Optimization Research of Clustered Riverbed Structure Based on Orthogonal Experimental Design

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Abstract: By using the $k-e$ turbulence model combined with the VOF model, this paper numerically simulates the influence of the size of different baffle piers on the energy dissipation effect of the tufted riverbed structure and the water flow characteristics of the river channel on the clustered riverbed. The results show that: 1. After changing the size of the baffle piers, it is found that the width has the greatest influence on the energy dissipation rate, followed by the length and finally the height. 2. Under the test conditions, the optimal test group is $A_2B_3C_1$, which is the test plan No. 6.

1. Research Background

The southwestern part of China is located on the eastern side of the Qinghai-Tibet Plateau. Most of the places are alpine valleys, so the water resources are extremely rich. Therefore, the construction of dams and water conservancy in rivers are widely used in the southwest. Due to the rapid cutting speed of the valley in the southwest and strong crustal uplift, as well as the heavy rain in the flood season, the strong water flow continuously washes down the riverbed. This destroys the stability of the riverbed and easily causes natural disasters such as collapse, landslides and mudslides. At the same time, the stability of the riverbed is also closely related to the safety of the roadbed and bridges on the banks. The river cuts down and causes the bank slope to become steep, providing energy for the occurrence of geological disasters [1], so collapses, landslides and mudslides often happen in these rivers [2]. Through more than ten years of field investigations and experimental studies, Wang Zhaoyin [3] discovers that the natural dam formed by the collapse of the landslide and mudslides is actually the result of negative feedback from the down-cutting of the river. After the natural dam is stabilized, it controls the river undercut, keeps the river stable and improves the ecology. This function mainly comes from the riverbed energy dissipation structure developed on the natural dam. Li Zhiwei [4] also points out that the riverbed structure of mountain rivers is the product of the interaction between water and sand and riverbed, which is of great significance for the calculation of riverbed resistance and sediment transport rate. Therefore, maintaining the stability of the riverbed by consuming the excess energy of the discharge stream plays a decisive role in protecting the geological environment of the river and its surroundings, reducing the frequency of natural disasters.

As there are mostly mountain rivers in the southwestern region, compared with plain rivers, the mountain rivers have larger water flows and narrower water surface, deeper water and more abundant in water energy. In contrast to plain rivers with smooth water flow and many curved roads, mountain rivers can only dissipate energy through the structural characteristics of the river bed. Wu [5]
numerically simulates the energy dissipation of four riverbed structures in the paper. By comparing the energy dissipation rates of the four structures, it is concluded that the energy dissipation effect of the bucket riverbed is optimal, while the cluster riverbed comes second. Wang Zhaoyin [6] pointed out that the appearance of the riverbed structure at least includes the following: (1) Step-pool structure. (2) Rib-like structure. (3) Cluster structure. These are the three most common bedside structures in mountain rivers, of which the cluster structure is the most common. It manifests itself as being piled up by several stones and lean against each other to resist the erosion of water. Each pile of stone is called a stone cluster, of which the stone piers are placed at regular intervals to form a barrier to the upstream water. This is to consume the huge energy converted from potential energy, thereby reducing the erosion of downstream riverbeds and the banks. Moreover, it is enabled to protect the river and the surrounding environment, and reduce natural disasters.

The orthogonal experimental design method used in this paper is an important branch of statistical mathematics, mainly used in scientific experiments in industrial and agricultural production and scientific research. Using this method can shorten the test times and cycles, lowering the test and production costs, and quickly find an optimization plan to achieve the maximum benefit. Based on probability and mathematical statistics, as well as professional technical knowledge and practical experience, standardized orthogonal tables are made fully use of to arrange experimental schemes of calculating and analyzing test results, which is undoubtedly a scientific calculation method to quickly locate optimization solutions [7].

In summary, the clustered riverbed can provide effective resistance to water flow, and control the riverbed undercut by dissipating the energy, which keeps the river stable and plays a positive role in the healthy development of the river. The purpose of this paper is to numerically simulate the structure of the clustered riverbed to optimize the size so that it can achieve the optimal energy dissipation effect, which can offer evidence to its control of mountain rivers.

2. Theoretical basis of numerical simulation

2.1 Numerical simulation method

The motion of three-dimensional water flow is complicated, so it is crucial to choose a suitable numerical simulation method. Practice has proved that the standard two-equation $k-\varepsilon$ turbulence model of RANS is a well-developed method for simulating the accuracy of natural rivers. In this paper, the gas–water two-phase flow VOF mode, combined with the standard two-equation $k-\varepsilon$ turbulence model of RANS is mainly used to carry out numerical simulation research. Taking the three-dimensional orthogonal curve as the coordinate system, the discrete method of the equation adopts the finite volume method, using the SIMPLEC method to couple pressure and velocity. Solving discrete equations uses a point implicit Gauss-Sedel method.

The VOF model used in this paper simulates the tracking of the free surface by solving the individual momentum equations and calculating the volume of the fluid in the grid unit. It is suitable for steady-state and transient processing of gas-liquid interfaces. Moreover, the governing equation of the method consists of a volume fraction equation and a conservation equation.

