Study on the impact of different pier structures on navigable flow conditions

Chuankai He
Datang Hydropower Science & Technology Research Institute Co., Ltd, Chengdu, Sichuan, 610074, China
*Corresponding author’s e-mail: 812980876@qq.com

Abstract. The navigable clearance scale is a key factor in the selection of bridge type schemes on urban navigable rivers, especially in the case of limited clearance, the restriction of pier size and shape on navigation. In this paper, the impact of different pier structures on navigable flow is analyzed through the two-dimensional flow mathematical model simulation of new bridge section of a river. The results show that the shape optimization of square pier chamfer can reduce the transverse velocity of navigable flow; and the larger size of pier, the greater transverse velocity of navigable waters. Furthermore, the transverse velocity of the navigable flow is the smallest on the condition of the same width but round form of head pier structure. The new design can effectively solve the contradiction between bridge navigation and landscape construction on urban navigable river, and provide a variety of options for bridge construction.

1. Introduction
The square pier, sheet pier, round head pier, cylindrical pier and other structural forms are applied widely. But at present, there is little research on the influence of the pier structure on the navigable flow conditions, Chen Jingkai [1] studied the effect of double cylindrical piers and square head piers on the flow velocity of the near embankment and the local flow field between the pier and embankment. Li Bin [2] studied the influence of the pier layout on the local flow field of the river by adjusting the angle between the pier and the oblique flow. Yang Zhongchao [3] and Wei Xianglong [4] analyzed the influence of bridge piers on navigable flow conditions through numerical simulation. Wu Jian [5] analyzed the navigable water flow conditions of cylindrical pier and round head pier by using flow-3D software, considering different inflow angles and the distance between the piers. The above researches have only studied the influence of the pier before and after the bridge construction on the navigable flow conditions or only studied the impact of the two pier structure forms on the flood or navigable water flow conditions, without systematically and comprehensively analyzing the impact of different bridge pier structure forms on navigable flow conditions.

The structure of the bridge is often determined by factors such as navigation, flood control, engineering investment, transportation organization, construction difficulty, landscape construction, and later maintenance. The construction of urban bridges across rivers will focus on the creation of landscapes. The magnificent style is an important element of urban bridges across rivers. The size of the bridge piers is often large. Therefore, to study the influence of the bridge structure on the navigable flow conditions through the two-dimensional flow mathematical model test can effectively take into account the urban bridge navigation and landscape construction, and provide a reference for the choice
of bridge type.

2. Numerical Simulation

2.1. Governing Equation
The two-dimensional flow control equation of the channel flow is as follows:

Continuous equation of water flow:
\[ \frac{\partial h}{\partial t} + h \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = 0 \]  

X directional momentum conservation equation:
\[ h \frac{\partial u}{\partial t} + hu \frac{\partial u}{\partial x} + hv \frac{\partial u}{\partial y} - h \rho \left[ E_u \frac{\partial^2 u}{\partial x^2} + E_v \frac{\partial^2 u}{\partial y^2} \right] + gh \left( \frac{\partial a}{\partial x} + \frac{\partial h}{\partial x} \right) + \frac{g \mu n^2}{(1.486 h \mu)^2} (u^2 + v^2)^{1/2} - \frac{\zeta V_a^2 \cos \psi - 2 h w \sin \phi}{0} \]

Y directional momentum conservation equation:
\[ h \frac{\partial v}{\partial t} + hv \frac{\partial v}{\partial x} + hu \frac{\partial v}{\partial y} - h \rho \left[ E_u \frac{\partial^2 v}{\partial x^2} + E_v \frac{\partial^2 v}{\partial y^2} \right] + gh \left( \frac{\partial a}{\partial x} + \frac{\partial h}{\partial x} \right) + \frac{g \mu n^2}{(1.486 h \mu)^2} (u^2 + v^2)^{1/2} - \frac{\zeta V_a^2 \sin \psi - 2 h w \sin \phi}{0} \]

Where: \( h \) is the water depth, \( u \) and \( v \) are the flow velocities in \( x \) and \( y \) directions respectively, \( t \) is the time, \( \rho \) is the density of the water, \( E \) is the eddy viscosity coefficient, \( g \) is the acceleration of gravity, \( a \) is the elevation of the bed surface, \( n \) is the Manning coefficient, \( \zeta \) is the wind stress coefficient, \( V_a \) is the wind speed, \( \psi \) is the wind direction, \( w \) is the earth's rotation angular velocity, \( \phi \) is the local latitude.

