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Development and Application of a New Auxiliary Diversion Structure for Mountain Ship Lock: A Case Study of Wuqiangxi Lock in China

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Abstract: Ship locks on mountain rivers usually experience difficulties owing to harsh flow conditions such as strong oblique flow and backflow, which significantly affect navigation safety and efficiency. To improve navigation conditions, a structural measure involving pile-foundation permeable dislocation-type diversion vanes, a new type of diversion structure, is proposed by analyzing the features and working mechanisms of the existing diversion structures. Based on a typical mountain ship lock—the Wuqiangxi Lock—model tests including various schemes were conducted to investigate the effects of the new diversion structure. The new diversion structure obtained better results than other existing diversion structures, particularly in terms of reducing the transverse flow velocity extremums. By controlling the diversion volume, stabilizing the deflection angle, and dissipating the flow energy, the new diversion structure could effectively weaken the oblique flow intensity at the entrance area. In addition, comparisons of its cost efficiency with that of a hybrid measure combining riverbed dredging and diversion piers was carried out. Moreover, its performance of practical application in the reconstruction project of the Wuqiangxi Lock was demonstrated. Based on the investigation presented herein, the new diversion structure is a promising approach for improving flow conditions at the entrance area of the lock approach.

Keywords: diversion structure; approach channel; navigation conditions; mountain rapids reaches; Wuqiangxi Lock; model test

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1. Introduction

The lock approach entrance area is the link between the ship lock and the river, and it also acts as the transition zone from quasi-static flow in the approach channel to dynamic flow in the river. The flow conditions in this area directly affect the safety of ships entering and leaving [1–4]. For the upstream entrance, the river cross-section shrinks, and for the downstream entrance, the river cross-section widens. Therefore, the water flow in the river is contracted or expanded. Owing to the influences of special boundary conditions, there often exists a strong oblique flow or backflow at the lock approach entrance area. These unfavorable flow patterns pose great risks to navigation safety; therefore, it is necessary to take structural or non-structural measures to improve the navigation conditions. One of the main structural measures is the construction of an auxiliary diversion structure [5–8]. Currently, the most commonly used auxiliary diversion structures include navigation wall, diversion piers, and partition dykes.

The navigation wall (i.e., guide wall) directs the water of the river side to flow parallel to it; thus, the water fluctuation in the approach channel can be effectively weakened. This measure has been widely used in engineering practices [9,10] such as the Lehmen Lock on the Moselle River and Rehlingen Lock on the Saar River in Germany; Belleville Lock on the Ohio River, Ozark Lock on the Arkansas River, and Columbia Lock on the Ouachita River in the United States [11]; and Xintan Lock on the Qijiang River [12], Fengdongzi Lock on the Qujiang River [13], Xinzheng Lock on the Jialing River [14], Guigang Lock on Xijiang River [15], Naji Lock on the You River [16], and Tugutang Lock on Xiangjiang River in China [17].

Diversion piers, which block the flow by the piers and divert the flow through the gaps of the piers, can effectively alleviate the oblique flow, reduce the backflow range and the deflection angle of flow at the entrance area, as well as weaken the intensity of cross-flow and backflow. This measure has been adopted more widely in China [18], such as for the Yuliang Lock on the You River, Dadingzishan Lock on the Songhua River [19], Dayuandu Lock [20], and Zhuzhou Locks and Changsha Locks [21] on the Xiangjiang River.

Partition dykes are commonly used in ship locks in mountainous areas [22]. The straight section of mountain river is relatively short; thus, the lock approach is generally arranged in a curved or slightly curved section where the angle between the mainstem of the river and the navigation route tends to be large, and the oblique flow at the lock approach entrance area is relatively strong. The upper portions of the partition dykes are used to block the flow, and the lower portions are used to divert the flow to effectively control the amount of diverging flow into the approach channel entrance area and limit the surface flow, thereby weakening the intensity of the surface oblique flow. This measure has been adopted successfully in various cases, including in the Yinpan Lock on the Wujiang River [23] and Yakou Lock on the Han River [24].

For the ship lock projects in the narrow and rapid river reaches in mountainous areas, there is a great difference in water level between upstream and downstream of hydro-junctions, and the river cross-sections are narrow, resulting in odious flow conditions. Owing to the constraints induced by the complex river regime and boundary conditions, the layout of the lock approach channel is constrained. When combined with the influences of the operating conditions of the constructed sluice gates, power stations, and other structures, the navigation conditions of the ship locks deteriorate, resulting in a low guaranteed rate of navigation that is extremely difficult to improve. However, most of the above-mentioned measures for improving navigation conditions can hardly take effects in the more severe navigable flow conditions under such multi-factorial constraints [25,26], and new diversion structures need to be developed.

The Wuqiangxi Lock is a typical mountain lock located in a narrow and fast-flowing river section, which experiences extremely harsh flow conditions. The obstruction in the downstream lock approach channel entrance has always been a bottleneck that restricts the operating efficiency of the Yuan River high-grade inland waterway. In this study, based on the ship lock renovation project of the Wuqiangxi hydro-junction, we propose a new type of diversion structure, the pile-foundation permeable dislocation-type diversion vanes (also referred to as the diversion vanes). Its effects on improving navigation condition were investigated by model tests, and its practical application research on the Wuqiangxi Lock was carried out. The new auxiliary diversion structure has the advantages of effectively suppressing oblique flow, stable structure, and easy maintenance, providing a novel and effective approach to alleviating the problem of oblique flow at the lock-approach entrance area.

2. Proposal of a New Diversion Structure

2.1. Analysis of Existing Diversion Structures

Navigation wall, diversion piers, and partition dykes have similarities and differences in structural composition, function, and working principles. The schematic of the three types is shown in Figure 1.

The navigation wall (as shown in Figure 1a) is composed of a contiguous solid wall that connects with the head pier of the ship lock approach. Its basic structural parameters are total length (L) and angle with the main flow direction of river (i.e., attack angle θ). It completely separates the flows from its left and right sides. The approach channel covered by the navigation wall is not directly affected by the oblique flow on the river side, but it may be affected by the backflow caused by the sudden expansion or contraction of flow downstream or upstream. The approach entrance area is directly affected by both oblique flow and backflow. The diversion piers (as shown in Figure 1b) are composed of a series of discrete piers or walls, and it can be seen as a broken navigation wall at a certain distance. Water on the river side can partially flow into the channel through the voids; therefore, the oblique flow intensity downstream could be reduced. The reduction effect depends on the ratio of the pier length to the void length. For diversion piers, the length of the unit (composed of a void and a pier) and the pier are two other important structural parameters besides the total length and attack angle. The partition dykes (Figure 1c) evolve from the diversion pier. Compared to the diversion piers, the upper portion of its voids is blocked, and water on the river side can only enter the channel side through the lower portions of its voids (i.e., clearance). In such structural type, the partition dykes can effectively prevent oblique flow of river side directly into the channel from the surface so as to avoid strong oblique flow intensity in approach channel when diverging flow from the river side. The clearance height (h) is another important structural parameter of partition dykes.

