Numerical simulation on optimization scheme of permeable hole of permeable sheet piling spur dike

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Abstract. Aimed at the problems about that permeable hole number and permeable hole layout of Permeable Sheet Piling Spur Dike (PSPSD) affecting the flow characteristic at spur dike area, CCHE2D flow simulation mathematical model is adopted, two dimensional flow numerical simulation is carried out for the permeable spur dike area of the physical model of the Qiman reach of the Tarim River main stream. The change law of cross section flow velocity, water level with different permeable hole number and layout are analyzed. The optimization scheme of permeable hole for the PSPSD is sought. The results show that the more number of permeable hole of the PSPSD, the higher the water level upstream of the spur dike, the lower the water level downstream of the spur dike, the smaller the flow velocity upstream and downstream of the spur dike, the better the velocity uniformity. The optimization scheme for the permeable spur dike with the best effect of flow retardation is that the number of permeable holes is 4 holes, and the spacing of permeable hole decreases gradually from the root to the head of the spur dike, which accounts for 9%, 8%, 7% and 6% of the length of the PSPSD respectively.

1. Introduction
Permeable Sheet Piling Spur Dike is a new type of permeable spur dike combined with hydraulic sheet piling technology and permeable well-column pile spur dike. The body of permeable sheet piling spur dike is arranged with permeable holes. When water flows through the permeable holes with different shapes, sizes and arrangement, flow fields in the spur dike area and the flow structure will be changed. Therefore, it is necessary to study the optimization scheme of permeable hole of permeable sheet piling spur dike. Former scholars have obtained some research results on the structure type of permeable holes of gabion box, tetrahedral permeable frame, pile column spur dike and other types of permeable spur dike[1-4]. Previous studies have also been made on the different permeable types of permeable sheet piling spur dike[5-8]. The permeable holes selected in the previous experimental research on permeable sheet piling spur dike are double row rectangular holes. The study on the permeable holes scheme of the permeable sheet piling spur dike is not perfect, and the optimal scheme of the permeable holes of the permeable sheet piling spur dike has not obtained. In this paper, CCHE2D flow numerical simulation is used to simulate the flow characteristic in permeable sheet piling spur dike area, to analyze the influence of the number of permeable holes and the hole layout of permeable sheet piling spur dike, to determine the optimization scheme of permeable hole. The
research results will provide a theoretical basis for the rational selection of the form and layout of the permeable sheet piling spur dike, and provide a theoretical foundation for the further study on the flow characteristics analysis and the effect of flow retardation and deposition promotion in permeable spur dike area.

2. Simulation test of permeable hole scheme

2.1. Physical model test overview
The physical experiment was conducted in the agricultural hydraulics lab of Xinjiang Agricultural University, China. The typical flow rate is 15.77 L/s. The width of the water flume is 1.0 m-1.8 m, the length is 4.5 m, the depth is 0.4 m, and the slope is 1:500. The scale of the physical experiment is shown in table 1.

| Horizontal scale λL | Vertical scale λH | Geometric variation scale e | Velocity scale λV | Flow scale λQ | Slope scale λJ | Time scale λt | Bed roughness scale λn |
|---------------------|-------------------|----------------------------|-------------------|--------------|----------------|--------------|----------------------|
| 250                 | 25                | 10                         | 5                 | 31250        | 0.1            | 50           | 0.54                 |

2.2. Simulating test scheme
Permeability is measured by the length of the penetration per unit length of spur dikes. The permeability of spur dike directly affects the permeable performance, which is one of the important design parameters of the permeable sheet piling spur dike. It is very important to select the permeability reasonably. Previous studies have found in the reasonable selection of design parameters of permeable spur dike that the reasonable permeability range is 20%-30%[9]. Former studies in the experimental study on the effect of different permeability on the scouring and deposition characteristics of the permeable sheet piling spur dike also found that when the permeability is 30%, scouring prevention and deposition promotion effect of the permeable sheet piling spur dike reached the optimal level[10]. Therefore, on the basis of previous research results, the permeability of the permeable sheet piling spur dike is 30%. In this simulation test, four schemes with the number of permeable holes n as 1, 2, 4 and 6 are designed separately. The permeable sheet piling spur dike is arranged in single row with the length of the spur dike b=25 cm. The strip sheet piling is uniformly arranged in the water flume.

