Article no. 34

THE CIVIL ENGINEERING JOURNAL 4-2023

RESEARCH ON THE PROTECTIVE EFFECT OF TWIN-GROYNE ARRANGEMENT ON RIVERBANK

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ABSTRACT

A curved channel with intersecting streams can be easily scoured by incoming flow, and the concave bank is badly damaged. The twin-groyne is a unit of the spur dike group, which can effectively adjust the flow structure and achieve the purpose of bank protection. This study simulates the intersection of river channels through experiments, and compares the influence of twin-groyne on the flow structure and protection of the curve. This research showed that the twin-groyne could effectively adjust and optimize the flow velocity distribution, change the shape of the free water surface of the bend, prevent erosion, and promote silting on the concave bank, and it could provide a scouring and silting effect on the convex bank. When the spacing of twin-groyne was increased to more than four times the body length of the single-groyne (spur dike), the protective effect on the concave bank was weakened, and the scouring and silting effect of the convex bank was reduced. Excessive spacing of the twin-groyne could cause local erosion damage to the concave bank. When the distance exceeded the theoretical optimum, it was equivalent to the effect of single-groyne. With the increase in the submergence degree of groynes, the velocity of the concave bank decreased first and then increased, while the velocity of convex bank decreased continuously. The protective effect of a non-submerged twin-groyne with a dam spacing of four times the body length of the single-groyne was better than that of other conditions, and it is recommended to be used in practice.

KEYWORDS

Erosion prevention, Hydraulics, Scour, Spur dike, Twin-groyne

INTRODUCTION

For a curved channel that intersects with branches, the flow patterns and hydraulic conditions are more complex than those of a straight channel or a channel with a single bend. Under the same flow rate, concave bank erosion and damage are severe. Convex bank siltation and the narrowness of the channel further aggravate the damage of the concave bank.

Riverbed evolution is the result of the interaction between water flow and riverbed. A certain riverbed morphology and composition determines the flow condition suitable for it, and a certain flow condition makes the riverbed morphology and riverbed composition produce a certain riverbed evolution suitable for it. The river conditions in nature are complex and diverse, and the complexity of flow patterns and hydraulic conditions of different types of rivers is often quite different. For example, curved rivers are more complex than straight rivers, and curved rivers with confluence of

DOI 10.14311/CEJ.2023.04.0034

tributaries are more complex than single bends. Generally, under the same conditions, the erosion damage of concave banks in curved river channels will be more serious, and the siltation of the convex bank narrows the river channel, which will further aggravate the damage of the concave bank, resulting in the acceleration of the evolution rate of the river channel in the unfavorable direction. As a common hydraulic structure of waterway regulation, spur dikes are widely used in river control engineering [1]. In a revetment project, the main function of spur dikes is to change the form of the original riverbed cross-section and adjust the surrounding flow structure to protect the riverbank from being scoured directly by incoming flow, resulting in brush damage [2]. For different types of rivers, different spur dikes arrangements are needed to achieve good protection effects. Generally speaking, the joint action of simultaneous spur dikes is usually used in engineering practice. The number and spacing of spur dikes will directly affect the engineering effect and cost, so it is of great significance to study the flow of spur dikes.

A twin-groyne is a combination of two independent spur dikes. The reasonable arrangement of a twin-groyne directly influences the effect of a waterway regulation project [3][4]. The spacing between two spur dikes and the submergence degree of groyne are two important parameters to describe the function of the twin-groyne. The spur dikes cannot cooperate with each other when the spacing is too large, and the purpose of river regulation cannot be achieved. Meanwhile, if the spacing is too small and the number of spur dikes increases, the quantity and cost of materials used in engineering will increase accordingly. The submergence degree of groyne is the ratio of the water depth to the height of the spur dikes. With the change of the submergence degree of groyne, the overflow of the dam top and the lifting action of the dam head will also change; so, the protective effect on the riverbank will also change accordingly [5]. Pandey et al. focused on experimentally assessing the temporal variation of the scour depth around a vertical wall spur dike and identifying the parameters that most influenced the spur dike performance for a channel bed surface composed of sand-gravel mixtures [6].

At present, there are many research results on the shape and pick angle of spur dikes. Vaghefi et al. studied the water flow near the T-type spur dike by numerical simulation, and analyzed the supporting structures upstream of several T-type spur dikes with different wing lengths [7]. Vaghefi et al. showed the flow patterns of 90° oblique t-shaped vertical breakwaters in repulsive, attractive and vertical positions. The numerical results show that with the increase of the angle of the straight dike, the size of the vortex downstream of the straight dike decreases [8]. Bahrami-Yarahmadi et al. studied the scour patterns formed around triangular spur dikes under different hydraulic conditions, and compared these patterns with the scour patterns of ordinary types of spur dikes (rectangular spur dikes) [9]. Haider et al. studied the turbulence and flow characteristics around the straight dike in the open channel. The results show that the permeable straight dike with pore angle is an ideal choice to protect the tip of the straight dike, the river bank and the aquatic habitat in extreme floods. It also reduces reattachment length and roughness coefficient [10].

