Experimental Study on Turbulent Characteristics of Flow Around A T-shaped Spur Dike in Bend

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While protecting the river bank from erosion, spur dike will also cause significant changes in the hydrodynamic characteristics of nearby water flow, which will have a significant impact on fish and other habitats. In order to explore the turbulent characteristics of T-shaped spur dike in curved flow field, the three-dimensional flow field was measured in this paper by Vectrino Profiler. In this study, the turbulence characteristics of T-shaped spur dike in bend flow field were studied from the depth-averaged velocity distribution, relative turbulence intensity and Reynolds stress. The results show that a spur dike had a great influence on turbulent intensity distribution and Reynolds shear stress distribution. The turbulent intensity near the wing of spur dike increased significantly, with the maximum vertical turbulent intensity appearing in the middle of flow. The extreme value of Reynolds shear stress near the wing appeared in the middle of the flume, and the Reynolds shear stress values alternate positively and negatively along the vertical line of flow depth. The lateral momentum exchange intensity and the vertical momentum exchange intensity near the spur dike wing were very large. This study lays a foundation for further understanding the impact of flow field disturbances in spur dikes on habitats such as fish.

# Introduction

Dikes can protect riverbanks from erosion, improve navigation capacity of rivers and play an important role in river management. Dikes disturb the flow, and the flow near the dikes presents strong three-dimensional turbulence. The turbulent characteristics near the spur dike are of great significance to the study of flow sediment carrying capacity and local scouring [1]. At the same time, changes in hydrodynamic characteristics near the spur dam may affect fish habitats. For example, turbulence of flow usually promotes mating of in vitro fertilized fish [2], and turbulence of flow will also promote the mixing of nutrients in water [3]. In recent years, it has been gradually found that T-type dikes have many advantages over straight type dikes in river treatment research. The vortex formed in the space surrounding the dam wing on the upstream side of T-type dikes will reduce the velocity of flow at the dam head and the eddy current disturbance on the downstream side of the dam wing will be reduced [4]. At present, people mainly focus on the velocity distribution and river bed scouring of T-type spur dikes, but seldom study the turbulent characteristics of flow.

In this paper, flow field measurements near T-type spur dikes are carried out in an flume model using a Doppler profile velocimeter to study the turbulence around the spur dikes.

# Experimental Setup

## Experimental model

The experiment was carried out in a 0.6 m wide, 14.4 m long recirculating flume with a longitudinal slope (*i*) of 0.001, located in the Sichuan University’s State Key Laboratory of Hydraulics and Mountain River Engineering. The main channel consisted of a 7 m long upstream, a 60° channel bend with a centerline radius bend (*R*c) of 4.2 m, and a 3 m long downstream straight reach. The groyne, with a thickness of 0.01 m, was positioned at the 30° center corner of the outer bank side of the bend. The length of the groyne wing and web was 0.1 m (Figure 1cd). To stabilize the flow, an energy dissipation grid was placed at the inlet of the flume. The measured cross-sections *S*0–*S*33 corresponded to the central angles of 0–33°, respectively, of the bend. Figure 2d is a three-dimensional illustration of the groyne with a submergence ratio (*H* − *h*) / *h* = 1. A natural coordinate system is established for the bend section as shown in Figure 1a, in which *n* is the radial coordinate and *s* is the tangential coordinate.

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| (a) Experimental model and line arrangement | (b) Tank model |
| (c) Dikes | (d) Riverbed |
| Fig.1 Experimental arrangements | |

## Experimental arrangement

The flow rate is 0.0428 m3/s, the water depth of the diversion channel section is 0.24 m, and the Froude number Fr = 0.19. Natural sand is used for the experiment, with the median particle size of 0.000642 m. The scouring depth at the head of spur dike is no longer changed with time, i.e. scouring reaches equilibrium. The river bed of the experiment section reaches scouring-silting equilibrium and then begins to be measured. The experiment period is 86 h. The deformation of riverbed on convex bank and concave bank at tailgate is basically the same. The measurement mainly includes three-dimensional flow field measurements in the experiment section and river bed topographic measurements after equilibrium.

## Measuring instrument

A Vectrino Profiler manufactured by Nortek Corporation was used for velocity measurements. This device consists of a down-looking measurement probe with a non-measurable region of 4 cm, a signal regulator, and a signal processor. The device can measure velocity within a range of 3 cm at one time, with a minimum layer thickness of 1 mm, an accuracy of ±1 mm/s, and a sampling frequency of 100 Hz. In the experiment, 3000 velocity samples were collected at one time. The correlation and SNR of the sample data are less than 90% and 30 dB respectively, and the suspected peak value is removed by phase space threshold method [5]. The topographic measurement instrument used was a RIEGL VZ400 laser scanner with a maximum scanning distance of 600 m and a single-point scanning accuracy of 2 mm at 100 m. The instrument had good applicability in measuring moving bed experiments [6].

# Results and Discussion

## Velocity distribution

The depth-averaged velocity is calculated by the following formula:



where,  is the depth-averaged velocity. *H* is water depth;  and  are longitudinal and transverse velocity.

