum-conservation equations that describe three-dimensional water motion in a tensor form are as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \left( \rho u_i \right)}{\partial x_i} = 0$$  \hspace{1cm} (1)

$$\frac{\partial \left( \rho u_i \right)}{\partial t} + \frac{\partial \left( \rho u_i u_j \right)}{\partial x_j} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} - \rho \frac{u_i u_j}{\rho} \right) + S_i$$  \hspace{1cm} (2)

where $\rho$ is the fluid density; $u_i$ and $u_j$ are the components of the fluid time-averaged velocity in $i$ and $j$ directions and take values of 1, 2, and 3; $\rho$ is the modified pressure; $\mu$ is the molecular viscosity coefficient; $\rho \frac{u_i u_j}{\rho}$ is Reynolds stress; and $S_i$ is the generalised source term.

2.2. Turbulence Model

Shaheed [22] compared the performance of the standard k-epsilon (k-$\epsilon$) model with the realizable k-$\epsilon$ model in predicting secondary flow behaviour and concluded that the standard k-$\epsilon$ model shows higher performance in curved channels. Wang [23] concluded that the realizable k-$\epsilon$ model addresses the limitations of the standard k-$\epsilon$ model by incorporating a variable turbulent-viscosity formulation, which enhances the prediction of flow separation and complex eddies. Gholami [24] and Niknezhad [25] experimentally demonstrated that the RNG k-$\epsilon$ model more effectively simulates flow regimes in a curved channel. Therefore, in this study, the RNG k-$\epsilon$ turbulence model was used for the numerical simulations of a 180° bend open channel. This model was obtained by Yakhot and Orzag’s Gaussian statistical expansion of the unsteady N-S equations to an equilibrium state and filtering with wave number segments of the pulsation spectrum. The equations for the turbulent energy and turbulence-energy-dissipation rate are expressed as follows:

$$\frac{\partial K}{\partial t} + \frac{1}{V_F} \left( u A_x \frac{\partial K}{\partial x} + v A_y \frac{\partial K}{\partial y} + w A_z \frac{\partial K}{\partial z} \right) = P_T + G_T + D_K - \varepsilon$$  \hspace{1cm} (3)

$$\frac{\partial \varepsilon}{\partial t} + \frac{1}{V_F} \left( u A_x \frac{\partial \varepsilon}{\partial x} + v A_y \frac{\partial \varepsilon}{\partial y} + w A_z \frac{\partial \varepsilon}{\partial z} \right) = \frac{C_{\varepsilon 1} \cdot \varepsilon}{K} \left( P_T + C_3 \cdot G_T \right) + D_\varepsilon - C_{\varepsilon 2} \frac{\varepsilon^2}{K}$$  \hspace{1cm} (4)

where $K$ is the methodical kinetic energy, $K = 1/2 \left( u'^2 + v'^2 + w'^2 \right)$, $V_F$ is the fluid volume fraction; and $A_x$, $A_y$, and $A_z$ are the components of the fluid fraction in three directions. The term $G_T$ represents the buoyancy-generating term and takes the value 0. The term $D_T$ represents the turbulent-dissipative diffusion; $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, and $C_3$ are dimensionless parameters, taking values of 1.42, 1.68, and 0.2, respectively. The term $P_T$ represents the methodical kinetic-energy production, expressed as follows:

$$P_T = \left( \frac{\mu}{\nu V_F} \right) \times \left[ \frac{2 A_x \left( \frac{v}{v_F} \right)^2 + 2 A_y \left( \frac{w}{v_F} \right)^2 + 2 A_z \left( \frac{w}{v_F} \right)^2}{1} + \left( \frac{u}{v_F} + \frac{w}{v_F} \right) \left( A_x \frac{v}{v_F} + A_y \frac{w}{v_F} \right) + \left( \frac{w}{v_F} + \frac{u}{v_F} \right) \left( A_z \frac{v}{v_F} + A_y \frac{w}{v_F} \right) \right]$$  \hspace{1cm} (5)

The term $D_K$ represents the turbulent diffusion, expressed as follows:

$$D_K = \frac{1}{V_F} \left[ \frac{\partial}{\partial x} \left( v_k A_x \frac{\partial K}{\partial x} \right) + \frac{\partial}{\partial y} \left( v_k A_y \frac{\partial K}{\partial y} \right) + \frac{\partial}{\partial z} \left( v_k A_z \frac{\partial K}{\partial z} \right) \right]$$  \hspace{1cm} (6)

where $v_k$ is the turbulent-viscosity coefficient, and $v_k = \rho C_{\mu} (K^2/\varepsilon)$. $C_{\mu}$ is an empirical constant in the model, taking the value of 0.0845. The term $\varepsilon$ represents the systematic
dissipation of kinetic energy, \( \varepsilon = 0.085^{3/4}(K^{3/2}/L) \), and the turbulence-length scale is represented by the variable ‘L’.