Gu et al. quantitatively studied the influence of the spacing threshold of non-submerged double spur dikes on the spacing threshold of non-submerged double spur dikes arranged orthogonally on the same side in a straight rectangular river by combining numerical research and experimental measurement [11]. Jiao et al. studied the influence of different spur dike lengths and riverbank elevation differences on hydraulic power through physical model experiments [12]. They found that the difference of riverbank elevation is the decisive factor of lateral water and sediment transport.

Shampa et al. found that the high-permeability spur dike group could reduce the longitudinal velocity and turbulence intensity along the channel and increase the transverse flow [13]. A staggered arrangement of the pile grid in the spur dike group could reduce the shear stress of the riverbed while improving the flow pattern in the turbulent area. Sharma et al. performed a study on the flow characteristics behind the spur dike of a curved river [14]. Kiani et al. evaluated the effect of the relative distance between two spur dikes in the bend on the scour using a laboratory Plexiglas flume with a rectangular section and a 180° bend [15]. They found that there was a direct relationship between the maximum relative depth of the scour and the relative length of the spur dikes, the relative distance between the spur dikes, and the Froude number. By increasing the relative distance, relative length, and Froude number, the maximum relative depth of the scour at the noses of the spur dikes increased.

Duan used a microacoustic Doppler velocimeter to study the three-dimensional turbulent flow field around a spur dike in a planar fixed-bed open channel in the laboratory and found that the maximum bed shear stresses estimated using Reynolds stresses were about three times as large as the mean bed-shear stress of the incoming flow[16]. The studies discussed above mainly examined the influence of the flow field, velocity, and flow behind dams with different spur dike structures in straight and curved river courses. However, there are few related studies on the use of twin-groyne in a curved channel with intersecting streams.

The protective effect of a groyne group can be correlated with a reduction in the magnitude of depth-averaged velocity along the channel bank. Through physical model tests and theoretical analysis, this research examined impermeable solid twin-groynes (double spur dikes). By changing the spacing and submergence degree of the spur dikes, the velocities, water surface line distributions, and water flow patterns near the bend were compared, and the effect of the twin-groyne layout on the protection of a curved channel connected to branches under the same flow rate was explored. The research results have a certain reference value for the selection, optimal arrangement, and rational use of the twin-groynes in waterway regulation and revetment engineering.