Figure 2 shows the velocity distribution near spur dike. The approaching flow forms a backflow at the inner side of the upstream dam wing, with a low velocity. Due to the contraction of the flow section, the velocity near the dam head increases, and the flow streamline deflects, resulting in a large transverse velocity; In addition, a large range of low velocity recirculation zone was formed at the inner side of the dam wing downstream of the spur dike.

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| Fig.2 Depth-averaged velocity distribution |

Fig. 3 is the vertical velocity distribution of the three velocity directions of the test line ( S30.5, *n* = 0.14 ). It can be seen that the vertical velocity distribution of the three directions presents a S-type distribution, which is significantly different from the logarithmic distribution law of the vertical velocity distribution of the simple open channel, indicating that the vertical velocity distribution is significantly affected by the spur dike, the bend circulation and the riverbed topography.



Fig.3 Velocity distribution of test line (S30.5, *n* = 0.14)

## Relative turbulence intensity

Turbulence intensity is the root mean square of fluctuating velocity. The relative turbulence intensity is calculated according to the following formula :



where,  is the fluctuating velocity (). is the average velocity of approaching flow section，0.297 m/s。

Figure 4 is the longitudinal turbulence intensity distribution of upstream and downstream sections of spur dike. The flow of S29-S31 section is affected by bend circulation, riverbed topography and spur dike. The ratio of radius of curvature to width of flume *R*c/*W* = 7 shows that flume bending has little effect on flow. At the same time, it can be seen from figure 4 that the terrain difference of each section from S29 to S31 is limited, and the spur dike has a significant impact on the flow ( see figure 2 ), so the existence of spur dike is the main factor affecting the flow of S29-S31 section. The S29 section is located in the upstream side of the spur dike. Overall, the transverse turbulence intensity of the S29 section at the bottom of the riverbed is large and gradually decreases from the riverbed to the water surface, which is basically consistent with the distribution law of the turbulence intensity of the typical section of the simple open channel. However, there is a layer of area with small turbulence intensity on the riverbed surface, because there is a viscous bottom at the bottom of the riverbed, and the flow pulsation in this area is inhibited. The turbulence intensity of the flow on the concave bank side ( 0 < *n* < 0.3 ) of section S29 is greater than that on the convex bank side ( 0.3 < *n* < 0.6 ), which is related to the mainstream bias to the concave bank under the action of the bend circulation in this region.

Compared with section S29, the turbulence intensity distribution of section S29.5-S31 changed obviously. The maximum value of vertical turbulence intensity near the dike wing no longer appeared at the bottom of the flow, but appeared in the middle area of the flow. This is mainly due to the action of spur dikes and other causes of vertical velocity redistribution at the dike wing ( Figure 3 ).

The turbulence intensity in the inner side of the dike wing ( 0 < *n* < 0.1 ) is generally reduced due to the formation of backflow and other reasons. However, in the upstream dike wing section ( S29.5 ), the turbulence intensity in the middle and upper parts of the inner side of the dike wing ( 0 < *n* < 0.05, − 0.05 < *z* < 0.2 ) is relatively large, which is mainly due to the deflection of the high-velocity inflow line and the flow pattern disorder. The turbulence intensity outside the dike wing ( 0.1 < *n* < 0.3 ) increases significantly, which is related to the narrow flow and the increase of velocity at the dike head ( Fig. 2 ).

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| (a) Section S29 | (b) Section S29.5 |
| (c) Section S30.5 | (d) Section S31 |
| Fig.4 Longitudinal turbulence intensity | |

Figure 5 is the transverse turbulence intensity distribution of S29-S31 section, and the distribution law of each section is basically consistent with the longitudinal turbulence intensity. In the S29 section, the distribution law is different from the longitudinal turbulence intensity distribution, and the transverse turbulence intensity of the section is smaller in the range of 0 < *n* < 0.1.

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| (a) Section S29 | (b) Section S29.5 |
| (c) Section S30.5 | (d) Section S31 |
| Fig.5 Transverse turbulence intensity | |

Figure 6 shows the vertical turbulence intensity distribution of S29-S31 section, which is basically consistent with the longitudinal and transverse turbulence intensity distribution. For straight ( or slightly curved ) flume or natural river channel, longitudinal turbulence intensity is usually slightly larger than transverse turbulence intensity, significantly greater than the vertical turbulence intensity [7,8]. In this experiment, under the dual action of spur dike and bend, the transverse flow at the dike wing is significantly enhanced, and the longitudinal turbulence intensity is basically equivalent to the transverse turbulence intensity. Even some sections ( S29 and S29.5 ) are slightly less than the transverse turbulence intensity, and the vertical turbulence intensity of each section is generally less than the transverse and longitudinal turbulence intensity ( see Figs. 4 – 6 ). In addition, it can be seen from the experimental results that the distribution of turbulence intensity has a great correlation with the scouring of riverbed topography. The scour depth in concave bank of S29 section and S29.5 section is bigger, the turbulence intensity is bigger. The scour zone near the dike wing ( 0.1 < *n* < 0.2 ) of S30.5 section and S31 section also corresponds to a larger turbulence intensity.