2.2. Project Overview
A newly built bridge is located on the Fuhe River, a tributary of the Minjiang River. The waterway of this section of the Fuhe River is positioned to improve the urban landscape and develop leisure tourism. Fuhe River is planned to be a class VI waterway, and the design representative ship type is 45.0×5.5×1.0m (length × width × design draft). The recommended bridge type scheme for newly built bridges is 3×25m (small box girder) + 100 m (through steel truss arch bridge) + 3×25 (small box girder). The structure of the main tower pier is square pier with dimensions of 9×12m (length × width), the navigation hole is the hole corresponding to the span of 100m. The center coordinates and span of the main pier of the navigation hole of the comparison bridge scheme are consistent with the recommended scheme. The main pier has a round head pier with a size of 10.3×3m (length × width).

2.3. Calculation area and grid settings
In this model, the length of the river section is about 1900m, and the entrance is about 950m away from the bridge position. The quadratic triangle six-node element and the quadrilateral eight-node element are mainly used to discretize the calculation area. Computational grids composed of quadrilateral finite elements have better computational stability, less number of triangular finite element grids under the same conditions, but poor adaptability to complex boundaries. The triangular finite element has strong adaptability, and the computing nodes can be encrypted at will, and the complex boundary is simulated more accurately. The triangular finite element is used for local encryption around the pier. After the bridge is built, there is no water treatment for the pier grid.

2.4. Model validation
According to the measured water level, velocity and flow data of the project, and the collection of corresponding flow data, and at the same time, the model is verified according to the flood regulation data of the project, and the roughness of the project is determined to be 0.026~0.032.
2.5. Calculation of boundary conditions

This study is to calculate the fixed-field flow, so when determining the upstream and downstream boundary conditions, only the upstream water flow and the downstream water level are needed. The engineering river section is a natural channel. According to the channel grade and hydrological data of the engineering river section, the navigable clearance scale control condition is once every 3 years. The corresponding boundary conditions are upstream inlet flow rate $= 1070 \text{m}^3/\text{s}$ and downstream outlet water level $h = 436.60 \text{m}$.

2.6. Measuring point layout

In order to study the influence of different pier types on navigable water flow conditions, relying on a representative bridge project example, quantitative analysis of the lateral velocity index related to the navigable net width. After arranging the main bridge piers of a recommended bridge type and a comparison bridge type scheme of a bridge respectively, according to Inland Navigation Standard (GB 50139-2014) [6], upstream of the bridge axis 3 times represents 154 measuring points within the range of $135 \text{m}$ (the distance between the measuring points in the direction of the bridge axis is $10 \text{m}$, and the distance between the measuring points in the flow direction is $10.4 \text{m}$), the arrangement of measuring points is shown in Figure 1. Derive the composite flow velocity of each measuring point and the angle with the normal direction of the bridge axis, and calculate the lateral velocity of each measuring point.

![Figure 1. Arrangement of measuring points in navigable flow](image-url)

3. Calculation results analysis

3.1. Analysis of calculation results of original plan

Within the range of navigable waters specified in the code, the maximum average lateral velocity of the recommended bridge scheme is $0.49 \text{m/s}$, which appears at the measuring points 98, 109, 120, 131, the recommended bridge type scheme has a larger lateral flow rate, which results in a clear navigation width that does not meet the requirements. The maximum average lateral velocity of the comparative bridge type scheme is $0.38 \text{m/s}$, which appears at the measuring points 109, 120, 131, and 142. The net width of the comparative bridge type scheme can meet the requirements.

The reason why the recommended bridge type scheme has a larger lateral velocity is that there is an angle of $5.6^\circ$ between the direction of the water flow and the normal of the bridge axis, and the large size of the pier and the right angle to the water surface. As a result, there is a clear flow around the bridge pier. The flow is deflected within $30 \text{m}$ upstream of the pier. The angle between the flow direction and the normal of the bridge axis becomes larger, resulting in a larger lateral velocity. Because the bridge position is the planned bridge position, the bridge axis is unique, and the span...
cannot be increased due to other factors, so the optimization plan considers the recommended plan, and the pier adopts a rounded arc structure, the radius are 2, 3, and 4 m, respectively. The recommended schematic diagram of the optimized pier structure is shown in Figure 2.