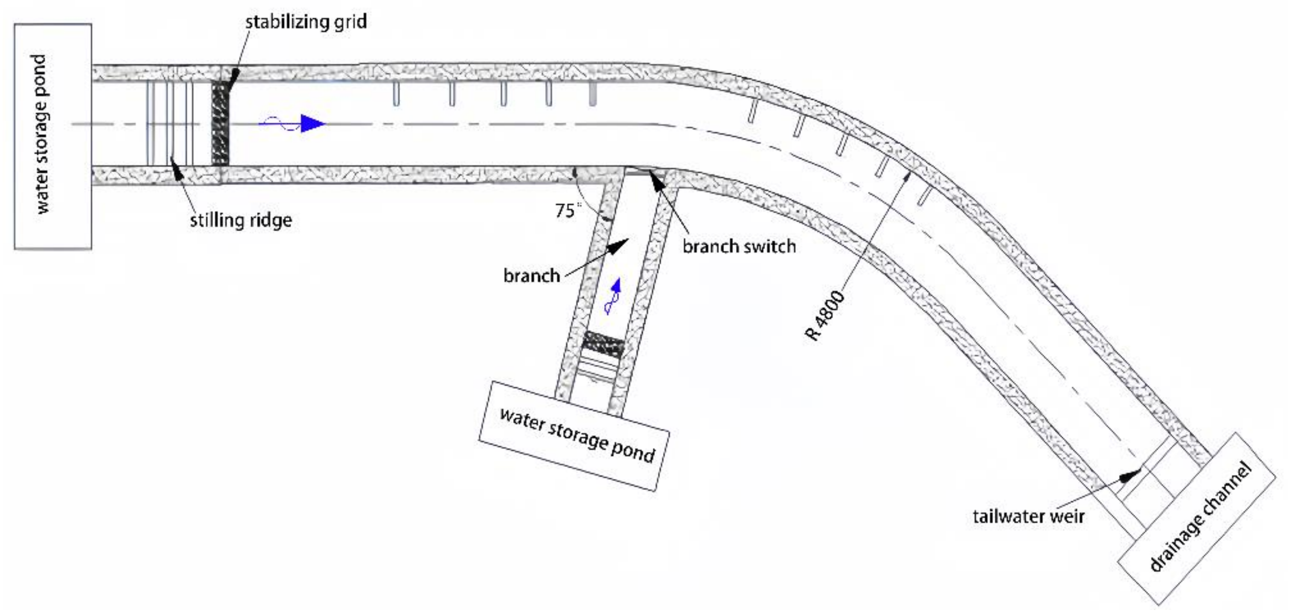
METHODS

Experimental model

The main structure of the model was a 45° curved flume attached to a straight section of branches. The water cross-sections of the main trough and branch trough were rectangular, and the trough depth h was taken as the reference length. The width of the main trough d was $1.5h$, the width of the branch trough was $0.75h$, and the radius of the outer curve R was $10h$. To ensure the stability of the flow conditions and the authenticity of the experimental simulations, the inlet and outlet of the bend were provided with a straight grooved transition section, and the head and tail of the flume were respectively provided with a steady flow grid and a water retaining weir to adjust the water level. The length of the spur dike was $D = 0.25d$, and the spur dikes were arranged on the concave bank of the bend perpendicular to the bank. The experiment used clean water, which was supplied by a pump. The water head was stabilized by a concrete reservoir, and the flow was regulated by a water-retaining gate. The flow depth H was defined as the reference depth in the middle of the inlet of the flume. The U was the mean longitudinal velocity in the inflow straight channel reach without spur dikes. Among them, one side of the experimental model had a branch, and the branch switch controled whether the water flow in the branch can enter the main channel. The “with branch” indicates that the branch switch is in an open state, and the water flow in the branch can flow into the main channel; the “no branch” means that the branch switch is in a closed state, and the water flow in the branch cannot flow into the main channel, as shown in Figure1 (a).

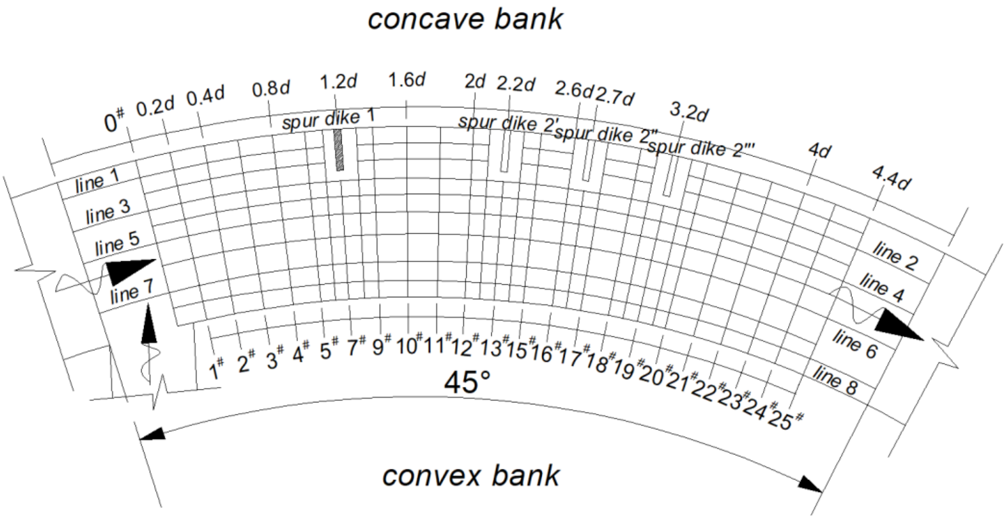
Experimental design

Details of the experimental model are shown in Figure 1 (a)-(e). Under all the working conditions shown in Table 1, the position of spur dike 1 remained unchanged at 1/4 of the river bend. Spur dikes 2’, 2’’, and 2’’’ had spacings of $4D$, $6D$, and $8D$, respectively, between two spur dikes, as shown in Figure 1 (d). The locations of the spur dikes, the locations where the velocity and water level were measured, and the grid of measuring points distributed on the bend section are shown in Figure 1 (a)-(e). Flow measuring sections were set along the outer arc, which contained measurement points with spacings of $0.2d$. Similar sections were established around the groyne dam. A total of 26 measurement sections were established. Each flow measuring section had eight measurement points, which were labelled as lines 1-8, with distances from the concave bank of $0.1d$, $0.2d$, $0.3d$, $0.4d$, $0.5d$, $0.6d$, $0.8d$, and $0.9d$, respectively.