2.3. Initial and Boundary Conditions

The volume of fluid (VOF) method is used to track the free-water surface by determining the interface between water and gas through geometric reconstruction. The volume fraction of water is represented by \( V_w \), and the volume fraction of gas is represented by \( V_a \).

\[
V_a = 1 - V_w
\]  

(7)

The equation for determining the water-volume fraction is as follows:

\[
\frac{\partial V_w}{\partial t} + u_i \frac{\partial V_w}{\partial x_i} = 0
\]  

(8)

where \( t \) is the time and \( u_i \) and \( x_i \) denote the velocity and coordinate components, respectively \((i = 1, 2, 3)\).

The boundaries of the wall were set as no-slip walls, and the standard wall-function method was used to solve the water flow near the wall. Boundary conditions were determined by controlling the inlet flow and outlet flow based on 180° bend-flume physics experiments. The inlet boundary was divided into two parts. The inlet water velocity was 0.5 m/s, the water depth was 0.16 cm, and the volume fraction of water was set to 1. Air was set as a pressure inlet, and the relative pressure was 0. The outlet boundary was defined as a pressure outlet, and the relative pressure was also 0. The outlet water-surface elevation was set to 0.15 m, and the bottom of the channel was taken as 0.

For the computational area, an unstructured grid was employed, with the grid’s surrounding spur dike encrypted and the total number of nodes close to \( 8 \times 10^6 \). A simple algorithm was used for pressure-velocity coupling. The initial turbulent-kinetic energy and turbulent-kinetic energy-dissipation rate were calculated using the following formulae:

\[
K = \frac{3}{2} \times (U \times 0.16 \times R_e^{-1/8})^2 = 9.25 \times 10^4, \quad \varepsilon = C_\mu \frac{3}{4} \times \frac{R_e^{3/2}}{L} = 4.186 \times 10^{-4}.
\]

3. Condition Design and Model Validation

3.1. Condition Design

The object being simulated is a high-precision variable-slope flume, illustrated in Figure 1. The flume is 0.8 m wide and 0.8 m high, with 16 m-long straight sections upstream and downstream. The middle section connects the 180° bend, which has an inner radius of 1.6 m and an outer radius of 2.4 m. The bottom slope of the upstream straight section is 0.001, while the curved section and the downstream straight section have a flat slope. To reduce fluctuations in water flow at the upstream inlet, three-stage energy-dissipation grids are continuously placed at the inlet position, ensuring stable water flow after a certain distance.

Figure 1. Test flume.
To investigate the effect of the pick angle of the spur dike and narrowing rate of river width on water flow in the bend, non-inundated round-ended thin-walled double-spur dikes were installed on the flume concave bank at 30° and 45°. The location and the pick angle of the spur dike are shown in Figure 2.

As depicted in Figure 2, the actual length of the spur dike is denoted as \( L \), while its effective length is represented as \( L' \). The width of the cross-section is denoted as \( B \). The narrowing rate of river width is controlled by the effective length of the spur dike, which is expressed as \( L' / B \). The inlet flow was set at 64 \( L/s \), the inlet level at 16 cm, and the outlet level at 15 cm. The initial Froude number and Reynolds number were calculated using Equation (9) to determine that the flow state is turbulent, ensuring the accuracy of the numerical simulation.

\[
F_r = \sqrt{\frac{U^2}{gL}} = 0.3993, \quad Re = \frac{\rho UL}{\mu} = \frac{\rho U (B + 2h)}{Bh} = 19175.5 \tag{9}
\]

Fifteen different conditions (shown in Table 1) were simulated and analysed to compare the changes in transverse drop, flow field, and turbulent kinetic energy attributable to the design of three effective lengths of spur dike and pick angles of 45°, 60°, 90°, 120°, and 135°.
Table 1. Statistics of working conditions.

<table>
<thead>
<tr>
<th>Case</th>
<th>Length (cm)</th>
<th>Angle (Degrees)</th>
<th>River Width Narrowing Rate</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td></td>
<td>45°</td>
<td>0.10163</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td></td>
<td>60°</td>
<td>0.12449</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>11.5</td>
<td>90°</td>
<td>0.14375</td>
<td>64 L/s</td>
</tr>
<tr>
<td>A4</td>
<td></td>
<td>120°</td>
<td>0.12449</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td></td>
<td>135°</td>
<td>0.10163</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td></td>
<td>45°</td>
<td>0.11047</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td>60°</td>
<td>0.13231</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>12.5</td>
<td>90°</td>
<td>0.15625</td>
<td>64 L/s</td>
</tr>
<tr>
<td>B4</td>
<td></td>
<td>120°</td>
<td>0.13231</td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td></td>
<td>135°</td>
<td>0.11047</td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td></td>
<td>45°</td>
<td>0.11931</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td>60°</td>
<td>0.14614</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>13.5</td>
<td>90°</td>
<td>0.16875</td>
<td>64 L/s</td>
</tr>
<tr>
<td>C4</td>
<td></td>
<td>120°</td>
<td>0.14614</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td></td>
<td>135°</td>
<td>0.11931</td>
<td></td>
</tr>
</tbody>
</table>

3.2. Model Validation

In this study, the flume test was conducted under the conditions of Case A5. Water level was measured using a water-level stylus at 5° intervals along the longitudinal direction. The average flow velocity was measured using an acoustic Doppler velocimeter at a water depth of 8 cm. Figure 3 presents a comparison between the measured and simulated water levels for the concave, median, and convex banks. Figure 4 shows a comparison between the measured and simulated flow velocities for the same banks.

