Comparative Study on Energy Dissipation Numerical Simulation of Different Energy Dissipators in Wide and Narrow Alternated Channels

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Abstract: This paper proposed clustered energy dissipators and ribbed energy dissipators in view of the energy dissipation of wide and narrow alternated river channels in mountainous areas. According to the structure and layout of energy dissipation piers, clustered energy dissipators are divided into several layout types: 1# “2-1 alternating” dissipator, 2# “2-1 inclined alternating” dissipator, 3# “4-3 alternating” energy dissipator; ribbed energy dissipator is divided into: 4# “ribbed” dissipator, 5# “ribbed + step-wise” dissipator. In this paper, we used a standard k-ε model to carry out 3D turbulent numerical simulation of energy dissipation of different energy dissipators in wide and narrow river alternated channels in mountainous areas, and analyzed its energy dissipation effect, which can provide design guidance for remediation and river bank slope protection.

1. Introduction
Mountain rivers have the characteristics of short flow path, short confluence time, steep slope, rapid water flow, and large potential energy. The increasing energy along the way can easily cause erosion and destruction of river beds and river banks; Due to the influence of geology and riverbed evolution, river channels in mountainous areas often show the morphological characteristics of wide and narrow alternated [1]. Wide and narrow alternated channels are common morphological characteristics of mountain rivers, which are very common in southwestern mountainous areas. There have been many explorations of wide and narrow alternated mountain rivers. Zhou Sufen et al. [2] established a 2D flow mathematical model of the wide and narrow river channels in the mountainous area based on the sink test and the hydrodynamic SMS software. Their results show that the width gradient of wide and narrow alternated river channel will cause changes in water depth and flow velocity. The water depth at the narrowest part of the channel drops to the smallest and the flow velocity is the largest. The water depth at the widest section reaches the peak value and the flow velocity is the smallest; Wang Wen’e et al [3] analyzed the longitudinal average flow velocity, turbulence intensity, Reynolds shear stress and turbulence energy distribution on a typical section based on the indoor generalized model test; Wu Huali et al. [4] focused on the change of the plane shape resistance caused by the change of the river width, and at the same time, combined with the natural wide and narrow channel water and sand changes to examine the existing results; Ye Chen et al. [5] explored the hydrodynamic characteristics of the riverbed of the boulder ladder array in mountain rivers based on the flume test and the field survey of typical boulder river sections. The results show that the intensity of 3D turbulence increases first and then decreases along the direction of water depth, and the intensity of turbulence near the
river bed can be significantly reduced with the increase of the density of boulder arrangement; Wang Zhaoyin et al [6] summarized the riverbed structure and energy dissipation and disaster alleviation mechanism of natural dam, concluded a quantitative calculation method for the energy dissipation rate of riverbed structure represented by step-deep pools, and introduced the successful experience of prevention and control of debris flow disasters in artificial step-deep pools system, which emphasis the feasibility and effectiveness of artificial simulation of natural dam energy dissipation structure in the field of disaster prevention and mitigation. However, the current research is mainly focused on the characteristics of mountain river flow, few scholars have discussed the specific energy dissipation methods.

2. Mathematical methods

2.1. Governing equation

The \( k-\varepsilon \) model is currently the most widely used two-equation turbulence model. A large number of engineering practice shows that this model can calculate more complex turbulence; In this paper, we used the standard \( k-\varepsilon \) model to perform the 3D turbulent flow simulation to the energy dissipation of different energy dissipators in the wide and narrow alternated channel. The \( k-\varepsilon \) model consists of two equations of turbulent kinetic energy \( k \) and turbulent dissipation rate \( \varepsilon \), where the turbulent viscosity is a function of \( k \) and \( \varepsilon \). The equation of the standard \( k-\varepsilon \) model can be expressed as:

\[
\begin{align*}
\text{Continuous equation:} & \quad \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \\
\text{Momentum equation:} & \quad \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] + G + \rho \varepsilon \\
\text{Equation } k: & \quad \frac{\partial k}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial k}{\partial x_j} \right] + G - C_{\mu} \varepsilon \frac{\varepsilon^2}{k} \\
\text{Equation } \varepsilon: & \quad \frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\mu} \varepsilon - C_{\mu} \varepsilon^2 \frac{\varepsilon^2}{k} \\
\end{align*}
\]