2.2 Governing equation

The movement of water flow is a three-dimensional problem with the three spatial directions along the path, water depth and river width. This study uses the $k-\varepsilon$ turbulence model combined with a VOF model to simulate it.

In the $k-\varepsilon$ turbulence model, the continuity equation, the momentum equation, the $k$ and $\varepsilon$ equation are expressed as follows:

Continuity equation:
\[ \frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \]  

Momentum equation:

\[ \frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \]

k equation:

\[ \frac{\partial \rho k}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \nu \frac{\partial^2 k}{\partial x_i \partial x_i} - \frac{\partial p}{\partial x_i} + G + \rho \varepsilon \]

\[ \varepsilon \text{ equation:} \]

\[ \frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \]

\[ \mu_t = \rho C_{\mu}^2 \frac{k^2}{\varepsilon} \]

\[ G = \mu \left[ \frac{\partial u_i}{\partial t} + \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \right] \]

\[ \frac{\partial \alpha_w}{\partial t} + u_i \frac{\partial \alpha_w}{\partial x_i} = 0 \]

In the above equation, \( \rho \) and \( \mu \) are respectively the density and molecular viscosity coefficients. \( P \) is the pressure term considering gravity. \( \sigma_k \) and \( \sigma_\varepsilon \) are the turbulent prandtl number of \( k \) and \( \varepsilon \). Let \( \sigma_k = 1.0 \), \( \sigma_\varepsilon = 1.3 \), \( C_{1\varepsilon} = 1.44 \) and \( C_{2\varepsilon} = 1.92 \). \( C_{1\varepsilon} \) and \( C_{2\varepsilon} \) are the constants of the \( \varepsilon \) equation. The turbulent viscosity coefficient \( \mu_t \) is obtained from the turbulent energy \( k \) and the turbulent dissipation rate \( \varepsilon \) via equation (5). In the equation (5), \( C_{\mu} \) is an empirical constant, and let \( C_{\mu} = 0.09 \). G is a turbulent energy generation term caused by an average velocity gradient, and the turbulent energy generation term can be defined by equation (6). Equation (7) is the governing differential equation for the water volume fraction \( \alpha_w \). Solving the governing differential equation is to simulate the tracking of the water-gas interface. \( u_i \) is the velocity component, \( \alpha \) is and the coordinate component, and \( t \) represents the time.

3. Simulation Calculation of River Flow Field

![Figure 1 Model plan](image-url)
As shown in Figure 1, the established model is divided into three typical areas, the upstream section, the slope energy dissipation section, and the downstream section. The total simulated river channel length is 144m, and the narrow section of the river channel slope is 13.5%. Both the upstream and downstream are horizontal, and the control flow is 12m$^3$/s.

Figure 2 shows a clustered channel model with 45 cuboid clusters in the narrow section of the channel. The cuboid stone cluster length is L, the width is B, and the height is H. The gap between the stone clusters is selected based on the experimental design requirements. Following the pattern of “878787”, it is evenly distributed on the energy dissipation section of the ramp.

Figure 3 is a schematic diagram of the meshing of typical areas. The whole model is composed of multiple bodies, and the mesh of the slope is more precise. The water inlet is defined as the boundary of the velocity inlet, the upper is the pressure inlet boundary, and the downstream is the pressure outlet boundary. The wall applies no-slip condition, the simulation is performed on the near wall using the standard wall function method. The total number of grids is controlled between 200,000 and 300,000.

4. Test Plan

4.1 Orthogonal test design
After analysis, based on the number of the same stone piers, consider the three parameters is considered into constituting the stone pier, including the height of the pier (A), the length (B), and the width (C). According to the characteristics of these three parameters, each factor takes 3 levels (see table 1), so there are 3 factors and 3 levels for each factor. Therefore, $L_9(3^4)$ table can be used to arrange the experimental scheme of factor impact analysis (see table 2), and 9 sets of numerical simulation orthogonal experiments are performed.

| No.  | A   | B   | C   |
|------|-----|-----|-----|
| Level 1 | 0.5 | 0.4 | 1   |
| Level 2 | 1.0 | 0.8 | 3   |
| Level 3 | 1.5 | 1.0 | 5   |

4.2 Determination of assessment indicators
According to the structure of the riverbed, after the energy dissipation, the corresponding evaluation indicators can be selected by the energy dissipation effect that the model can achieve. The energy dissipation rate is an important criterion for measuring the energy dissipation capacity in water conservancy engineering facilities. Therefore, the energy consumption rate is selected as the decisive index for examining the characteristics of baffle piers.
4.3 Energy Dissipation Rate
Since the water flow passes through different model test groups, and the size of the baffle piers is different, the energy is consumed to different extents. The energy dissipation equations of different test groups are calculated by the total flow energy equation. Let X=50m be the upper section of the river channel, X=105m be the downstream section of the river channel, and then list the energy equation of the upstream and downstream sections and the calculation equation of the energy dissipation rate:

$$\frac{\alpha_1 U_1^2}{2g} + d_1 + H_S = \frac{\alpha_2 U_2^2}{2g} + d_2 + h_f$$