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| (a) Section S29 | (b) Section S29.5 |
| (c) Section S30.5 | (d) Section S31 |
| Fig.6 Vertical turbulence intensity | |

## Reynolds stress

Reynolds stress is calculated as follows :



where, when *i* is equal to *j*, is the Reynolds positive stress, and its distribution along the vertical line is the same as that of the relative turbulence intensity, so this paper does not study its distribution law. When *i* is not equal to *j,* is Reynolds shear stress.

The shear stress is composed of viscous shear stress and turbulent shear stress ( Reynolds shear stress ). Only the shear stress at the viscous bottom of the riverbed is dominated by viscous shear stress. For the fully developed turbulence flow far from the riverbed, the shear stress is dominated by turbulent shear stress. Reynolds shear stress is the shear stress generated by the mixing of liquid particles between the layers. The magnitude reflects the intensity of momentum exchange between the layers, and the positive and negative represent the direction of shear stress. Fig. 7 shows the Reynolds shear stress distribution of S29 – S31. The change of Reynolds shear stress near riverbed at each section is intense, while the change of Reynolds shear stress is more uniform in the zone far from riverbed. The Reynolds shear stress of each section ( S29-S31 ) is generally positive, but there is a large negative area of Reynolds shear stress near the riverbed outside the dike wing ( 0.15 < *n* < 0.3, -0.1 < *z* < 0 ). The negative zone is larger in the two sections ( S29.5 and S30.5 ) of the dike wing than in the other two sections, indicating that the formation of the negative area is closely related to the action of the spur dike. The extreme value of Reynolds shear stress in each vertical line of section S29 is mainly located near the riverbed. From section S29.5 – S31, it can be seen that due to the influence of spur dike, the extreme value of Reynolds shear stress at the dike wing ( 0.1 < *n* < 0.15 ) is located in the middle of the flume, and even there is a positive and negative alternation of Reynolds shear stress along the vertical line, which is related to the S-shaped distribution of vertical velocity distribution.

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| (a) Section S29 | (b) Section S29.5 |
| (c) Section S30.5 | (d) Section S31 |
| Fig.7 Reynolds shear stress | |

Fig. 8 and Fig. 9 show the distribution of  and  in S29 – S31, reflecting the vertical momentum exchange intensity. The Reynolds shear stress  and  respectively reflect the shear stress caused by the mixing of liquid particles between the upper and lower fluids in the longitudinal and transverse directions, so the extreme value of Reynolds shear stress near the riverbed ( or the value extrapolated to the bed surface ) can be used as the estimated value of the bed shear stress. In the area near the riverbed at the concave bank of section S29 ( 0 < *n* < 0.1 ), the Reynolds shear stress is negative, indicating that the bed shear stress is opposite to the longitudinal direction, which also confirms that this area is a recirculation zone, and the near-bottom velocity is opposite to the longitudinal direction ( Fig. 2 ).

In the section of the dike wing ( S29.5 and S30.5 ), the Reynolds shear stress at the bottom of the inside of the dike wing ( 0 < *n* < 0.1 ) is smaller, and the bed shear stress is also smaller; the Reynolds shear stress at the bottom of the outer dike wing ( 0.1 < *n* < 0.6 ) is large, and the bed shear stress is large, which is consistent with the distribution of velocity. In sections S29 – S31, the maximum value of Reynolds shear stress is mainly distributed at the bottom of the outer dike wing ( 0.1 < *n* < 0.3 ), indicating that a large transverse bed shear stress is formed on this side, which is related to the large transverse velocity generated by the spur dike head. The Reynolds shear stress  near bed is significantly greater than , which is consistent with the longitudinal velocity greater than the transverse velocity. Reynolds shear stress  represents transverse momentum exchange strength.  and  vertical momentum exchange strength. It can be seen from Figs. 7 – 9 that the transverse momentum exchange intensity is basically equivalent to the vertical momentum exchange intensity represented by , which is significantly greater than the vertical momentum exchange intensity represented by .

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| (a) S29断面 | (b) S29.5断面 |
| (c) S30.5断面 | (d) S31断面 |
| Fig.8 Reynolds shear stress | |

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| (a) S29断面 | (b) S29.5断面 |
| (c) S30.5断面 | (d) S31断面 |
| Fig.9 Reynolds shear stress | |

# conclusion

( 1 ) The spur dike greatly changed the distribution of turbulence intensity in the flow field. The turbulence intensity at the dike wing increases significantly, and the maximum vertical turbulence intensity no longer appears near the bed, but in the middle area of flow.

( 2 ) The extreme value of Reynolds shear stress at the spur dike wing is located in the middle of flow, and the value of Reynolds shear stress appears positive and negative alternation along the vertical line of flow depth.

( 3 ) The transverse momentum exchange intensity is basically equivalent to the vertical momentum exchange intensity represented by , which is significantly greater than that represented by .

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