![Figure 3. Comparison of water levels: measured vs. simulation.](image1)

![Figure 4. Comparison of velocity: measured vs. simulation.](image2)
The figures show good agreement between the measured and simulation results, indicating the feasibility of using the RNG k-ε turbulence model to simulate water-flow characteristics near the spur dike in the 180° bend.

4. Results

4.1. Transverse Ratio Drop of the Water Surface

The transverse ratio drop of a water surface is the ratio of the height difference between the left and right banks of a river cross-section to the width of the corresponding cross-section, i.e.,

\[
\text{Transverse ratio drop} = \frac{h_l - h_r}{B}
\]  

(10)

where \(h_l\) is the height of the water level on the left bank, \(h_r\) is the height of the water level on the right bank, and \(B\) is the width of the corresponding cross-section.

If the change in the transverse ratio drop is significant, the lateral-flow velocity gradient also exhibits a large change, leading to an increase in the shear force and, consequently, enhancing the erosion effect of the water flow on the riverbed. Conversely, if the change in the transverse ratio drop is small, the flow velocity gradient decreases, weakening the erosion of the riverbed by the water flow. Thus, the change in the transverse ratio drop strongly affects the alteration of riverbed morphology. Double-spur dikes were deployed on the concave bank side of the 180° bend to adjust the main flow from the concave bank side to the centre of the river channel. This would reduce the transverse ratio drop of the water surface, enhance the water flow on the convex bank, reduce siltation on the convex bank, and protect the stability of the bank slopes.

Figure 5 shows the variation in the transverse ratio drop of the water surface under different pick-angle conditions at a spur-dike length of 13.5 cm. The plot reveals two primary results. First, the transverse ratio drop follows a consistent trend. The transverse ratio drop of the water surface in both the upstream and downstream straight channels remains relatively stable, ranging from −2‰ to 2‰. Before the primary spur dike, the transverse ratio drop gradually increases and reaches the maximum value. After passing through the primary spur dike, the water level in the central axis is elevated, and the water level in the concave bank decreases sharply, leading to a decrease in the transverse ratio drop. Subsequently, the transverse ratio drop between the double-spur dikes tends to decrease and then increase under the action of the secondary spur dike. After passing the secondary spur dike, the transverse ratio drop gradually decreases. Near the top of the bend (90° of the flume), the transverse ratio drop tends to stabilize until the flow exits the bend. Finally, the transverse ratio drop is restored to zero. Second, under the same length of the spur dike with different pick angles, the transverse ratio drop of the water surface exhibits a regularity. The upward and positive pick angles exhibit a larger transverse ratio drop than the downward pick angle. The maximum transverse ratio drop decreases with the increasing pick angle. The maximum drop is 30.375‰ at a pick angle of 45° and 13.713‰ at 135°, which is nearly double the difference. This is because when the picking angle of the spur dike is upward, the width of the concave bank side in front of the spur dike decreases, the water level rapidly rises, the transverse ratio drop increases, and the water level downstream of the spur dike continues to exhibit the trend of “high at the concave bank and low at the convex bank”. While the pick angle of the spur dike is downward, the water-level difference between the concave and convex banks decreases, the transverse ratio drop decreases, and the mainstream water flow develops towards the centre of the river channel. Therefore, when the pick angle of the spur dike is downward, the transverse ratio drop is minimized, resulting in a stable water flow. This also allows for a better adjustment of the mainstream water flow from the concave bank towards the central axis and the position of the convex bank.
Figure 5. Scatter plot of transverse ratio drop along the curved section for conditions C1 to C5.

Figure 6 displays the plot of the transverse ratio drop of the water surface for the same pick angle and various lengths of the spur dike. As shown in Figure 6a, the transverse ratio drop experiences a significant decrease after the water passes through the two-stage spur dike with a pick angle of 45°. Specifically, the maximum transverse ratio drop of the water surface is observed at a spur dike length of 12.5 cm. Figure 6b displays the maximum area of obstruction to the water flow for three lengths of the spur dike with the pick angle at 90°. The trend of the transverse ratio drop is similar. The transverse ratio drop reaches its maximum value in front of the primary spur dike when the length is 11.5 cm and 13.5 cm, but it lags and occurs in front of the secondary spur dike when the length is 12.5 cm, reaching 36.25‰. Figure 6c shows the spur dike with a pick angle of 120°. The maximum value of the transverse ratio drop is 26.875‰ at a spur dike length of 11.5 cm, 17.5‰ at 12.5 cm, and 21.863‰ at 13.5 cm. As the length of the spur dike increases, the effect of the transverse ratio drop of the water surface is weakened, provided that the pick angle remains the same.
4.2. Cross-Sectional Flow-Velocity Distribution