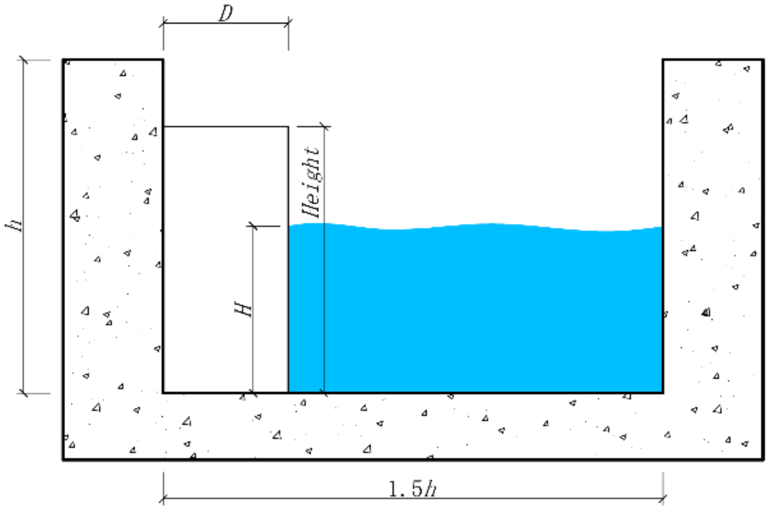


(a) planview of experimental model

(b) overall layout *(c) detailed view to the model section with groynes*



(d) experimental measurement line distribution diagram



(e) diagrammatic cross-section

Fig. 1 - Experimental model

Experimental conditions

The empirically determined spacing of impervious non-submerged twin-groynes is usually 2–4 times the dam length, and the optimal theoretical value of the dam spacing is 9*D*[17]. Based on the empirical values and the optimal theoretical value of the dam spacing, the dam spacing and degree of submergence were varied for comparison experiments. These experiments involved a total of six working conditions, and the characteristics of each experimental condition are shown in Table 1.

The submergence degree of groynes (σ) as follows:

$$\sigma = H / Height$$

It should be noted that in formula and Table 1, the *Height* represented the height of the spur dikes, as shown in Figure 1 (e). Among them, submergence degree of groynes (σ) greater than 100% indicated that the flow depth exceeded the height of the spur dikes.

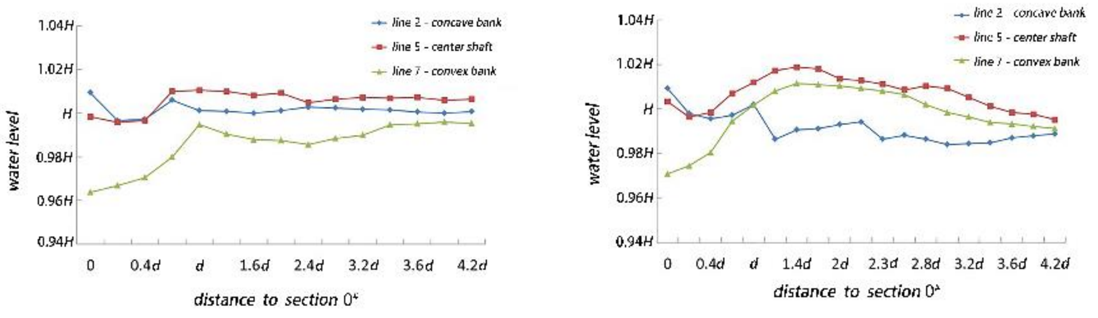
Tab. 1 - Working conditions

Condition	Height	Submergence degree of groynes(σ)	Spacing between two spur dikes
1	-	-	-
2	0.5*h*	100%	4*D*
3	0.4*h*	125%	4*D*
4	0.8*h*	62.5%	4*D*
5	0.8*h*	62.5%	6*D*
6	0.8*h*	62.5%	8*D*