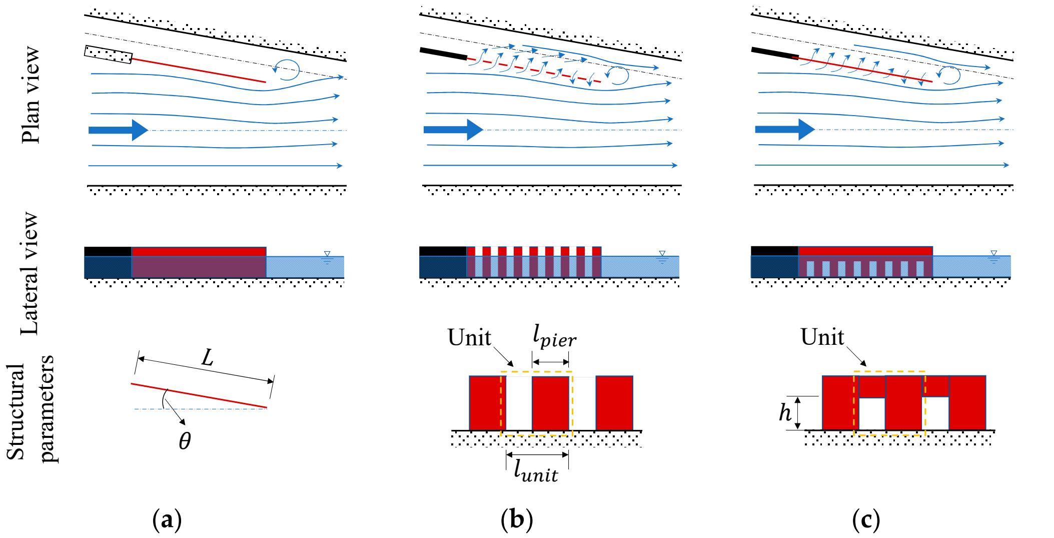


Figure 1. Schematic of three types of existing diversion structures. (**a**) Navigation wall, (**b**) diversion piers, and (**c**) partition dykes.

The existing diversion structures can work well in cases where flow conditions are not severe; however, they fail in cases where flow conditions are extremely terrible, such as in mountain rivers with strong oblique flow. Many studies and engineering practices have shown that existing diversion structures do not work in such situations. The features of existing diversion structures are as follows: (1) navigation wall—in its range of action, it can shield the influence of water flow on the river side to the greatest extent, but it is difficult to prevent the effects of sudden flow expansion and contraction and cannot reduce the oblique flow intensity at the downstream outlet; (2) diversion piers—they can divert the oblique flow as well as reduce the backflow range and deflection angle of the flow in the entrance area; however, they cannot effectively control the diverging flow that enters the entrance area, thus exhibiting limited effect in terms of weakening the strength of the oblique flow; (3) partition dykes—they can control the diverging flow into the entrance area and weaken the cross-flow on the surface of the entrance area; however, they cannot control the angle between the diversion and the channel. Moreover, at the flow rate of a flood, undesirable flow patterns such as whirlpools and bubbling water easily form in the entrance area. Each of the existing diversion structures has its unique advantages and limitations that restricts their general application.

2.2. New Type of Diversion Structure

Based on the limitations of the existing technology in improving the flow conditions at the entrance area of the approach channel, we propose a new type of diversion structure for ship locks experiencing strong oblique flow conditions. The structure fully combines the advantages of diversion piers and the partition dykes, and integrates the functions of flow blocking and flow diverging. By controlling the diverging flow and the angle between the diverging flow and the navigation centerline simultaneously, not only is it possible to weaken the transverse flow on the surface of the entrance area, but it is also possible to suppress flow patterns that are unfavorable for ship navigation, such as vortices and bubbling swirling water. The structure is referred to as a pile-foundation permeable dislocation-type diversion vanes; hereafter, it is referred to as diversion vanes, according to its physical characteristics and functional properties.

2.2.1. Structural Features

The diversion vanes consist of bottom pile foundations, bearing platforms, upper connecting piers, and inserted vanes. Its basic structure is shown in Figures 2 and 3. The angle between the inserted vane plane and navigation centerline is defined as the inserted vane deflection angle, and the width of the lateral gap between adjacent inserted vanes is defined as the inserted vane gap. In addition to the above-mentioned structural parameters (i.e., total length, attack angle, unit length, pier length, and clearance height), a total of seven parameters was used to characterize the structural parameters of the diversion vanes. The size of each parameter is based on the optimal navigable flow conditions at the entrance area of the approach channel, which are determined by the planned layout of the approach channel entrance area, topographic characteristics of the riverbed downstream of the dam, and stream characteristics of the river flow.

The mechanisms utilized by the diversion vanes to improve the navigable flow conditions at the approach channel entrance area are as follows: in the vertical direction, the clearance below the inserted vanes is used to divert the oblique flow so as to lead partial flow into the approach channel and reduce the oblique flow intensity on the river side at the same time. In the horizontal direction, the inserted vanes and gaps between them are used to guide the surface oblique flow into the approach channel along the orientation of vanes instead of the original direction. In this way, the transverse velocity as well as the transverse thrust and the torque of the flow on the vessels can be reduced. In addition, the flow through the gaps between inserted vanes can offset the upwelling flow resulting from the vertical expansion of water flow through the lower clearance.

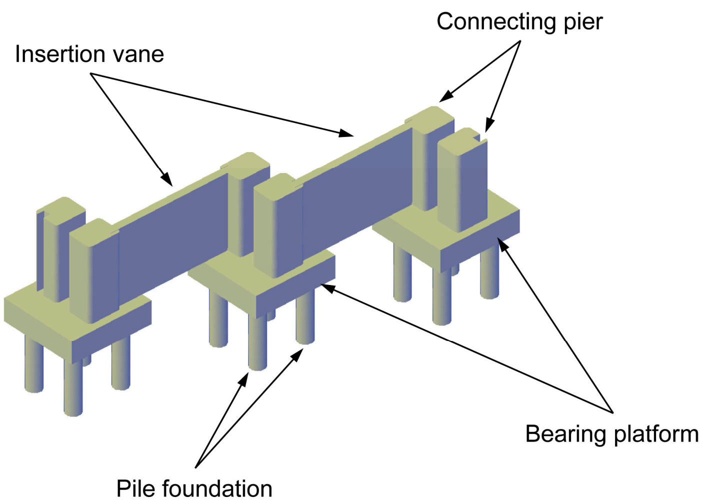
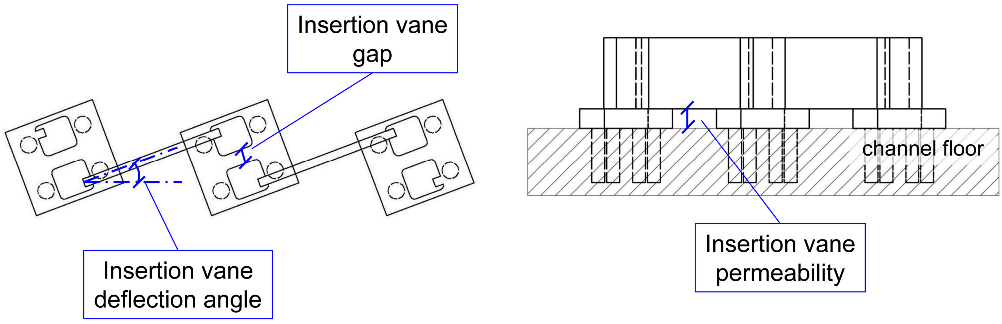


Figure 2. Schematic of the diversion vanes structure.