The water movement in the bend corresponds to a complex three-dimensional turbulence. Under the influence of bend circulation, a phenomenon of “concave bank scour, convex bank siltation” often occurs. In actual projects, concave banks are protected from erosion by laying spur dikes. Spur dikes induce different flow structures depending on the pick angle and length. Figure 7 shows cloud diagrams of the cross-sectional flow velocity distribution for a spur dike length of 11.5 cm under the conditions of upward, positive, and downward pick angles. The six sections, namely S1, S2, S3, S4, S5, and S6, are located at 18°, 30°, 37°, 45°, 52°, and 60° on the concave bank. The six cross-sections cover the majority of the area in front of, between, and behind the spur dike, providing a clearer understanding of the changing flow structure in the bend.

Figure 7. Cross-sectional flow-velocity distribution at different pick angles for a length of 11.5 cm.

The figure shows that the installation of the spur dike effectively shifts the mainstream flow towards the convex bank. Moreover, compared to a downward pick angle, upward or positive pick angles lead to higher stream velocities on the convex bank than on the concave bank. Changes in the length of the spur dike have a minimal impact on the distribution.
of flow velocity. Cross-section S1 is located in front of the primary spur dike. The flow is hindered by the spur dike, and the flow velocity in front of the spur dike decreases in the concave bank. Part of the flow is directed towards the convex bank, resulting in an increase in flow velocity in the convex bank. The average flow velocity in the cross-section gradually increases from the concave bank to the convex bank. Cross-section S2 is located at the primary spur dike. From Cross-section S1 to S2, under the influence of the spur dike, the water flow moves from the concave bank towards the middle of the river in the direction of the convex bank. The area close to the concave bank of the spur dike is in the backflow zone, where the water flow is slow, and the velocity is below 0.1 m/s. In the middle of the cross-section towards the convex bank, the water-flow rate increases, leading to an increase in water-flow speed, with the maximum water-flow speed reaching up to 0.65 m/s. Cross-section S3 is positioned in the centre of the double-spur dike. In this section, the water flow is biased towards the middle of the flume, leading to an overall increase in flow velocity across the transect. The flow velocity is higher in the middle than in both the surface and bottom. On the near-left bank, the water flow is affected by three factors: backflow behind the primary spur dike, congestion in front of the secondary spur dike, and the concave bank boundary. These factors increase the extent of the low-flow velocity zone. For instance, in Case C3, the low-flow velocity zone covers around 25% of the cross-sectional area. The velocity distribution in the convex bank remains largely unchanged compared to section S2. The high-velocity area persists near the convex bank and extends towards the concave bank, leading to a decrease in the maximum velocity. Cross-section S4 is located at the secondary spur dike and is similar to Cross-section S2. However, it is affected by the return zone between the two spur dikes and has a larger low-flow velocity zone near the concave bank. Cross-sections S5 and S6 are located behind the secondary spur dike. The entire cross-sections are overwatered, lowering the average flow velocity. As the influence of the spur dike diminishes, the impacts of the concave and convex bank boundaries and the gravity of the flow are enhanced. Consequently, the flow velocities are higher in the middle position than at the bottom and surface, and slightly higher on the convex bank compared to the concave bank.

Figures 8 and 9 display cross-sectional flow-velocity cloud plots for different pick angles at spur dike lengths of 12.5 cm and 13.5 cm. The upward, positive, and downward pick angles have a greater impact on flow structure for the same length of the spur dike.