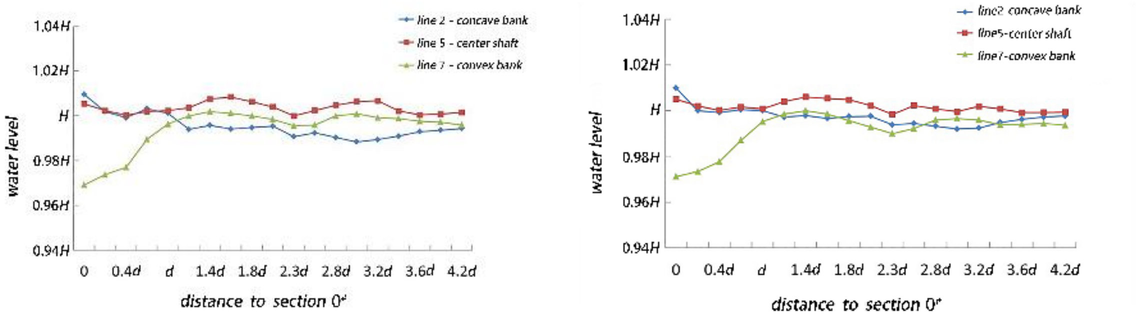
RESULTS AND DISCUSSION

Analysis of influence of arrangement of twin-groyne on river surface line

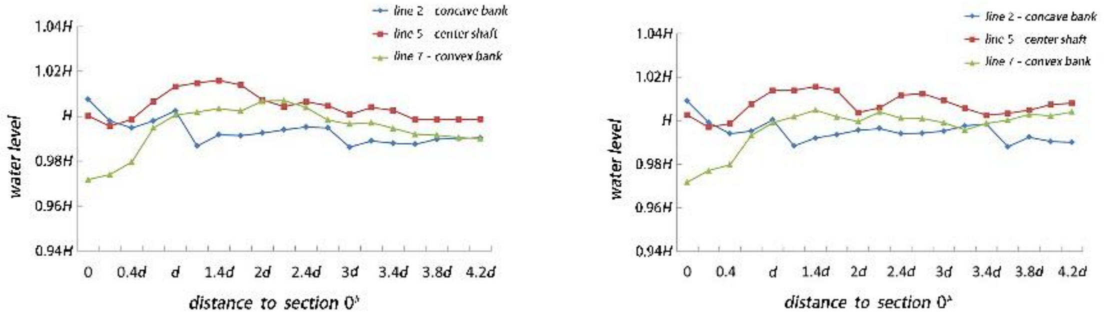
Figure 2 shows the distribution of the longitudinal water surface lines in the curved channel with the twin-groyne and connected branches under the same flow. The velocity measurement method here adopts the three-point method in hydraulics: the velocity measurement points were set at 0.2, 0.6, 0.8 relative water depths below the water surface, and the average or weighted average of the velocity of the three measuring points is the vertical average velocity. The channel flow was affected by the twin-groyne, and the water surface line changed significantly. The water level near the central axis was relatively high, and the highest water level appeared between the spur dikes. The top-thrusting action of the branches caused the water surface line to be inclined to the central axis and the concave bank side. The concave bank of section 0# had the highest water level of the whole measured bend, while the convex bank had the lowest water level, which was mainly caused by the arrangement of the twin-groyne on the concave bank, and the twin-groyne blocked and deflected the water flow. From the characteristics of the water flow itself, the first spur dike blocked the water, causing the upstream water level to rise. The water level along the dam head was higher than the back water level, and the water level near the central axis of the bend and along the convex bank increased significantly. The water level near the head of the spur dike was again elevated due to the high flow velocity in the narrow area of the downstream beam. The water level near the central axis of the bend and along the convex bank increased again. A certain distance after the second dam, the water level slowly decreased and gradually became stable.