2.3. Numerical simulation of flow

2.3.1. Model grid generation. The CCHE-MESH 2D structured mesh is needed when building model mesh. The grid number setting is crucial. If the grid number is set too much or too little, the calculation result will be inaccurate. Therefore, on the premise of ensuring the reliability of calculation, the dotted line connected by the control points should be orthogonal to the boundary as far as possible. The direction of the grid lines I and J should be controlled to satisfy the orthogonality and smoothness of the grid. Finally, the quadric optimization grid function of Rk orthogonal grid built by the grid generator is adopted for optimization. Number of the longitudinal mesh lines I max=100, and number of the lateral mesh lines J max=300, and the total count of grids is 30000. Figure 1 shows the numerical model structure and grid diagram.
2.3.2. Set initial boundary conditions. To set the initial water surface, according to the results of the water flume experiment, set the average water surface elevation of the water flume inlet section as 0.841 m and the average water surface elevation of the outlet section as 0.826 m. To set the roughness coefficient \( n \), some scholars have simulated different roughness values[11]. Therefore, the roughness coefficient selected \( n \) as 0.018. To set the inlet and outlet boundary conditions, the total inlet flow rate is selected as the inlet boundary condition, and the flow rate is 15.77 L/s, the average water surface elevation of the outlet cross-section is 0.826 m.

2.3.3. Water flume model validation. The numerical simulation results are verified by comparing the measured data of the physical model with the simulated data. The simulated value of cross-sectional flow velocity 5 cm distance downstream the permeable spur dike is compared with the measured value, as shown in figure 2.

![Simulated vs Measured Velocity](image)

As can be seen from figure 2, all points of the simulated velocity and the measured velocity basically coincide well. The error is within a reasonable range. The results show that the CCHE2D flow numerical simulation can simulate the water flume accurately.

3. Numerical simulation results and analysis

3.1. Effect of permeable hole number on water level

After the spur dike is placed in the water flume, the flow structure will change. The water level and flow velocity will be redistributed. In this paper, the typical cross sections at 5 cm upstream, 5 cm, 20 cm and 60 cm downstream of the permeable spur dike axis are selected as the water level measurement cross sections. The water level distribution curve of each cross section in the permeable sheet piling spur dike area, as shown in figure 3.
Figure 3. Distribution of water level in different cross sections of the PSPSD area

As can be seen from figure 3, the water surface line of the action area of the spur dike changes significantly after the permeable sheet piling spur dike is arranged on the right bank of the water flume. The horizontal water level increases gradually upstream of the spur dike. The water level decreases gradually downstream of the spur dike. This is because the permeable spur dike has the ability to block part of the flow, the flow of upstream the spur dike appears stagnation phenomenon, and some of the kinetic energy of the flow turns to potential energy. Therefore, the water level is high upstream the spur dike, and the water level decreases downstream the spur dike. When the number of permeable hole reaches 4, the water level is less affected by the number of permeable holes upstream and downstream of the spur dike.

Table 2 shows the variation value of backwater height upstream the permeable spur dike. The table shows us that with the more number of permeable holes, the backwater height of water level increases. When the number of permeable holes reaches 6, height of backwater reaches the maximum. When the number of permeable holes reaches 4, the change of height of backwater is small upstream of the spur dike. Therefore, the optimization scheme of permeable hole number is 4 holes.