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

Figure 3. Schematic of the diversion vanes structural parameters. (**a**) Plan view; (**b**) side view.

2.2.2. Preliminary Design Principles

According to the model test results in the early stage, the navigation condition of the approach channel entrance area is closely related to the values of the structural parameters of the diversion vanes. The following principles are referenced when designing the structural parameters of the diversion vanes: ① The direction of the diversion vanes layout is parallel to the approach channel navigation centerline; ② the length of the diversion vanes layout is equal to the length of the approach channel entrance area; ③ the clearance height below the inserted vanes is considered to be 0.75 times the minimum navigable water depth at the entrance area of the approach channel; ④ the gap between the inserted vanes is considered to be 0.5 times the clearance height; and ⑤ the inserted vane deflection angle is considered to be between 10° and 20°.

3. Experiments

The effect of the diversion structure on improving the navigation condition of lock approach entrance area was investigated based on the Wuqiangxi Lock, which is a typical ship lock severely affected by strong oblique flow. The following describes in detail the profile of the Wuqiangxi hydro-junction, model design, test conditions, and evaluation methods for performance on improving navigation conditions.

3.1. Project Overview

The Wuqiangxi hydro-junction is located on the mainstem of the Yuan River, which runs through south-central China and offers a combination of benefits such as power generation, flood control, and navigation. Its location and layout are illustrated in Figure 4. With a reservoir capacity of 4.2 billion m^3 and an installed capacity of 1200 MW, it is one of the largest hydropower stations in China, with a capacity of more than one million kilowatts. The hydro-junction is composed of a concrete gravity dam, power station on the right bank, dam spillway, and three-step continuous ship lock on the left bank. The total water level difference that the ship lock must overcome is 60.9 m. The downstream approach channel of the ship lock is connected to the river through the entrance area, and approximately 1 km downstream of it is the Lanziwan Bridge.

The Wuqiangxi Lock was officially opened for operation in February 1995. However, as the hydro-junction is located on a typical river reach in a mountainous area, the river channel is narrow and deep, and the water-level variation is large. The navigable flow conditions of the downstream approach channel entrance area of the ship lock are poor owing to the effects of the river boundary conditions, operating conditions, and the existing project layout. The actual maximum navigable flow rate is considerably lower than the designed maximum navigable flow rate. To change the unfavorable navigation situation, it is necessary to upgrade the Wuqiangxi Lock, and the design of the diversion structure becomes a key problem.

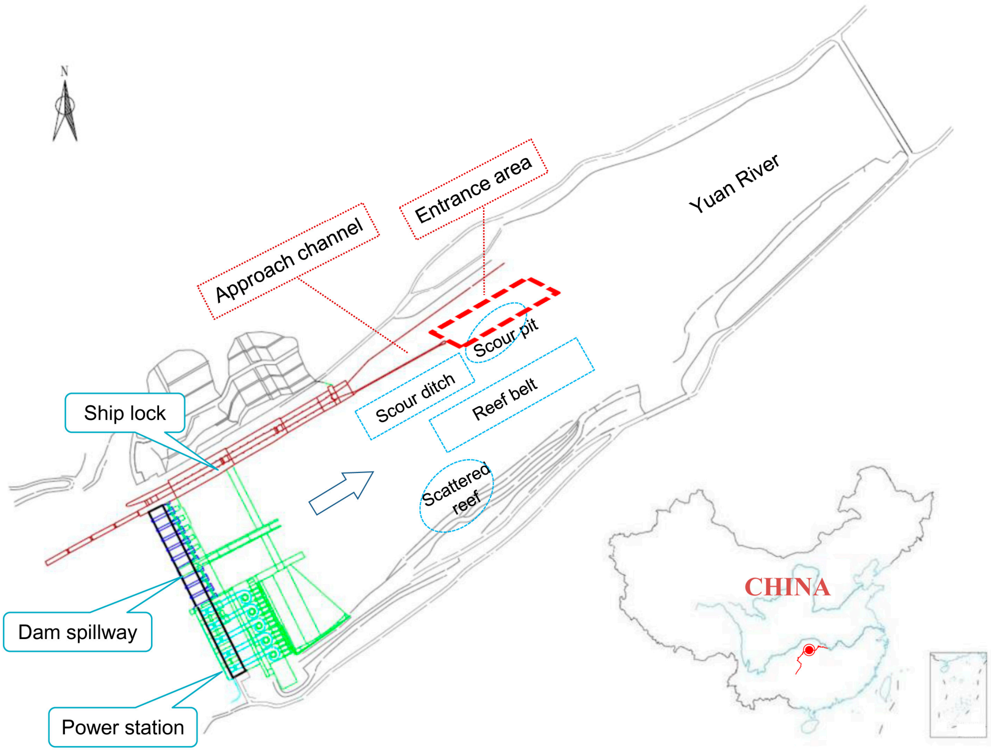


Figure 4. Location and layout of the Wuqiangxi hydro-junction.

3.2. Model Design and Validation

The physical model (1:100 scale) was designed in accordance with the gravitational similarity criterion. The length of the simulated prototype river channel is approximately 5.2 km, of which approximately 1.2 km is upstream of the dam site, and approximately 4.0 km is downstream of the dam site. The prototype width of the model is 400–900 m. The prototype and model image of the Wuqiangxi hydro-junction are shown in Figure 5.

Figure 5. Image of the Wuqiangxi hydro-junction. (**a**) Prototype; (**b**) model.

In the experiments, the river flow field was observed using a flow-field real-time measurement system (VDMS, see Figure 6), which can realize the large-scale synchronous measurement of non-contact surface flow field using a digital camera and particle tracking measurement technology, and the measurement error was less than 5%. Velocities in several key locations were measured by the Nortek Vectrino II profiler, a widely used acoustic doppler current meter with a measurement accuracy of ±0.5% or ±1 mm/s. The water level was measured by an ultrasonic level transmitter with a measurement accuracy of ±0.1 mm and a sampling frequency of 40 Hz.