(a) condition 1 — with branch *(b) condition 2*



(c) condition 3 *(d) condition 4*

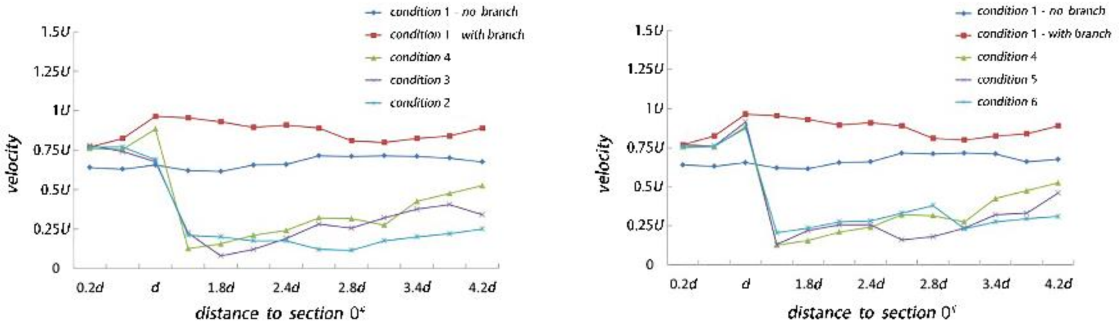


(e) condition 5 *(f) condition 6*

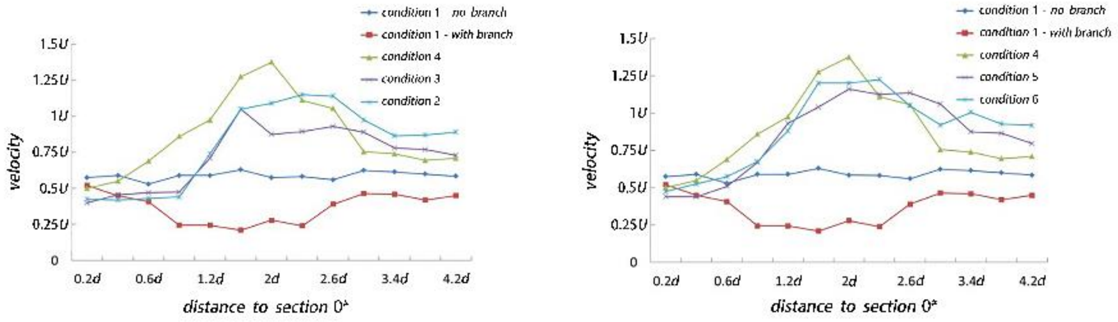
Fig. 2 – Longitudinal water surface line distribution diagram under each working condition

Analysis of influence of arrangement of twin-groyne on velocity of river concave bank and convex bank

The velocity measurement method here adopts the three-point method in hydraulics: the velocity measurement points are set at 0.2, 0.6, 0.8 relative water depths below the water surface, and the average or weighted average of the velocity of the three measuring points is the vertical average velocity. Figure 3 shows the longitudinal velocity distribution of the concave bank (line 2) and convex bank (line 7) under each working condition. It can be observed that the velocity along the concave bank was greater than that along the convex bank after adding a branch for the same flow. Under condition 1, the maximum scouring velocity of the concave bank was 0.2 m/s. After the twin-groyne was installed, the velocity of the concave bank decreased significantly, while the velocity of the opposite bank increased significantly, with a maximum value of 0.28 m/s. The maximum velocity of the concave bank and the minimum velocity of the convex bank were located upstream of the twin-groyne, and the minimum velocity of the concave bank and the maximum velocity of the convex bank occurred between the two spur dikes. Due to the obstruction of the spur dikes, a relatively still area formed behind them. The flow velocity of the dam head increased due to the bunching action of the spur dike. After bypassing the spur dike, the flow deflected to the side without the spur dike and formed a shear flow with a relatively still area between the two spur dikes, resulting in a vortex between the spur dikes.



(a) concave bank



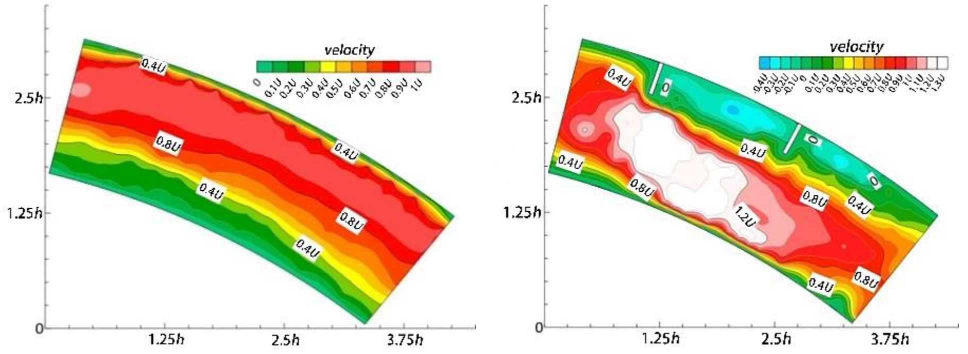
(b) convex bank

Fig. 3 – Comparisons of flow velocities in cross-sections of bending channels

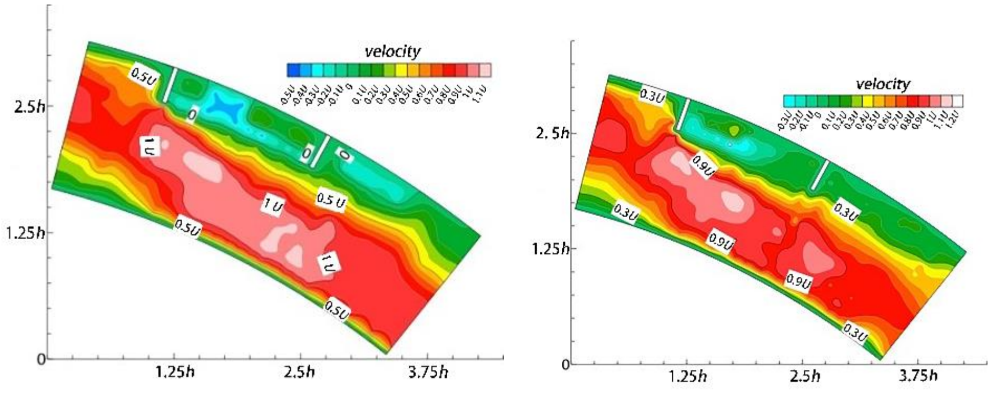
Based on contrastive analysis of Figure 2 and Figure 3, the water level difference in the bend caused the exchange of flow potential energy and kinetic energy, and the water level and flow velocity changed differently along the channel under different twin-groyne arrangements. However, the variation characteristics were generally similar. The twin-groyne obstructed the flow and caused the water level behind the spur dike to decrease. The flow around the dam consumed the kinetic energy of the flow and the velocity behind the spur dike decreased significantly. The narrow flow of the spur dike caused the water level of the central axis and convex bank of the bend to rise, and the water flow area suddenly decreased, thus increasing the flow velocity. A certain distance after spur dike 2, the flow velocity gradually became stable.