(1) Cross-section S1: An upward pick angle of the spur dike has a greater influence on the flow-velocity distribution at the cross-section in front of the spur dike. In terms of flow velocity at the convex bank, the pick direction can be ranked as follows: upward pick > positive pick > downward pick. (2) Cross-section S2: When the pick angle is upward, the cross-section is located behind the head of the spur dike. The overflow cross-section is slightly contracted, resulting in an increase in the average flow velocity. A reflux zone is created at the rear of the spur dike, reducing the flow velocity to below 0.05 m/s. When the pick angle is positive, the cross-section is parallel to the primary spur dike. This results in the largest obstruction area to the water flow and a contracted overwater cross-section. As the water flow passes the spur dike, a high-flow velocity zone is formed before and after the head of the spur dike, which extends upstream and downstream, and the highest flow velocity reaches 0.75 m/s. When the pick angle is downward, the cross-section is located at the front end of the primary spur dike. At this point, the overwater cross-section has not yet contracted, and the direction of the pick angle is biased towards the direction of the water flow. As a result, the water-blocking effect is weakened, and a small congestion occurs in front of the spur dike, producing a small reflux zone. The velocity of the water flow in the reflux zone is relatively low, while the velocity of the water flow is higher at intermediate depths than at the surface and bottom. The velocity of the water flow at the centre of the cross-section towards the convex bank remains relatively unchanged compared to that at Cross-section S1. (3) Cross-section S3: When the pick angle is upward, the impact on the flow is concentrated near the head of the spur dike. When the pick angle is downward, the impact on the flow is concentrated downstream of the head of the spur dike. Therefore,
in this cross-section, the low-flow velocity zone formed near the concave bank is larger for the upward pick angle than for the downward pick angle, and the flow velocity in the high flow velocity zone formed near the convex bank is generally higher with the upward pick angle than with the downward pick angle. When the pick angle is positive, the reflow zone behind the primary spur dike reaches its maximum, and the area of the low-flow velocity zone near the concave bank is at its maximum. As observed in Cases A3, B3, and C3, the flow velocity in Cross-section S3 is notably higher compared with the upward or downward pick angle. Regarding the small high-flow velocity zone formed in the middle of Cross-section S2, in the process of the downward water flow, lateral movement is enhanced, flow velocity increases, and the range of the high-flow velocity zone gradually expands. As shown in Case C3 of Figure 8, large and small high-flow velocity zones in Cross-section S2 develop into two high-flow velocity zones of nearly the same area in Cross-section S3.

(4) Cross-section S4: When the pick angle is upward, the cross-section is located behind the head of the secondary spur dike. The cross-section shrinks and the flow velocity near the head of the spur dike increases. The low-flow velocity zone near the concave bank is reduced by almost 50% compared to Cross-section S3. When the pick angle is positive, the cross-section is parallel to the secondary spur dike, the overflow section shrinks the most, the mean flow velocity at the cross-section is higher than that for the upward or downward pick angle, and the area of the low-flow velocity zone is the smallest near the concave bank. When the pick angle is downward, the cross-section is at the front end of the secondary spur dike. The concave bank is affected by the return zone in front of the spur dike, forming a low-flow velocity zone with a smaller area, but the area of this low-flow zone is larger than that of the low-flow zone of the primary spur dike (Cross-section S2). As the pick angle of the spur dike increases, the area of the low-flow velocity zone near the concave bank in front of the secondary spur dike shows a tendency to decrease and then increase.

(5) Cross-sections S5 and S6: The concave bank remains within the influence of the reflux zone after the spur dike, and the small low-flow-velocity zone near the concave bank moves downward while decreasing in size with distance from the head of the spur dike and spreads out towards the water surface. At Cross-section S6, the spur dike is no longer a major factor influencing the change in flow structure, with boundary conditions and gravity being the main factors.

Figure 8. Cross-sectional flow-velocity distribution at different pick angles for a length of 12.5 cm.
With increasing spur-dike length at the same pick angle, the effect of the spur dike on the overall flow structure in the bend weakens. Nevertheless, it continues to affect the flow field near the head of the spur dike. Cross-sections S1, S5, and S6 are further away from the head of the spur dike. In these cross-sections, the change in the length of the spur dike has a negligible effect on the flow rate since the pick angle remains the same. Cross-section S2 is the closest to the head of the spur dike. As the length of the spur dike increases, the overflow cross-section decreases and the mean flow velocity increases. Cross-section S3 is located behind the head of the spur dike. The high-flow velocity zone near the convex bank develops progressively towards the concave bank. In addition, the low-flow velocity zone near the concave bank expands as the length of the spur dike increases. In Cross-section S4, which is similar to Cross-section S2, the maximum flow velocity and the high-flow velocity zone increase with the increasing length of the spur dike.

Figure 9. Cross-sectional flow-velocity distribution at different pick angles for a length of 13.5 cm.

4.3. Flow Field of the Plane

Planar-flow velocity vectors are used to visualise the structure of the flow field. This study investigated the effect of different lengths and pick angles of the spur dike on the flow-field structure at a water depth of $Y = 8$ cm. Figures 10–12 show the flow-velocity vector and streamline diagrams of the spur dike with upward, positive, and downward pick angles lengths of 11.5 cm, 12.5 cm, and 13.5 cm.

Following the deployment of the spur dike, the mainstream of the water flow contracts near the spur dike, and the mainstream flow increases at the head location, forming a distinctive vortex between the two levels of the spur dike and at the downstream location, respectively. The vortex scales differ with varying lengths and pick angles of the spur dike. From the diagram of the planar-flow field, the following observations can be made:

1. Congestion occurs in front of the primary spur dike, and flow velocity gradually decreases along the spur dike from the head to the root. When the pick angle is upward or positive, a smaller vortex is created at the root of the spur dike. The magnitude of the vortex is greater for the upward pick angle than for the positive pick angle. When the pick angle is downward, water flows along the side wall of the spur dike without forming a vortex. This results in minimal head loss and reduces erosion on the spur dike.
(2) As water flows around the head of the primary spur dike, the over-water cross-section shrinks, causing an increase in flow velocity and the formation of a bypass flow near the head of the spur dike. Due to inertia, the cross section continues to contract, the flow behind the spur dike begins to separate, part of the flow between the two spur dikes forms backflow, and the flow velocity decreases to less than 0.15 m/s. The scale and central position of the vortex are determined by the length and pick angle of the spur dike. For a constant length of the spur dike, the position of the vortex centre moves upwards with the increasing pick angle. The vortex scale is the largest with a positive pick, followed by the upward pick, and it is the smallest with a downward pick.