Table 2. Backwater height value with different number of permeable holes.

| Permeable hole n (hole) | 1   | 2   | 4   | 6   |
|------------------------|-----|-----|-----|-----|
| Backwater height Δz (cm) | 0.381 | 0.412 | 0.501 | 0.512 |

3.2. Effect of permeable hole number on flow velocity distribution

In this paper, the typical cross sections at 5 cm upstream, 5 cm, 20 cm and 60 cm downstream of the permeable sheet piling spur dike axis are selected as the measurement sections of the flow velocity. The flow velocity distribution curves of each cross section in the permeable sheet piling spur dike area, as shown in figure 4.
Figure 4. Flow velocity distribution of different cross sections in the PSPSD area

As can be seen from figure 4, the permeable spur dike is arranged in the water flume. The cross-section flow velocity decreases upstream and downstream of the spur dike. The cross-section flow velocity increases far from the spur dike. The decrease of flow velocity upstream of the spur dike is due to the blocking effect of permeable spur dike, the water level begins to rise upstream of the spur dike. When the flow rate remains unchanged, the cross section area of flow increases, which leads to the decrease of flow velocity upstream spur dike[12]. The reason for the decrease of the flow velocity downstream of the spur dike is that the friction between the flow through the spur dike and the permeable hole causes a large local head loss, which leads to the decrease of the flow velocity downstream of the spur dike. When the number of permeable holes reaches 4, the change of flow velocity tends to be stable. The increase of the number of permeable holes has little influence on the flow velocity downstream of the spur dike. This is because the more permeable holes arranged, the greater the local resistance. The local resistance is related to the degree of boundary change. However, for multiple local obstacles, the total local resistance is generally not equal to the sum of the resistance of separate local obstacles[13]. Thus, when the flow rate is 15.77 L/s, the permeability of spur dike is 30%, the relative spur dike length (b/B) is 0.2, and the single row and straight spur dike is adopted, the optimization scheme of permeable hole number is 4 holes.

The effectiveness of the permeable spur dike to reduce flow velocity is studied as a function of the flow velocity retardation ratio ($\eta$), which is defined as:

$$\eta = \frac{\bar{V}_0 - \bar{V}_1}{\bar{V}_0} \times 100\%$$  \hspace{1cm} (1)

Where, $\bar{V}_0$ is the average velocity of cross section when without permeable sheet piling spur dike is placed; $\bar{V}_1$ is the average velocity of cross section when permeable sheet piling spur dike is placed.

Table 3 is a comparative analysis table of flow retardation ratio with different number of permeable holes. It can be seen from the table that when the number of permeable holes is 6, the flow retardation
effect is the best. When the number of permeable holes reaches 4, the flow retardation ratio changes little. With the increase of the number of permeable holes, the flow retardation ratio increases gradually, which indicates that the flow retardation effect of permeable sheet piling spur dike is better.

Table 3. Comparison of flow retardation ratio with different number of permeable holes.

| Permeable hole n (hole) | CV 1 (%) | CV 2 (%) |
|-------------------------|----------|----------|
| 1                       | 47.3     | 48.0     |
| 2                       | 48.8     | 49.2     |

In order to determine the optimal scheme of permeable holes, it is necessary to analyze not only the effect of flow retardation, but also the velocity uniformity of the flow field. In this paper, the Relative Standard Deviation (RSD) is used to analyze and evaluate the uniformity of velocity of permeable spur dike with different number of permeable holes.

The relative standard deviation calculation formula is as follows:

\[ CV = \frac{S}{\bar{V}} \times 100\% \]  
\[ S = \left[ \frac{1}{n-1} \sum_{j=1}^{n} (V_j - \bar{V})^2 \right]^{1/2} \]

Where, CV is the velocity uniformity; S is the standard deviation; \( V_j \) is the velocity value of the j sampling point; \( \bar{V} \) is the average velocity of all sampling points; n is the number of sampling points.