(8)

$$\beta = \frac{h_f}{\frac{\alpha_1 U_1^2}{2g} + d_1 + H_S}$$

(9)

In the equation, \(U_1\) and \(U_2\) are the average flow velocity of the upstream and downstream sections, \(d_1\) and \(d_2\) are the water depths of the upstream and downstream sections, \(H_S\) is the step height, that is, the elevation difference of the bottom of the riverbed in the upstream and downstream sections, \(\alpha_1\) and \(\alpha_2\) are the kinetic energy correction coefficients of upstream and downstream, \(h_f\) is head loss, \(g\) is gravitational acceleration, and \(\beta\) is the energy dissipation rate.

5. Test Design Results and Analysis
Table 2 shows the results of the model test calculations, and Tables 3 and 4 show the range analysis and variance analysis of the energy dissipation rate, respectively. The range analysis is consistent with the calculation results of the variance analysis.

Table 2 orthogonal test plan and calculation results

| A(m) | B(m) | C(m) | H(m) | Q   |
|------|------|------|------|-----|
| 1    | 0.5  | 0.4  | 1    | 1   | 82.13|
| 2    | 0.5  | 0.8  | 3    | 2   | 83.20|
| 3    | 0.5  | 1    | 5    | 3   | 82.83|
| 4    | 1    | 0.4  | 3    | 3   | 82.99|
| 5    | 1    | 0.8  | 5    | 1   | 83.18|
| 6    | 1    | 1    | 1    | 2   | 83.87|
| 7    | 1.5  | 0.4  | 5    | 2   | 83.85|
| 8    | 1.5  | 0.8  | 1    | 3   | 83.57|
| 9    | 1.5  | 1    | 3    | 1   | 77.77|

Remarks: \(H\) is the upstream and downstream water level difference (m), \(Q\) is the energy dissipation rate.

Due to the balanced collocation and comparability of the orthogonal tables, it can be considered that the fluctuation of the test results is caused by the change of the factor level on the premise that the experimental error is relatively small. By comparing the difference of a certain factor's assessment indicators at different levels, it can reflect the influence of the level change of the factor on the indicator.

The average effect of each factor on the indicator can be seen in Table 3. The range is the difference between the maximum and minimum values in different levels, which is an important indicator to measure the fluctuation of data. The large difference factor has a great influence on the indicator, which proves to be the main factor affecting the indicator. Conversely, the small difference in the factor has little effect on the indicator, which proves to be a secondary factor affecting the indicator. According to the range analysis data of Table 3, the width of the pier has the greatest influence on the energy dissipation rate, and the length is second, and the height has the least influence. It can be deduced that the width of the stone pier is the main factor affecting the energy dissipation rate.

Figure 1 Indicators - the peak value of each factor analyzed by the extreme difference of factors, indicating the average value of the maximum energy dissipation rate of each factor at a certain level.
Table 3 Energy dissipation rate analysis table

| Level | A (%) | B (%) | C (%) |
|-------|-------|-------|-------|
| 1     | 82.72 | 82.99 | 83.19 |
| 2     | 83.35 | 83.32 | 81.32 |
| 3     | 81.73 | 81.49 | 83.29 |
| Range | 1.62  | 1.83  | 1.97  |
| Order | 3     | 2     | 1     |

Figure 4 Indicators - Factor Range Analysis

Table 4 Variance analysis

| Factor | Sum of squares deviations | Degree of freedom | Significance | Order |
|--------|---------------------------|-------------------|--------------|-------|
| A      | 0.9234                    | 2                 | *            | 3     |
| B      | 1.9026                    | 2                 | **           | 2     |
| C      | 2.4626                    | 2                 | ***          | 1     |

In summary, under the premise of the design conditions of this test:

1. Among the factors affecting the energy dissipation efficiency of the size of the baffle pier in the clustered riverbed, the width has the greatest influence on the energy dissipation rate. Its range is 1.97%, and the sum of squared deviations is 2.4626%, so width is the most significant factor.
2. Height and length are also important factors, and their range is 1.62% and 1.83%, respectively. However, from the analysis results of variance, their squared deviations are 0.9234% and 1.9026%, which are quite different, indicating that the length is more influential than the height.
3. According to the known results of the test, it can be concluded that the optimal scheme selected by the orthogonal test is $A_2B_3C_1$, that is, the test plan No. 6. The optimal experimental scheme obtained from the analysis in Figure 1 is $A_2B_3C_3$, which is the experimental scheme No. 5. However, the test result of the test plan No. 6 is higher than that of the plan No. 5, so the test plan No. 6 is the optimal solution in the specific case.

6. Conclusion

1. After the size of the baffle pier of the clustered riverbed is changed, the energy dissipation efficiency changes significantly. The width of the baffle pier has the most significant influence on the change of the energy dissipation rate, followed by the length, and finally the height.
2. Under the conditions of this test design, the optimal test plan for energy dissipation is $A_2B_3C_1$, which is the test plan No. 6.
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