(3) When the pick angle of the spur dike is upward, a large-scale vortex and a small-scale vortex are formed between the two spur dikes. When the pick angle of the spur dike is positive, a large-scale vortex is formed between the two spur dikes. Nevertheless, the upward pick angle induces a larger vortex scale. When the pick angle of the spur dike is downward, a smaller vortex is formed between the two spur dikes. The lateral

Figure 10. Vectors and streamlines of flow velocity at different pick angles for a spur−dike length of 11.5 cm.
width and length of the vortex are significantly smaller than the vortex scale when the pick angle of the spur dike is upward or positive.

(4) Likewise, vortices of varying scales form behind the secondary spur dike. In terms of the size of the vortex scale, the pick angles can be ranked as positive > upward > downward.

(5) Under a constant pick angle, the vortex formed near the concave bank increases slightly with the effective length of the spur dike. Both the length and the pick angle of the spur dike have different effects on the flow structure of the bends. In particular, the dominant factor influencing the flow is the pick angle, followed by the length.

Figure 10. Vectors and streamlines of flow velocity at different pick angles for a spur−dike length of 11.5 cm.

(a) Pick angle of 45°

(b) Pick angle of 90°

(c) Pick angle of 135°

Figure 11. Vectors and streamlines of flow velocity at different pick angles for a spur−dike length of 12.5 cm.
Following the deployment of the spur dike, the mainstream of the water flow contracts near the spur dike, and the mainstream flow increases at the head location, forming a distinctive vortex between the two levels of the spur dike and at the downstream location, respectively. The vortex scales differently with varying lengths and pick angles of the spur dike. From the diagram of the planar flow field, the following observations can be made:

(1) Congestion occurs in front of the primary spur dike, and flow velocity gradually decreases along the spur dike from the head to the root. When the pick angle is upward or positive, a smaller vortex is created at the root of the spur dike. The magnitude of the vortex is greater for the upward pick angle than for the positive pick angle. When the pick angle is downward, water flows along the side wall of the spur dike without forming a vortex. This results in minimal head loss and reduces erosion on the spur dike.

(2) As water flows around the head of the primary spur dike, the over-water cross-section shrinks, causing an increase in flow velocity and the formation of a bypass flow near the head of the spur dike. Due to inertia, the cross section continues to contract, the flow behind the spur dike begins to separate, part of the flow between the two spur dikes forms backflow, and the flow velocity decreases to less than 0.15 m/s. The scale and central position of the vortex are determined by the length and pick angle of the spur dike. For a constant length of the spur dike, the position of the vortex centre moves upwards with the increasing pick angle. The vortex scale is the largest with a positive pick, followed by the upward pick, and it is the smallest with a downward pick.

(3) When the pick angle of the spur dike is upward, a large-scale vortex and a small-scale vortex are formed between the two spur dikes. When the pick angle of the spur dike is positive, a large-scale vortex is formed between the two spur dikes. Nevertheless, the upward pick angle induces a larger vortex scale. When the pick angle of the spur dike is downward, a smaller vortex is formed between the two spur dikes. The lateral

4.4. Turbulent Kinetic Energy Distribution

Turbulent kinetic energy is a key physical parameter in the study of turbulent motion. It represents the intensity of the turbulent motion, and its magnitude characterises the magnitude of the turbulent shear stress. Turbulent kinetic energy can be estimated through experimental measurements, such as Laser Doppler Velocimetry (LDV), Particle Image Velocimetry (PIV), and Particle Tracking Velocimetry (PTV). However, these experimental methods are constrained by limitations in spatial and temporal resolution [26]. In this study, the distribution of turbulent kinetic energy was determined by numerically solving the equations of the turbulence model using computational fluid dynamics (CFD). The flow-velocity distribution in the curved flow structure is highly uneven. This unevenness is further exacerbated by the deployment of a spur dike on the concave bank, resulting in a more complex turbulent flow field. Figure 13 shows the distribution of turbulent kinetic energy at 1 cm, 8 cm, and 15 cm from the bottom of the river bed for a spur dike length of 11.5 cm and a positive pick angle.
Figure 13. Distribution of turbulent kinetic energy at different water depths when the length of spur dike is 11.5 cm and the pick angle of the spur dike is positive.