Among them: \( \rho \) is the density; \( \mu \) is the molecular viscosity coefficient; \( t \) is the time; \( u_i \) is the velocity component; \( x_i \) is the coordinate component; \( p \) is the pressure term after considering gravity; \( \sigma_k \) is the turbulent Prandtl number of \( k \), setting \( \sigma_k = 1.0 \); \( \sigma_\varepsilon \) is The turbulent Prandtl number of \( \varepsilon \), takes \( \sigma_\varepsilon = 1.3 \); \( C_{1k} \) is the constant of \( \varepsilon \) equation and \( C_{1\varepsilon} = 1.44 \); \( C_{2k} \) is the constant of \( \varepsilon \) equation and \( C_{2\varepsilon} = 1.92 \); \( \mu_t \) is the turbulent viscosity coefficient; \( k \) is turbulent kinetic energy; \( \varepsilon \) is the turbulent dissipation rate; \( C_{\mu} \) is the empirical constant, and \( C_{\mu} = 0.09 \); \( G \) is the turbulent energy generation term caused by the average velocity gradient.

2.2. VOF model

In this paper, the free water surface adopts the surface tracking method of the VOF model built on a fixed Euler grid. In a cell, if the volume fraction of the qth phase fluid is \( \alpha_q \), then there may be the following three cases: (1) \( \alpha_q = 0 \), that is, there is no the q-th phase fluid in the cell, (2) \( \alpha_q = 1 \), that is, the cell is full of the q-th phase fluid, (3) \( 0 < \alpha_q < 1 \) means that the unit contains the interface between the q-th phase fluid and single-phase or other multi-phase fluids. Based on the partial value of \( \alpha_q \), suitable attributes and variables are assigned to each control unit within a certain range.

The interface between the tracking phases is accomplished by solving a continuous equation for the volume ratio of one or more phases. For the q-th phase:
\[
\frac{\partial \alpha_q}{\partial t} + \mathbf{u} \cdot \nabla \alpha_q = \frac{S_{\alpha}}{\rho_0}
\]  

(6)

Where \( S_{\alpha_i} \) is the mass source, here it is set to 0; \( \mathbf{u} \) is the velocity vector; the calculation of the volume fraction of the phase is based on the following constraints:

\[
\sum_{q=1}^{n} \alpha_q = 1
\]  

(7)

2.3. Numerical Methods

The finite volume method is used to discrete governing equation, the difference format is QUICK difference format, and the velocity-pressure coupling is solved by SIMPLE algorithm.

3. Numerical simulation domain overview and boundary conditions setting

3.1. Model Overview

To facilitate the description of the model, the wide and narrow alternated channels were divided into five sections. The narrow section A of the upstream inlet was 15m long and the channel was horizontal; the wide section B was 30m long and the slope was 1°; the narrow section C was designed for energy dissipation, which was 15m long, and the slope was 5°; the wide section D was 20m long and the channel was horizontal; the narrow outlet section E was 20 m long and the channel was horizontal; the narrow channel section was 8m wide and the maximum width was 17m. The top view of the design of the wide and narrow river channel is shown in Figure 1.

![Fig. 1 The top view of the the wide and narrow river channel design](image)

We used Cartesian coordinate system with the X axis as the direction of water flow, the Z axis as the vertical direction, and the y axis as the river width direction. Section C was designed with 5 different types of energy dissipators. Clustered energy dissipators were divided into three layout types: 1# “2-1 alternated” layout energy dissipator, 2# “2-1 inclined alternated” layout energy dissipator, 3# “4-3 alternated” layout energy dissipator; and ribbed dissipators were divided into two layout types: 4# “ribbed” layout energy dissipator and 5# “ribbed + step-wise” layout energy dissipator. The energy dissipator was evenly distributed in the section C of the channel, and the channel width was 8m, so it can be ensured that the incoming water cannot flow through the C section without resistance. The design flow was 6m³/s, and the design of energy dissipator and the distribution of energy dissipation piers at section C are shown in Figure 2.
3.2. Mesh generation
Discrete calculation area adopted hexahedral structured grid, and the number of 5 different forms of energy dissipator was around $18 \times 10^4$. The design section of C dissipator is the key research object, and the flow structure is more complicated. Therefore, when designing the mesh, the mesh size was smaller than 0.2 m. The grid division of the energy dissipation design section of section C is shown in Figure 3.