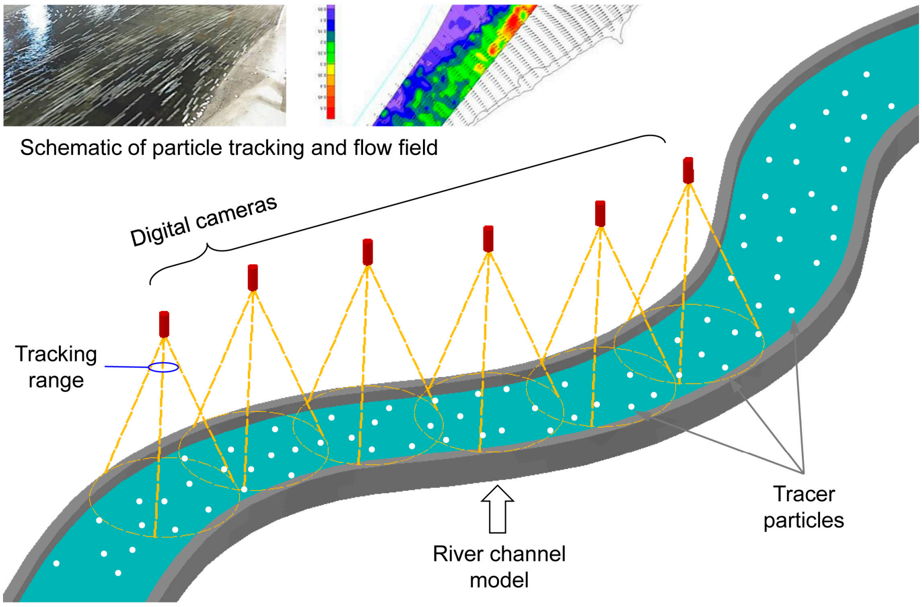


Figure 6. Schematic of the flow-field real-time measurement system (VDMS).

The physical model was verified using the on-site measured water levels and cross-section flow velocities downstream of the dam under typical flow rates. The water levels in the model were basically consistent with those in the prototype, and the water level error was within ±0.1 m (as shown in Figure 7), which is relatively small compared with the water depth. The flow velocity distribution in the model section was also consistent with that in the prototype; thus, the physical model could meet the requirements of similar resistance and flow motion.

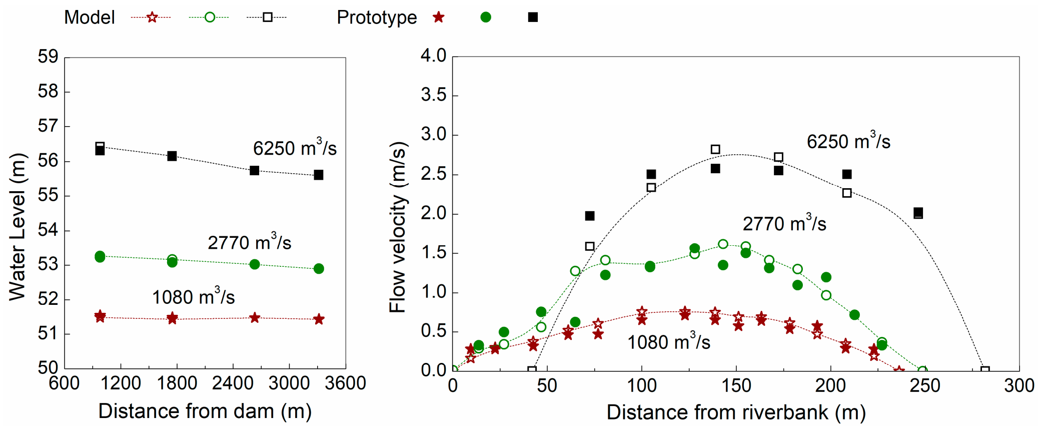


Figure 7. Comparison of water level and cross-section flow velocity between the prototype and the model.

3.3. Experimental Conditions

The model test experimental conditions are listed in Table 1, and the water surface curves downstream of the dam at different flow rates are shown in Figure 8. The flow rate varies from the minimum navigable discharge rate to the maximum discharge rate. As the flow rate increases, the water level gradually rises, and the water surface gradient also gradually increases. The water surface gradients at flow rates of 2500 and 7800 m^3/s are 0.2‰ and 0.47‰, respectively.

Three types of tests were conducted: (a) under original condition (there is a large and deep scour pit near the head of the navigation wall, as shown in Figure 4); (b) under improved conditions of different diversion structures; and (c) under riverbed-dredging condition and diversion piers. For the last two types of tests, the scour pits were backfilled.

Table 1. Test operating conditions.

No.	Flow Rate (m^3/s)	Discharge Mode
1	390 (minimum navigable flow rate)	Power station only
2	1500	Power station only
3	2500 (average flow rate over the years)	Power station only
4	3500	Power station + dam spillway
5	5000	Power station + dam spillway
6	6500	Power station + dam spillway
7	7800 (maximum navigable flow rate)	Power station + dam spillway

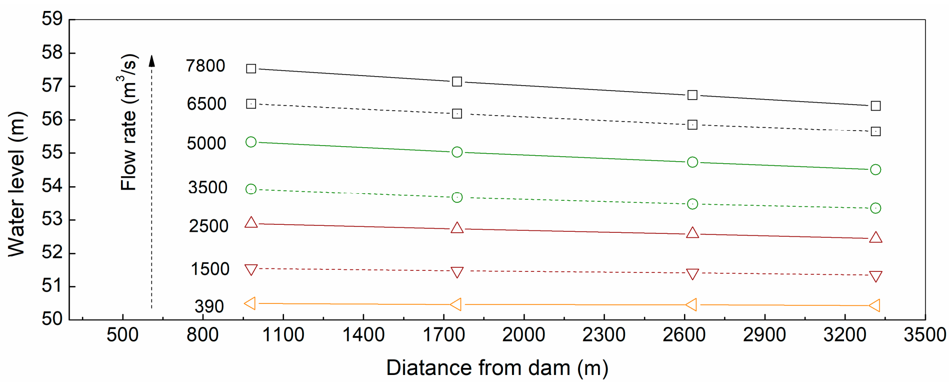


Figure 8. Water surface curve distribution downstream of the dam at different flow rates.

3.4. Evaluation Methods

Usually, the navigable flow conditions in the entrance area of the lock approach channel are characterized by the extreme values of the flow velocity in each direction on the water surface. For the project case used in this study, the designed maximum ship tonnage of the Wuqiangxi Lock is 500 t, and the corresponding lock grade is Class IV. According to the "Navigation Standard of Inland Waterway (GB50139-2014)" [27] that was promulgated in China, to ensure the navigation safety of ships in and out of the lock, when the ship lock is classified as Class IV, the longitudinal flow velocity parallel to the navigation line, transverse flow velocity perpendicular to the navigation line, and backflow velocity of the water surface should not be greater than 2.0 m/s, 0.3 m/s, and 0.4 m/s, respectively. In the model tests, these values were used as reference values to determine whether the improved navigation conditions meet the requirements and gain significant effects.

4. Results and Discussions

4.1. Flow Conditions under Current Situation

The flow-field distribution under typical flow rate at the entrance area of the approach channel and the velocity extremums of surface flow at different flow rates are shown in Figure 9.

Greater flow rates result in greater velocity extremums of surface flow in entrance area and more severe navigable flow conditions. The oblique flow intensity within the approach channel entrance area of the ship lock is extremely high. With the exception of the minimum navigable flow rate of 390 m^3/s, the extreme values of the transverse flow velocity in the entrance area under the other flow rates all exceeded the standard limits, and the extreme value of the transverse flow velocity under the maximum navigable flow rate of 7800 m^3/s reached 0.75 m/s. When the flow rate $Q \geq 5000$ m^3/s, the extreme values of the longitudinal and back flow velocities within the approach channel entrance area also exceeded the reference limits.