Analysis of influence of inundation degree on velocity distribution

Figure 4 shows the velocity distribution of the river channel under different submergence degrees. The distribution of the main flow area of the curve changed from the side near the concave bank to the side near the convex bank after the twin-groyne was added on the concave bank. The velocity of the concave bank decreased, some basins had negative velocities, and the maximum velocity appeared on the opposite side between the two spur dikes. With the increase in the submergence degree of groyne, the flow velocity in the main flow area that was greater than the scour velocity *v* was significantly reduced, and the scour and silting effect was weakened. The area of the negative velocity zone between the two spur dikes and downstream decreased, and the submergence degree of groyne was 125%. The negative velocity zone behind spur dike 2 basically disappeared, which was not conducive to the siltation of the dam field. For working conditions 2 and 3, the flow velocity distribution in the concave bank between the two spur dikes was unstable. The flow velocity of condition 2 on the convex bank side was larger and relatively uniform, and thus, this condition was more conducive to river protection than condition 3. Under condition 4, the maximum negative flow velocity of concave bank was 0.05 m/s, and the flow velocity in the vortex areas between and behind the two spur dikes was small and relatively uniform, which was conducive to the erosion and silting prevention of the concave bank. However, the convex bank side had a large flow rate and a better scouring and silting effect, which was more conducive to the overall river protection than the submerged condition.



(a) condition 1 — with branch (b) condition 4



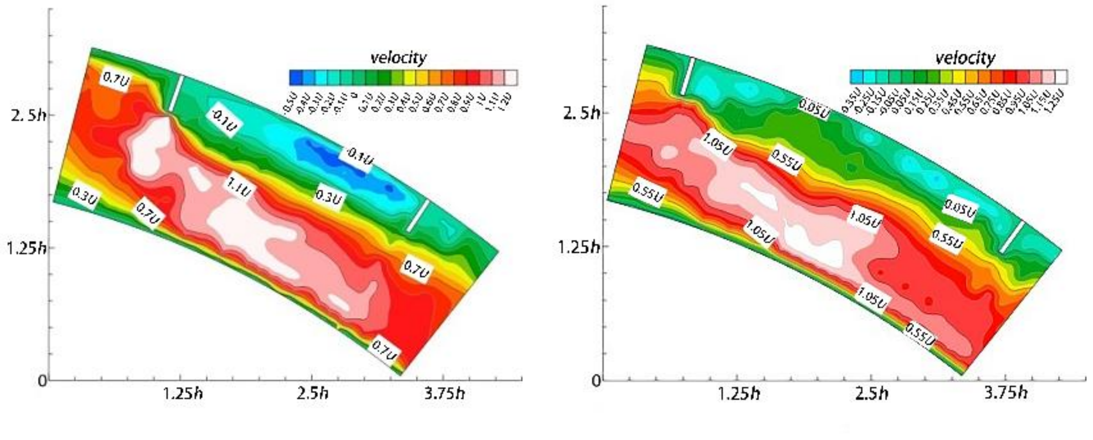
(c) condition 2 (d) condition 3

Fig. 4 – Velocity distribution of the river channel under different submergence degrees

From the perspective of the flow characteristics of the submerged twin-groyne, the water flowing past the dam body was divided into two parts: surface flow and bottom flow, and there was a water separation phenomenon at the top of the dam [2]. Under the same incoming flow, the discharge of the surface water through the dam crest increased with the increase in ΔH ($\Delta H = Height - H$), leading to a decrease in the range of the return area between and behind the two spur dikes. Part of the bottom flow rose over the top of the dam and flowed downstream, and it tended to spread toward the head of the dam, while the other part went around the head and released. The interaction conditions between the surface flow and bottom flow led to the presence of two horizontal and vertical return zones with different rotation directions between and behind the spur dikes, and their interactions consumed a large amount of kinetic energy [6]. When ΔH was small, the bottom flow had significant action around the dam, and the water level changes and velocity distribution were similar to those of the non-submerged twin-groyne. As ΔH increased gradually, the water blocking ability of the double groyne dam bundle weakened, the surface water discharge increased, the convex bank velocity decreased continuously, and the local shore–base erosion and silting effect weakened. The flow velocity of the concave bank changed significantly, the effect of the bottom flow was gradually weakened, the surface flow gradually became dominant, and the flow velocity increased after it decreased to a certain extent, which was not conducive to the protection of the bank.