3.3. Boundary conditions
The inlet of the river channel adopted the definition of velocity inlet; the contact surface of the river channel and the air was defined as the pressure inlet, and the corresponding atmospheric pressure was given. At the same time, the outlet end was connected to the atmosphere and the pressure outlet was used for calculation; Standard wall function method was adopted for the calculation of the near-wall surface, and the roughness n was 0.03.

4. Results and analysis

4.1. Water surface flow regime
The flow regimes of the energy dissipators along the river and in the direction of river width are quite different. It is better to use 3D flow surface visualization and set the isosurface with a water volume fraction of 0.5, as shown in Figure 5; From Figure (a), (b) and (c), it can be seen that clustered energy
dissipation piers cause different level fluctuations in the flow of the river section, showing obvious 3D characteristics. The energy dissipation pier of 2# inclined energy dissipator is conducive to water flow, and its fluctuation amplitude is larger than that of the 1# energy dissipator, and the water level change of the 3# energy dissipator section is wavy; From Figure (d) and (e), the mainstream water potential energy is converted into kinetic energy after passing through the ribbed energy dissipation pier and occurs the typical hydraulic drop phenomenon, the water level in the width direction of the river is gentle, showing obvious 2D characteristics; For the flow regime of the 5 types of energy dissipation works, the turbulent degree of clustered energy dissipators are larger than that of the ribbed energy dissipation, of which 2# dissipation works fluctuates the most at the direction of river width, the average water depth of the 5# energy dissipator is the deepest, and the minimum water depth of the 4# energy dissipator is 0.10 m~ 0.30 m after falling, which is easy to cause the mainstream to directly wash the bottom of the river bed, and not conducive to the stability of the river bed.

Fig. 4 The flow regime of different energy dissipation works with the water volume fraction is 0.5

4.2. Velocity field distribution
The y = 0 section of C section in Cartesian coordinate system is shown in Fig. 5; the flow rate of the water flow changes drastically before and after passing through the stone pier. The water flows against the stone pier and then spreads out. In Figure (a), mainstream of 1# energy dissipator produces lateral vortexes from the sides of the stone pier, which enhances the flow resistance; In Figure (b), part of the water flow in 2# energy dissipation pier generates transverse vortices and rolls, and at the same time, the phenomenon of energy dissipation pier jumping by impact is obvious, which is conducive to energy dissipation by mixing air; In Figure (c), 3# energy dissipator water flow occurs transverse vortices and rolls, and it will obviously cause water flow hedging; The velocity distributions of 4#
energy dissipator and 5# energy dissipator have little change in the lateral direction, and the water flow is blocked by the ribbed stone pier, which raises the water surface and increases the depth of the water cushion, and the buffer effect is obvious. The local flow of the pier forms many vortices at the local impact, the mainstream moves downward, and a small part moves backwards in the opposite direction to the mainstream to raise the water level; compared with 4# energy dissipation, the water cushion of 5# energy dissipation is deeper, the vortex effect is more obvious, and the energy dissipation mechanism is similar to the energy dissipation in the deep pool.

![Velocity changes of the flow cross section along the river](image)

4.3. **Velocity changes of the flow cross section along the river**
The average cross-sectional velocity of the cross section of the 5 sections of the energy dissipator is measured at every 1 m of the narrow section in the C channel. Figure 6 shows the average flow velocity of over-current cross section of different energy dissipators. The over-current cross section of the energy dissipator suddenly decreases and increases, causing the average velocity of the 1#, 2#, 3# cross-section of the energy dissipator to have different periodic fluctuations along the river, and the speeds are ranged from 0.50 m/s to 1.00 m/s; the ribbed energy dissipation pier structure of 4# and 5# energy dissipator make the water surface rise in front of the pier, and after passing through the pier, the water potential can be converted into kinetic energy, resulting in a sudden increase in the longitudinal velocity of the flow through the pier. Because the cushioning effect of the water cushion makes the water flow rate drop significantly, the flow velocity is unevenly distributed along the river, and the range of change is relatively large; Among them, the longitudinal velocity and lateral flow velocity of the 4# energy dissipator are increased, and the velocity change is the largest; Comparing the inflow cross section X = 45 and the outflow cross-section X = 60 m velocity change, 1# energy dissipator increased by 3.58%, 2# energy dissipator increased by 4.93%, 3# energy dissipator decreased by 2.84%, 4# energy dissipator increased by 14.36%, 5# energy dissipator is reduced by 8.93%. Therefore, the average velocity of the water flow increases mostly is the flow through the 4# energy dissipator, and the largest decrease occurs in the average velocity of the outflow through the 5# energy dissipator.
Fig. 6 Average velocity of over-current cross section of different energy dissipators