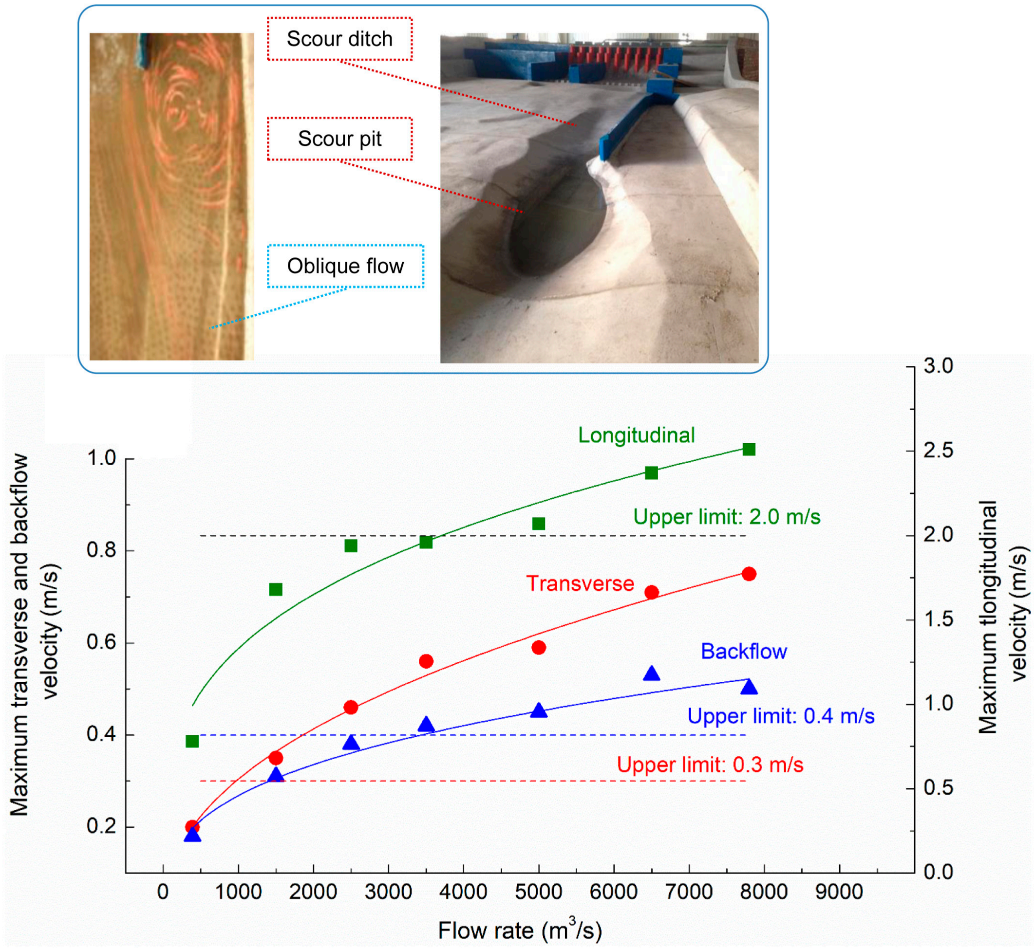


Figure 9. Surface velocity field and velocity extremums at the entrance area of the approach channel under current situations.

The poor flow conditions of the current situation are related to the river boundary conditions and complex riverbed morphology (as shown in Figures 4 and 9). The layout of the riverbed below the dam is "low on the left and high on the right" with a "deep pool on the left and reef on the right". As a result of the influence from the suction flow of the deep pool on the left side and the convex bank on the right side, there is a strong oblique current at the entrance area of the downstream approach channel that causes the transverse flow velocity and return flow velocity on the surface of the water within the entrance area to substantially exceed the permitted specification values.

4.2. Flow Conditions with Different Diversion Structures

For the three types of auxiliary diversion structures—diversion piers, partition dykes, and diversion vanes—multiple layout schemes were studied through model tests separately by changing the structural parameters except the total length, and the optimal arrangement of each diversion structure was obtained based on the optimal effect in terms of improvement in the navigation flow conditions. The optimal arrangement and surface flow field of different diversion structures are shown in Figure 10, and the extreme values of surface velocity at the entrance area of the approach channel are shown in Figure 11.

- Diversion piers scheme

The optimal arrangement of diversion piers is as follows: Nine piers with the same length of 20 m were installed, with the space between the first six piers being 10 m and the last three piers being 20 m. In contrast to the current situations, the results of diversion piers scheme show that the oblique flow and backflow intensity within the entrance area of the approach channel were significantly reduced. The extreme values of the longitudinal flow velocity and backflow velocity can meet the specification requirements in the test flow rate range; however, when the flow rate $Q \geq 3500\ m^3/s$, the transverse flow intensity was still relatively high, and the maximum value of the transverse flow velocity was 0.49 m/s.

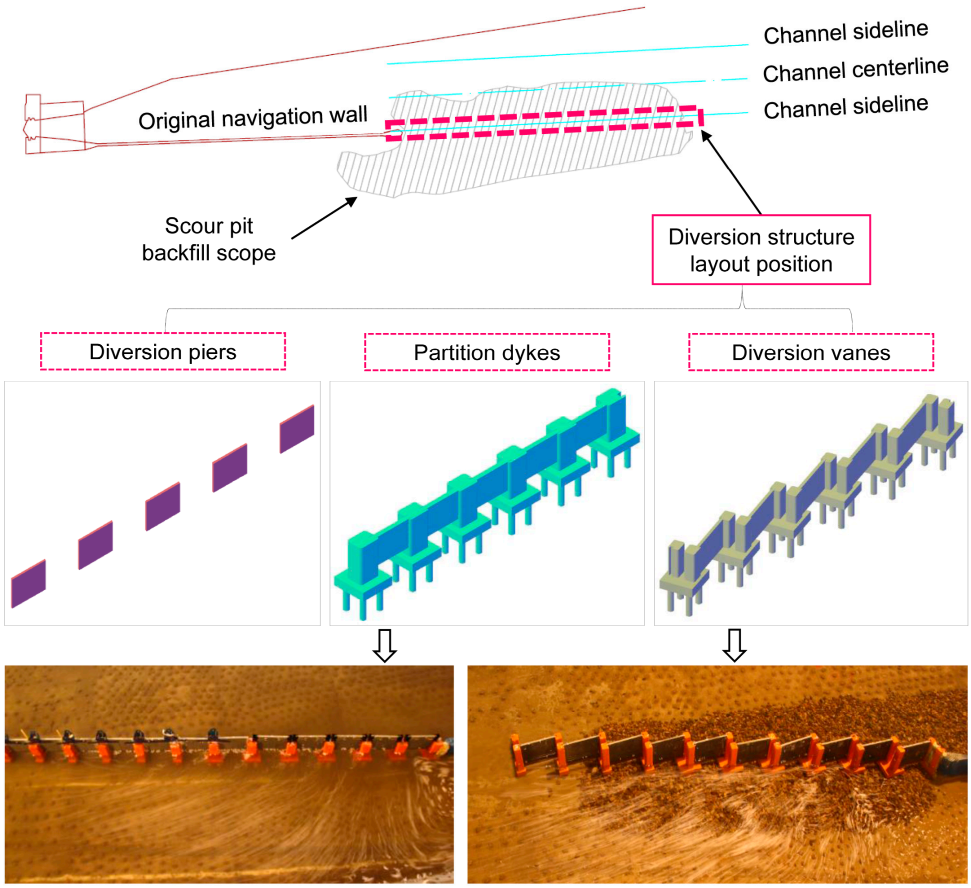


Figure 10. Schematic of optimal arrangement of different diversion structures.