The figure shows an increase in turbulent kinetic energy at locations in front of, at the head of, and behind the spur dike. Turbulent kinetic energy shows a decrease between the two spur dikes and an increase behind the secondary spur dike. In contrast, the turbulent kinetic energy of the flow does not show any significant change on the convex bank side. With increasing water depth, the distribution of turbulent kinetic energy shows the pattern of “the largest near the surface, the second largest near the bottom, and the smallest in the middle”. The increased turbulent energy near the surface is a result of the strong turbulence at the water surface, which generates significant Reynolds stresses and velocity gradients. Viscous shear stresses (i.e., viscous bottom) exist at the near-bottom surface. As the flow transitions from laminar to turbulent, water masses mix and friction increases, resulting in a wider distribution of turbulent kinetic energy near the bottom. The intermediate flow is more stable than the bottom and surface flows, with a uniform distribution of flow velocity, lower turbulence intensity, and minimum turbulent kinetic energy. The flow structure is negligibly affected by the length of the spur dike. In order to investigate the effect of the pick angle of the spur dike on the turbulent kinetic energy, cloud diagrams of the turbulent kinetic-energy distribution near the spur dike at the intermediate water depth of 8 cm for upward, positive, and downward pick angles were generated (Figure 14).

Figure 14. Variation of turbulent kinetic energy at the same water depth and different pick angles.

A change in flow velocity results in a corresponding rise in the flow gradient, which subsequently leads to an enhancement of turbulent kinetic energy. A comparative analysis of the flow-velocity variations (Figures 10–12) revealed that flow separation is initiated at the head of the spur dike, with the most significant changes in flow velocity occurring near the separation zone. Figure 14 highlights the development of a region characterized by high turbulent kinetic energy at the head of the spur dike, oriented towards the separation.
zone and extending into the return zone. In contrast, the main flow zone exhibits minimal alterations in flow velocity and lower levels of turbulent kinetic energy. The turbulent kinetic energy varies under different pick angle conditions for the same length of the spur dike. The maximum value of turbulent kinetic energy is 0.01 m$^2$/s when the pick angle of the spur dike is 60$^\circ$, 0.012 m$^2$/s when the pick angle is 90$^\circ$, and 0.013 m$^2$/s when the pick angle is 135$^\circ$. In the area between the two spur dikes and behind the secondary spur dikes, the turbulent kinetic energy increases as the pick angle of the spur dike increases. In terms of the area of influence of the turbulent kinetic energy, it is larger when the pick angle of the spur dike is upward or positive, and smaller when the pick angle is downward, with a small vortex behind the spur dike and an overall smoother water flow.

5. Discussion

This study also comparatively reviewed studies on spur dike-placement locations. In experiments conducted in a curved flume, Rashedipoor observed that positioning a spur dike at 75$^\circ$ in a 180$^\circ$ bend resulted in the maximum scour depth. However, the study did not discuss the influence of the spur dike on flow dynamics. The experimental results presented in this paper indicate that significant scouring begins in the concave bank area at 30$^\circ$ of the bend. When placed at 30$^\circ$, the spur dike effectively redirects the main flow and mitigates scouring of the concave bank. Therefore, to enhance the engineering effectiveness of the spur dike, it is advisable to position the spur dike according to the location where the water flow initiates significant scouring.

Water-level changes in the river channel after the installation of the spur dike were also compared. Li [27] installed spur dikes with varying pick angles in a straight river channel and concluded that the water level was higher behind a 90$^\circ$ spur dike. Consistent with the findings of Li, this study found that the change in the transverse ratio drop is least significant when the pick angle of the spur dike is downward in the 180$^\circ$ bend, whereas the change is most significant when the pick angle is 90$^\circ$. Additionally, the influence of the narrowing rate of river width on the transverse ratio drop of the water surface was found to be less significant than that of the pick angle.

Studies on the flow velocity in the mainstream area and the extent of the reflux zone were further compared. Ren [28] reported a positive correlation between the maximum flow velocity in the main flow zone and the extent of the return zone with the narrowing rate of river width following the placement of a spur dike in a straight channel. They compared three pick angles—67.5$^\circ$, 90$^\circ$, and 112.5$^\circ$—and revealed that the pick angle of the spur dike had a relatively minor impact on the cross-sectional flow velocity and the extent of the return zone located behind the spur dike. Tripathi [29] positioned a T-spur dike on a 60$^\circ$ concave bank within a 180$^\circ$ bend. Experiments indicated that under high-flow conditions, localized scour near the spur dike may extend towards the riverbank. From an engineering perspective, prolonged scouring could result in a structural failure of the spur dike, ultimately leading to its collapse. However, in this study, when a constant pick angle was maintained, the flow field near the head of the spur dike showed only slight alterations with an increase in the river-width-narrowing rate. In contrast, the pick angle had a more pronounced influence on the distribution of flow velocities. This effect was particularly evident at a pick angle of 90$^\circ$, leading to the formation of two distinct high-flow velocity zones within the cross-section between the double-spur dikes. The results of this study contradict those of Ren, primarily because of differences in the subjects examined and the distinct flow structures between straight and curved channels. Nevertheless, consistent with Tripathi’s results, potential issues related to the high-flow velocity zone near spur dikes were identified. Therefore, in river-training projects, it is crucial to pay special attention to these high-flow velocity zones adjacent to spur dikes, as the concentration of flow velocity may increase the risk of scour. Additional reinforcement measures should be implemented to prevent excessive scour and structural damage.