![Figure 2. Schematic diagram of the optimization of the recommended piers](image)

### 3.2. Analysis of calculation results of optimization plan

According to the pier optimization scheme, under the same calculation boundary conditions and parameters, derive the composite velocity of each measuring point within the range of navigable waters of different pier types, and the angle between it and the normal direction of the bridge axis, calculate the lateral velocity of each measuring point. The comparison charts of the velocity, flow direction and lateral velocity of each measuring point of different pier types are shown in Figures 3–5.

![Figure 3. Comparison of flow velocity of each measuring points of the optimization scheme](image)
3.3 Analysis of calculation results of different pier types

In order to further study the influence of different bridge pier structure forms on navigable water flow conditions, calculate the navigable flow conditions of the flat pier and cylindrical pier (Figure 6) with the same width of the round head pier in the comparison bridge scheme, the calculation results are shown in Figures 7~9.
Figure 7. Comparison chart of velocity at different measuring points of different pier types

Figure 8. Comparison chart of flow direction of each measuring point of different pier types

Figure 9. Comparison of lateral velocity at each measuring points of different pier types

Comparative analysis of cross-flow velocity of key parameters of optimization schemes and other pier-shaped navigable flow conditions (Table 1).
Table 1. Comparison Table of Transverse Velocity of Different Measuring Points of Different Pier Types

| Pier structure               | measuring point lateral velocity (m/s) | The maximum average lateral velocity of 4 bold measuring points (m/s) |
|-----------------------------|----------------------------------------|---------------------------------------------------------------------|
|                             | 76  | 87  | 98  | 109 | 120 | 131 | 142 | 153 |                                    |
| Before building the bridge  | 0.20| 0.21| 0.22| 0.24| 0.24| 0.23| 0.20| 0.24| 0.20                                  |
| Square head                 | 0.20| 0.22| 0.26| 0.35| 0.63| 0.72| 0.12| 0.20| 0.49                                 |
| Square chamfer 2m           | 0.20| 0.22| 0.26| 0.35| 0.62| 0.72| 0.09| 0.18| 0.24                                 |
| Square chamfer 3m           | 0.20| 0.22| 0.26| 0.34| 0.58| 0.71| 0.08| 0.18| 0.49                                 |
| Square chamfer 4m           | 0.20| 0.22| 0.26| 0.33| 0.56| 0.71| 0.08| 0.17| 0.46                                 |
| Flaky pier                  | 0.21| 0.23| 0.26| 0.31| 0.40| 0.61| 0.38| 0.23| 0.42                                 |
| Round head pier             | 0.21| 0.23| 0.25| 0.28| 0.34| 0.47| 0.42| 0.23| 0.38                                 |
| Cylindrical pier            | 0.20| 0.21| 0.24| 0.27| 0.32| 0.47| 0.51| 0.30| 0.40                                 |

It can be seen from the data in Table 1 that after taking the chamfering optimization measures, the measuring points of the maximum average cross flow are consistent with those before the optimization, the synthetic flow rate at each measuring point does not change much. The larger the chamfer radius, the angle between the water flow direction and the normal direction of the bridge axis is reduced within 50m upstream of the bridge axis, and the lateral velocity is also reduced correspondingly. The square head pier, chamfer 2m, chamfer 3m, and chamfer 4m upstream 3 times represent the length of the ship type. The maximum average lateral flow velocity in the navigable water area is 0.49, 0.49, 0.47, 0.46m/s. The chamfering through the other side's head pier is not conducive to the calculation of the net width of the navigation.

By comparing the navigable water flow conditions of sheet pier, round pier and cylindrical pier with the same width, the maximum average lateral velocity of round pier is the smallest, which is 0.38m/s, Cylindrical pier and sheet pier are 0.40 and 0.42m/s respectively, which shows that the round head pier has the least influence on the navigable flow conditions. The maximum average cross-flow corresponding to the sheet-shaped pier, round-headed pier and cylindrical pier with a total width of 3m is less than the maximum average cross-flow corresponding to the square-headed pier with a width of 12m, which indicates that the wider the pier, the greater the corresponding lateral velocity.

4. Conclusion
(1) The square head pier can reduce the lateral velocity value of the unfavorable net width scale by rounding optimization method. The larger the pier size is, the greater the lateral flow velocity accelerates to cause the more unfavorable to the net width of navigation. The minimum lateral velocity in the navigable water area corresponding to the round head pier structure of the same width.
(2) The study of the impact of the bridge pier structure on the navigable flow conditions can effectively solve the contradiction between the navigable bridges on the urban navigable rivers and the landscape creation, which provides a variety of options for bridge construction plan.

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