- Partition dykes scheme

The optimal arrangement of partition dykes is as follows: Fifteen sections comprising 16 bearing platforms and 15 inserted vanes were installed, with a distance of 20 m between the bearing platforms and a clearance height of 3.5 m below the inserted vanes. In comparison with the diversion piers scheme, the results of the partition dykes show that the extreme values of longitudinal flow velocity and backflow velocity at the entrance area were reduced further. However, the improvement in the extreme values of the transverse flow velocity was unsatisfactory. When the flow rate exceeded 5000 m^3/s, the transverse flow velocity increased sharply, with the extreme values of transverse flow velocity under the maximum navigable flow rate reaching 0.81 m/s. Under a high flood flow rate, the oblique flow intensity entering the entrance area of the approach channel was also large, and the diffused flow through the clearance below the inserted vanes into the entrance area led to the formation of an upwelling flow, resulting in poor flow patterns such as vortex and bubble swirls, thereby causing an increase in the transverse flow intensity at the entrance area.

- Diversion vanes scheme

The optimal arrangement of diversion vanes is as follows: Ten sections comprising 11 bearing platforms and 10 inserted vanes were installed, with a distance of 20.8 m between the bearing platforms. The transverse gap, bottom clearance height, and deflection angle of the inserted vanes were 2.5 m, 3.5 m, and 16°, respectively. Although the layout length of the diversion vanes was shorter than that of the diversion piers and partition dykes, they were more effective in improving water flow conditions. Under all the test operating conditions, in addition to the longitudinal flow velocity and backflow velocity extreme values that could meet the specification requirements, the cross-flow intensity at the entrance area was also significantly reduced, and the transverse flow velocity was only slightly in excess of the specification requirements at individual points under the maximum navigable flow rate, with a maximum value of 0.33 m/s. The significant difference in transverse velocity extremums between partition dykes and diversion vanes schemes indicates that the flow into the channel through gaps between the inserted vanes has favorable effects on reducing the transverse velocity. There are two reasons for this: (a) by deflection resulting from the inserted vanes, the incidence angle of the surface oblique flow into the channel is reduced, and then, the longitudinal component of the oblique flow velocity increases, while the transverse component decreases. (b) The oblique flow through the gaps can effectively suppress the upwelling of the flow through the clearance and tends to drive it to flow downstream.

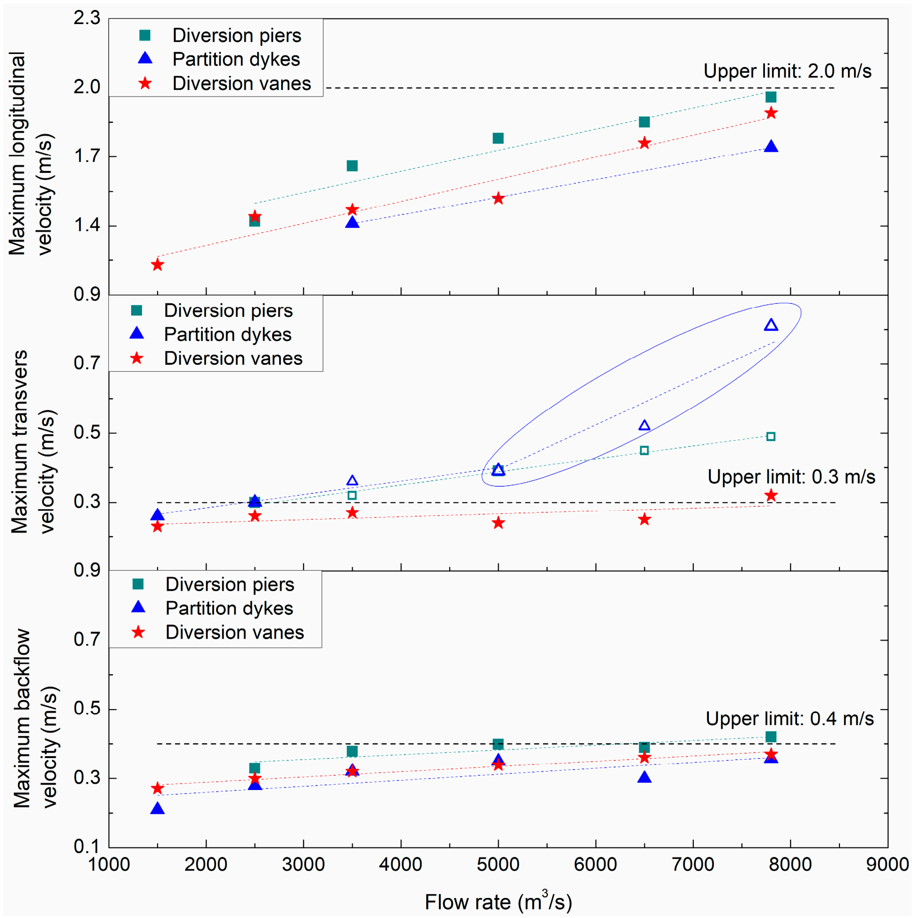


Figure 11. Distribution of extreme values of surface flow velocity at the entrance area of the approach channel of different diversion structures.

In addition, according to the model test results, the channel transverse flow from the entrance area of the approach channel to the downstream bridge also decreased, and the extreme value of the transverse flow velocity under the maximum navigable flow decreased from 0.61 m/s to 0.52 m/s. Under the diversion vanes scheme, the navigable flow conditions at the entrance area of the ship lock approach channel and its downstream channel were significantly improved.

4.3. Flow Conditions with Riverbed Dredging and Diversion Piers

Dredging of the riverbed was also considered according to the morphological characteristics of the downstream riverbed, that is, the reef explosion scheme. It was found that the navigable flow conditions can be improved to the greatest extent by dredging the riverbed and installing the diversion pies simultaneously, and the riverbed-dredging scope and diversion piers layout are shown in Figure 12. The dredging scope of the riverbed was 1.5 km long and 80 m wide, and four diversion piers with a length and a gap of 20 m were installed at the entrance area of the approach channel.