4.4. Turbulent kinetic energy distribution

In turbulent flow, fluid mass points are continuously doped with each other in motion, making the velocity, pressure, and other element points change irregularly. Figure 7 is a turbulent kinetic energy distribution diagram of different energy dissipators at 0.5 times of the water depth along the river bed; from Figure 7, it can be seen that the distribution of turbulent kinetic energy of the 5 energy dissipators has a similar law: Near the back of energy dissipation pier, the turbulent intensity of turbulent area reaches maximum and turbulent kinetic energy contours are the most dense, and gradually decrease from the center area to the side wall and downstream; For the clustered energy dissipator, in Figure (a), (b) and (c), 3# clustered energy dissipator has the widest distribution of turbulence, and the turbulence dissipation is stable; 1# and 2# clustered energy dissipators are close to the river backflow, their turbulence intensities are mainly distributed behind the energy dissipation pier, and after the water flows through the 2# fastigiate clustered energy dissipating pier, the water flow hedging is strengthened, and the energy is converted from fluid shear to turbulent kinetic energy. The turbulent distribution area is wider than the turbulent distribution of the 2# clustered energy dissipator; In the 4# and 5# energy dissipators, as the water flows from the ribbed energy dissipating pier drops, the water flow generates vortices, and the mechanical energy is converted into turbulent energy consumption. In Figure (d) and (e), the turbulence area is more concentrated in the rear-concave angle area of the ribbed energy dissipating pier, and the peak intensity of turbulence is larger.
4.5. Energy dissipation rate
In this paper, the X = 45 m cross section of the upstream flow cross section and the X = 60 m cross section of the downstream flow cross section are selected to establish the energy equation to study the energy dissipation laws of different energy dissipators on the channel flow. The energy dissipation rate $\eta$ is:

$$\eta = \frac{\Delta E}{E_1} \times 100\% = \frac{E_2 - E_1}{E_1} \times 100\%$$  \hspace{1cm} (8)

$$E_1 = \Delta Z + H_1 + \frac{\alpha_1 v_1^2}{2g}$$  \hspace{1cm} (9)

$$E_2 = H_2 + \frac{\alpha_2 v_2^2}{2g}$$  \hspace{1cm} (10)

In the formula, $E_1$ and $E_2$ are the total energy of the calculated cross section of the upstream and downstream sections; $\Delta Z$ is the relative height of the upstream and downstream sections, that is, the difference in elevation of the bottom of the river beds at the upstream and downstream sections; $H_1$ and $H_2$ represent the average water depth of upstream and downstream sections, respectively; $v_1$ and $v_2$ are the average velocity of water flow in the upstream and downstream sections; $g$ is the acceleration of gravity, setting as 9.81 m/s$^2$; $\alpha$, $\alpha_2$ are the kinetic energy correction coefficients of the upstream and downstream sections, setting $\alpha_1 = \alpha_2 = 1.0$.

The energy dissipation rate of 1#, 2#, 3#, 4#, 5# energy dissipator is 68.01%, 64.12%, 65.75%, 67.73%, 69.81%; 2# energy dissipator has the worst energy dissipation effect, and the energy
dissipation rate is 64.12%, 5# energy dissipation works best for energy dissipation.

5. Conclusion
a) The 3D characteristics of the free water surface along the clustered energy dissipator are very significant. The water flows on the stone pier and then spreads out. The two sides of the main stream produce lateral swirling around the flow, and a small part of the water flow jumps up. The free water surface of the ribbed energy dissipator has obvious 2D characteristics, and the average flow velocity along the cross section fluctuates greatly. After the water falls, many vortices are generated at the concave corner of the pier behind the pier, which is beneficial to energy dissipation.

b) In different energy dissipation works, the turbulence area reaches the maximum intensity of turbulence and the densest contour of turbulence energy near the energy dissipation pier, and gradually decreases as it develops from the central area to the side wall and downstream.

c) Among the 5 types of energy dissipation workers, the energy dissipation rate of 5# energy dissipator is 69.81%, and the energy dissipation effect is the best.

In summary, the 5# “step-wise + ribbed” energy dissipator can form a water cushion, which is beneficial to protect the river bed from direct impact of water flow, and make the water flow smooth and the energy dissipator work effectively, so that it is superior to other energy dissipation schemes.

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