Analysis of influence of distance between two spur dikes on velocity

Figure 5 shows the velocity distributions for different dam spacings. Based on the comparison of Figure 4 and Figure 5, with the increase in the dam spacing, the velocity distribution in the main flow zone and the vortex zone changed significantly. Under condition 5, the distance between the two spur dikes was 6*D*, and the variation of the longitudinal velocity between the two spur dikes was larger than that under condition 4. The maximum negative velocity in the vortex zone reached 0.1 m/s, which was not conducive to the deposition of sediments in the concave bank. Under condition 6, when the spacing between the two spur dikes reached the theoretical optimal value of 9*D*, the vortex zone between the two spur dikes was disconnected. Currently, the two spur dikes were outside the mutual cover range, and the disconnection position in the return area could easily cause partial scouring damage, which was unfavourable for the protection of the river. For the convex bank, the increase in the dam spacing increased the range of scouring and silting, but the scouring and silting effect was lower in local areas. The flow velocity at the tail area of the convex bank under condition 6 was uneven in the transverse distribution, and the overall scouring and silting effect was weaker than that under condition 4.



(a) condition 5 *(b) condition 6*

Fig. 5 – Velocity distribution diagram with different dam spacings

From the perspective of the flow characteristics of the non-submerged twin-groyne, the first spur dike (spur dike 1) had a strong flow deflection ability, a large flow inertia effect, slow flow velocity recovery across spur dike 1 to the downstream area, and a large scouring range of the flow. The placement of the second spur dike (spur dike 2) weakened the inertial action of the water flowing over it, and the water flow could be diverted to the main channel, which not only reduced the scouring effect on the concave bank but also promoted the scouring and silting effect on the convex bank. If the dam spacing were too large or too small, it would not be conducive to riverbank protection. If the dam spacing were too large, it would be equivalent to the two spur dikes playing separate roles. If the dam spacing were too small, the full effect of spur dike 2 would not be realized. Under each experimental condition, when the spacing of the two spur dikes was 4*D*, it had an ideal effect on the river protection.

CONCLUSIONS

Twin-groynes with different dam spacings and submergence degrees were established on the concave bank of a curved river channel with intersecting branches. Through comparative analysis of the effect of the twin-groynes on the water level, velocity change, and flow characteristics, the protective effects of different arrangements on the curved river bank were determined.

(1) The water blocking of the twin-groyne led to water free surface and velocity changes in the curved channel. A twin-groyne arranged in the curved channel could prevent erosion, promote silting on the concave bank, and provide a scouring and silting effect on the convex bank. The differences of the water level in the bend led to the exchange of potential energy and kinetic energy of the flow. When the twin-groyne layout was changed under the same inlet flow, the water level and velocity changed differently along the channel, but the overall variation characteristics were similar.

(2) The non-submerged twin-groyne had a more significant effect on the flow structure and velocity distribution of the bend. When the spacing of twin-groyne was greater than 4*D*, the velocity distribution of the concave bank was unstable, and the scouring and silting effect of the convex bank was reduced. When the distance was greater than the theoretical optimum, it was equivalent to two spur dikes playing separate roles, the concave bank of the local damage was severe, and the configuration was not conducive to river protection.

(3) The water level variations of the bend were smaller than those of the channel with a non-submerged twin-groyne. With the increase in the submergence degree of groyne, the overflow effect of the dam crest was strengthened, the water blocking and water flow deflection effects of the dam head were weakened, the velocity of the concave bank decreased first and then increased, the velocity of the convex bank decreased continuously, the velocity of the convex bank gradually approached the condition with no dam, and the overall protective effect of the river was weakened.

(4) The non-submerged twin-groyne with a spacing of 4*D* allowed the full effect of the twin-groyne on controlling water potential and deflecting water flow, and the surface flow pattern of the bend was stable, which had a better protective effect on the riverbank compared to other spacings.

ACKNOWLEDGEMENTS

This research was supported by the Department of Science and Technology of Fujian Province (grant number: 2023J011046), the Education Department of Fujian Province (grant number: JAT220379), Innovation and entrepreneurship training program for college students (grant number: S202310397060), Wuyi University (grant number: YJ202216), Sichuan University (grant number: SKHL2117), and Nanping Science and Technology Bureau Resources Chemical Industry Science and Technology Innovation Joint Funding Project (grant number: N2021Z008). The authors declared that they have no conflicts of interest to this research.

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