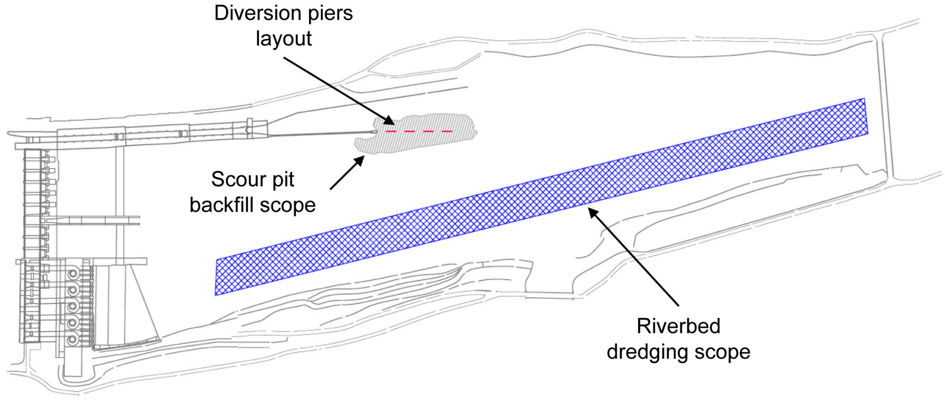


Figure 12. Schematic of optimal arrangement of riverbed-dredging scheme.

Figure 13 shows a comparison of the navigable flow conditions between the optimal riverbed-dredging scheme and optimal diversion vanes scheme. The extreme values of flow velocities in all directions are slightly larger for the riverbed-dredging scheme than for the diversion vanes scheme, but they are still able to meet the overall specification requirements. Riverbed dredging can also improve navigable flow conditions at the entrance area of the approach channel. However, the riverbed-dredging scheme requires extensive blasting, a large amount of underwater construction work, and high investment, whereas the diversion vanes scheme affords the advantages of easy construction and uninterrupted navigation during the construction period. If the two options are compared in terms of cost-effectiveness, the diversion vanes option can save approximately CNY 43 million in investment.

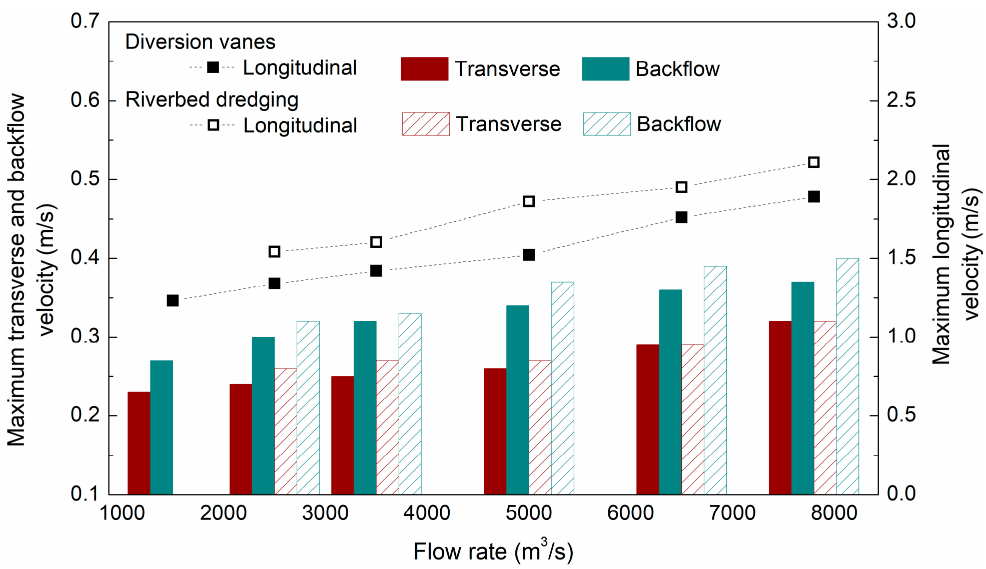


Figure 13. Comparison of navigable flow conditions between optimal riverbed-dredging and optimal diversion vanes schemes.

In summary, based on the improvement effect on the navigable flow conditions at the entrance area of the downstream approach channel and cost effectiveness, the developed diversion structure (diversion vanes) is a solution with great potential for improving the navigation conditions of mountain ship locks.

5. Application

The recommended diversion vanes scheme has been fully adopted for the ship lock renovation project of the Wuqiangxi hydro-junction, and the actual diversion vanes layout is shown in Figure 14. Prototype hydrographic observation and real-ship seaworthiness tests were performed to verify the improvement effect of navigable flow conditions after the implementation of the project and to prove the rationality of the navigable flow conditions scheme. The test flow rates were 4500, 5500, 6500, and 7500 m^3/s. The test design was based on a 500-ton standard motorized barge with a ship scale of 67.5 m × 10.8 m × 1.6 m (length × width × draught).

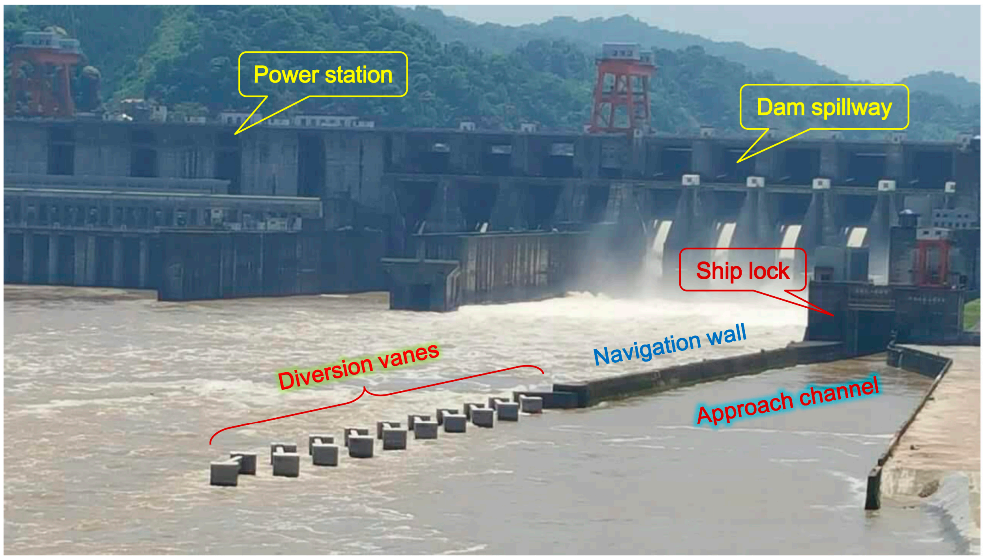


Figure 14. Actual layout of diversion vanes in the Wuqiangxi hydro-junction.

5.1. Navigable Flow Conditions

According to the results of the hydrological observation of the prototype, the navigable flow conditions at the entrance area of the downstream approach channel were significantly improved after the implementation of the project. The water flow was smooth and steady, and navigable conditions were generally favorable. The results of the actual navigable flow conditions measured at the entrance area of downstream approach channel are shown in Figure 15. The extreme values of the surface flow velocity at the entrance area of the prototype and those of the results of the model are consistent. When the flow rate was 4500 and 5500 m^3/s, the maximum longitudinal and transverse flow velocities within the entrance area were less than the tolerable values; when the flow rate was 6500 and 7500 m^3/s, the longitudinal flow velocity within the approach channel entrance area and the transverse flow velocity in most of the areas were within the tolerable range, and only the transverse flow velocity at individual points was slightly higher than the standard 0.3 m/s requirement.