Regarding vortex structures, Fan [30] showed that the deployment of a positively picked double-spur dike in a straight river channel leads to instability in the flow pattern.
of the water behind the spur dike as the rate of river-width narrowing increases. This instability results in oscillation phenomena downstream, as well as an increase in both the number and range of vortices formed behind the spur dike. In this study, as shown in Figures 10–12, the river-width-narrowing rate has a minimal influence on the number and magnitude of eddies when spur dikes are positioned in 180° bends. This is attributable to the flow pattern within a bend being predominantly shaped by the curvature of the bend and centrifugal force. Consequently, the change in the river-width-narrowing rate does not significantly affect vortex formation. Further analysis revealed that the pick angle of the spur dike significantly influences the formation and size of vortices. The formed vortex exhibits greater concentration and regularity when the pick angle is downward, whereas the turbulence of the water flow is more intense and the formed vortex is more complex when the pick angle is positive. This phenomenon can be attributed to the fact that varying pick angles modify the deflection angle and flow path of the water, subsequently affecting the generation and development of eddies. Therefore, when deploying spur dikes in curved rivers, the potential effects of strong eddies on both aquatic organisms and the riverbed should be considered. It is crucial to avoid ecosystem disturbances and negative environmental impacts caused by swirling zones of higher intensity.

Regarding the distribution of turbulent kinetic energy, experimental investigations conducted by Jafari [31] under rectangular-channel ice-cap conditions revealed that a spur dike with a pick angle of 90° induced the highest levels of turbulence and subsequently led to the formation of the deepest scour crater. Zhang [32] showed that turbulent kinetic energy reaches its maximum in the flow separation zone located behind the spur dike when a spur dike is deployed within a 60° bend. Emre Ulu reported that a cluster of thin-walled spur-dike groups, staggered at various angles on both sides of a straight channel, achieved maximum energy dissipation when the pick angle was 120°. Wu [33] showed that the pick angle of a spur dike in a straight channel significantly influences the turbulent kinetic energy at the head of the spur dike. Specifically, a smaller pick angle results in increased turbulent energy at the head of the spur dike. Additionally, as the narrowing rate of the river width increases, both the extent of the turbulence and the maximum turbulence value also increase. Similar to the findings of Zhang [32], Jafari [31], and Wu [33], this study also found that the maximum value of turbulent kinetic energy occurs in the flow-separation zone behind the spur dike. A spur dike with a positive and upward pick angle was found to have a larger range of influence of turbulent kinetic energy than that with a downward pick angle. In addition, by comparing the turbulent kinetic energy at different water depths, the turbulent kinetic energy was found to be the highest near the water surface. Therefore, the effects of water depth and flow rate on the distribution of turbulent kinetic energy should also be considered in river-training projects. By optimising the design of the pick angle of the spur dike, the distribution of turbulent kinetic energy can be adjusted to reduce the impact on the ecological environment.

6. Conclusions

In this study, the flow dynamics in the vicinity of double-spur dikes were investigated with a focus on the problem of the placement of spur dikes in a curved river. The effects of the pick angle of the spur dike and the narrowing rate of the river width on the flow characteristics near the spur dikes were analysed and discussed. From the results, the following conclusions can be drawn.

(1) The pick angle of the spur dike significantly influenced the directionality of mainstream flow and the distribution of water levels. When the pick angle is 90°, the obstruction to flow reached its maximum intensity, resulting in the most pronounced difference in water levels near the front and rear of the spur dike.

(2) The pick angle of the spur dike has a predominant effect on water flow, with the length of the spur dike being secondary. The size of the vortex in the reflux zone is the largest at a positive pick angle, smaller at an upward angle, and the smallest at
a downward angle. For a particular pick angle, the vortex size increases with the narrowing rate of the river width.

(3) When the narrowing rate of the river width is the same, at an upward or positive pick angle of the spur dike, the area of influence is larger and the maximum value of turbulent kinetic energy appears behind the spur dike of the second stage. When the pick angle of the spur dike is downward, the area of influence of turbulent kinetic energy is small, and the overall flow of water is relatively smooth. The maximum value of turbulent kinetic energy shows a trend of increase and subsequent decrease along with the increase of the pick angle.

(4) In river-training projects, the selection of pick angles for spur dikes significantly influences both flow structure and riverbed scour. It is essential to consider the scouring effects produced by high-flow velocity zones and strong eddy formations adjacent to the spur dikes. Future research will investigate the impacts of multiple spur dike groups and staggered spur dikes on flow structure and riverbed scouring in bends, building upon the findings presented in this study.

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