The uniformity of flow velocity on the section is evaluated by comparing the CV values of different number of permeable holes. The smaller the CV value, the higher the uniformity of flow velocity. In figure 5, CV 1 and CV 2 are divided into flow velocity uniformity of different number of permeable holes 5 cm and 20 cm downstream of the spur dike. It can be seen from the figure that the flow velocity uniformity decreases gradually with the increase of the number of permeable holes. When the number of permeable holes reaches 4 holes, the uniformity of flow velocity tends to be stable. Therefore, when the flow rate is 15.77 L/s, the permeability of spur dike is 30%, the relative spur dike length (b/B) is 0.2, and the single row and straight spur dike is adopted, the optimization scheme of permeable hole number is 4 holes.

3.3. Effect of permeable hole spacing on flow velocity

When the flow rate is 15.77 L/s, the permeability of spur dikes is 30%, the relative length of spur dikes (b/B) is 0.2, and the single row and straight spur dike is adopted. The optimum number of permeable holes for permeable sheet piling spur dike is 4 holes by numerical simulation. On this basis, according to the optimum scheme of permeable holes, the numerical simulation of the different spacing of permeable holes is carried out, including three layout schemes from the spur dike root to the spur dike head: uniform (7.5%, 7.5%, 7.5% and 7.5% of the length of the spur dike respectively), from small to large (6%, 7%, 8% and 9% of the length of the spur dike respectively) and from large to small (9%, 8%, 7% and 6% of the length of the spur dike respectively). The influence law of the spacing of permeable holes on the flow structure is obtained. Table 4 shows the changes of average flow velocity in cross sections with different spacing of permeable holes.
Table 4. Average cross-sectional flow velocity of permeable holes in different spacing.

| Spacing of permeable holes | Average flow velocity (m·s⁻¹) |
|---------------------------|-------------------------------|
|                           | x=-5 cm | x=5 cm | x=20 cm | x=60 cm |
| Uniform                   | 0.161   | 0.156  | 0.153   | 0.190   |
| From small to large       | 0.162   | 0.157  | 0.157   | 0.194   |
| From large to small       | 0.161   | 0.140  | 0.141   | 0.183   |

Table 4 shows that when the number of permeable holes is the same, and the spacing of permeable holes decreases gradually from the spur dike root to the spur dike head, the average cross-sectional flow velocity reaches the minimum. When the spacing of permeable holes increases gradually from the spur dike root to the spur dike head, the average cross-sectional flow velocity reaches the maximum. It shows that the best effect of flow retardation is the spacing of permeable holes decreasing gradually from the spur dike root to the spur dike head. The spacing of permeable holes accounts for 9%, 8%, 7% and 6% of the length of the permeable spur dike respectively. The spacing of the permeable holes of the permeable sheet piling spur dike is consistent with the pile-column permeable spur dike, it shows that the spacing of the permeable holes of the permeable sheet piling spur dike is reasonable.

4. Conclusions

In this paper, in order to the optimal scheme of permeable holes in permeable sheet piling spur dike is sought. Under constant flow rate, permeability of the spur dike and other factors, CCHE2D is used to conduct numerical simulation on the number of permeable holes and the spacing of permeable holes in permeable sheet piling spur dike. The main conclusions are as follows:

With the more number of permeable holes, the higher the water level upstream of the spur dike, the lower the water level downstream of the spur dike, the smaller flow velocity upstream and downstream of the spur dike, the better the effect of flow retardation. When the number of water holes reaches 4, the water level and flow velocity of upstream and downstream of permeable spur dike change little, and the effect of flow retardation does not change obviously. The results show that the number of permeable holes has great influence on water level and flow velocity. The optimization scheme of permeable hole number is 4 holes.

The optimization scheme for the permeable spur dike with the best effect of flow retardation is that the number of permeable hole is 4 holes, and the spacing of permeable hole decreases gradually from the root to the head of the spur dike, which accounts for 9%, 8%, 7% and 6% of the length of the permeable spur dike respectively.

This paper provides a reference for the study of the optimization scheme of the downward permeable spurs and their groups, and lays a theoretical foundation for the further study of the flow characteristics and the effect of flow retardation and deposition promotion in the permeable sheet piling spur dike area.

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