5.2. Ship Navigation Parameters

According to the results of the real-ship seaworthiness test, the test ships were able to smoothly pass the test section through the entrance area of the approach channel downstream of the ship lock to the test channel in the bridge area at all flow rates, and the actual channel line of the ships largely matched the designed channel line. The ship navigation parameters at various flow rates are listed in Table 2, and the changes in the ship navigation parameters with navigation time at a typical flow rate are shown in Figure 16. The overall variation in the ship drift angle was −4.6° to 12.6° when the ship passed through the entrance area of the approach channel downstream of the ship lock, and the instantaneous speed of the ship was greater than 4 km/h. The navigation parameters of the ship were within the tolerable range, and the seaworthiness was appropriate. The overall variation in the ship rudder angle was −10° to 16°, reaching 20° in some cases, but there was no case of 35° at full rudder. The ship rudder angle was within the normal and reasonable range with suitable maneuvering performance.

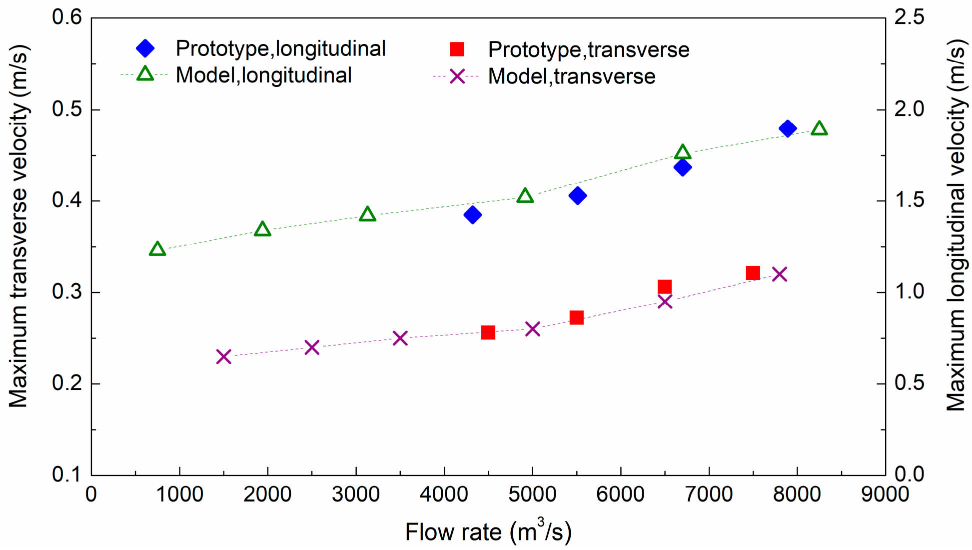


Figure 15. Comparison of extreme values of the surface flow velocity at the entrance area of the approach channel between the prototype and the model.

Table 2. Statistics of ship navigation parameters at different flow rates.

No.	Direction	Flow Rate (m^3/s)	Drift Angle Statistics (°)		Rudder Angle Statistics (°)		Speed Relative to Shore (km/h)	
			Extreme Value (+)	Extreme Value (−)	Extreme Value (+)	Extreme Value (−)	Minimum Value	Maximum Value
1	Upstream	4500	1.9	−3.3	14	−8	5.4	7.2
2		5500	1.1	−4.6	20	−10	5.8	6.4
3		6500	3.9	−4.0	16	−10	5.3	6.9
4	Downstream	4500	12.6	−3.2	10	−2	4.4	12.4
5		5500	12.0	−3.8	6	−10	6.9	14.0
6		6500	12.6	−2.3	10	−2	6.7	17.9

The rationality of the diversion vanes scheme was verified through hydrological observation of the prototype and seaworthiness test of real ships. Furthermore, the improvement effect of the diversion vanes structure on navigable flow conditions was confirmed. Since the implementation of the renovation, the passing capacity of the ship lock has been significantly improved, with the maximum navigable flow rate increasing from 1500 m^3/s to 7800 m^3/s and the annual navigable days increasing by approximately 40 to 60 days, generating social and economic benefits of approximately CNY 240 million/year.

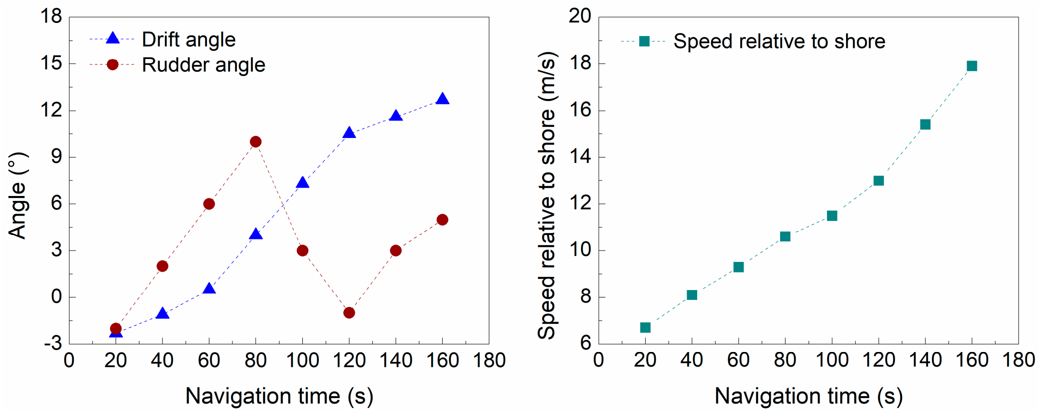


Figure 16. Change process of ship navigation parameters with navigation time at a typical flow rate (Q = 6500 m^3/s).

6. Conclusions

The intensity of oblique flow and backflow at the approach channel entrance area of ship locks on the mountain rapids reaches are usually strong in some cases, and the existing traditional diversion structures are not suitable or inefficient for improving navigation condition. Thus, a new type of diversion structure—the pile foundation permeable dislocation-type diversion vanes structure—was developed. It evolved from diversion piers and partition dykes and combined their advantages. The results of model tests show that the new diversion structure can significantly reduce the velocity extremums of transverse flow and obtain better effects on improving flow condition than other existing diversion structures. The working mechanisms of the new diversion structure were confirmed; that is, the structure integrates the functions of flow blocking and flow diverting, enabling the flow-blocking function of the upper inserted vane, flow-diverting function of the clearance below the inserted vanes, and flow-diverting function of the gaps between the inserted vanes to control the diverging flow rate and the angle of the water flow as well as to weaken the oblique flow in the entrance area downstream, thereby achieving the purpose of improving the flow conditions. In addition to being effective in improving navigation conditions, it is also cost-efficient. Its application in a typical mountain ship lock project—the ship lock renovation project of the Wuqiangxi hydro-junction—is quite successful, which has been confirmed by on-site hydrological observations and real-ship seaworthiness tests. In conclusion, the proposed diversion structure is a promising and effective solution to the navigation obstruction problem caused by fast-flowing waters at the approach channel entrance area of ship locks in narrow mountainous reaches. However, to promote the application of the new diversion structure in engineering practice, further studies are needed on the systematic influence law of diversion vanes structural parameters on the navigation conditions as well as detailed and sound principles for structure design.

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