Numerical Simulation Study On Flows In Natural-like Fishway Of Low-head Junction

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Abstract: Based on a certain low-head ecological weir project’s requirement of the fishway construction and fish migration, a three-dimensional mathematical model of a natural fishway was established. The structure of the fishway which includes the bottom slope and the number of partition walls has great influence on the water flow conditions of the fishway pond room, which were analyzed from three aspects: the flow pattern of the tank room, the mainstream flow velocity, and the turbulent kinetic energy. The numerical simulation results were verified by model tests. The results of the research show that when the bottom slope is set to \(i = 1:35\), the natural fishway has an obvious three-dimensional water flow structure. What’s more, under this circumstance, the mainstream of the fishway is clear, the flow pattern is good. The overall turbulent kinetic energy is not large, and the maximum flow velocity at the vertical joint is basically the same, slower than 1.5ms⁻¹, which basically meets the target fish’s traceability requirements. With pebbles applied, the flow of the water in the pond room becomes richer. With the traceback path increased, the efficiency of fish communities can be vastly improved. The actual application of the fishway should adjust to the design of the ecological weir and its topographic and geological conditions.

1. Introduction
Ever since the 1960s and 1970s, in small mountain rivers a large number of low-water head weirs have been constructed to meet people’s needs, which are farmland irrigation, saving drinking water, small hydropower development and beautifying the environment. The construction of the barrage has made an irreplaceable contribution to the local place’s mode of production and economic development. However, at the same time, the construction of the barrage also cuts off the longitudinal communication channel of the river, which can block the fish’s upward path, and destroy the aquatic habitat\(^{[1-3]}\). The construction of the fishway can also restore the upstream path and connect fishes from the upstream and downstream, which in turn enriches the fish genetic exchange diversity. At the same time, it is also the only ecological compensation engineering measure to alleviate the adverse effects on fish caused by changes in hydrological conditions and the obstruction of weirs.

At present, the fishway is rarely applied in low-head weirs, it is mainly used in large and medium-sized projects or when the fish belongs to migratory fish. Therefore, it is safe to say that most researches focus on high-waterhead fishways. The fishway can be generally divided into two categories of engineering fishway and natural fishway. Compared to natural fishway, the vertical seam type fishway engineering fishway, which is a representative of engineering fishway has been widely used in research and application, owing to its structural rules, good water flow, adaptability to different water level fluctuations, and ease of construction and so on. On top of traditional fishway, natural
fishway made a move on broadening the basic concept of fishway construction. Fishway building materials and structural forms has been ecologically optimized to simulate the characteristics of natural rivers as much as possible to meet the retrospective requirements of different fish rather than knowledge migratory fish. The cross-section pattern of the natural fishway is flexible, and its structure and flow pattern are more abundant. Besides, compared with the traditional engineering fishway, it can better meet the requirements of biodiversity, and thus has received more and more attention in recent years. When it comes to the hydraulic characteristics and structural design of a natural fishway, researchers at home and abroad have taken the effects of block obstacles, staggered stone walls, permeable pebble walls, and plant modules on the hydraulic characteristics of the fishway into consideration[4-12]. In this paper, the thesis author combined the above existing research results and the actual characteristics and the fish passing requirements of a natural fishway-like construction in a low-head ecological barrage project. It performed a three-dimensional numerical simulation study of a natural pebble-like fishway[9], and analyzed the influence of structural changes such as the bottom slope and the number of walls on the hydraulic characteristics of the fishway. In doing so, this paper attempts to provide a technical reference for the construction of a mimicking natural fishway at the low-head ecological weir.

2. Three dimensional mathematical model

2.1. Control equations

The fluid motion follows the principle of mass conservation and Newton's second law, so the calculation needs to satisfy the continuity equation and the momentum conservation equation. The flow field simulation in this paper uses FLOW-3D software, and the "FAVOR" technology is used in the modeling, that is, the parameters containing area and volume fraction are added to the model, which are expressed in X.Y.Z system as:

**Continuity Equation:**

\[
\frac{\partial (uA_x)}{\partial x} + \frac{\partial (vA_y)}{\partial y} + \frac{\partial (wA_z)}{\partial z} = 0
\]  

**Momentum Equations:**

\[
\frac{\partial u}{\partial t} + \frac{1}{V_e} (uA_x \frac{\partial u}{\partial x} + vA_y \frac{\partial u}{\partial y} + wA_z \frac{\partial u}{\partial z}) = \frac{1}{\rho} \frac{\partial p}{\partial x} + G_x + f_x,
\]

\[
\frac{\partial v}{\partial t} + \frac{1}{V_e} (uA_x \frac{\partial v}{\partial x} + vA_y \frac{\partial v}{\partial y} + wA_z \frac{\partial v}{\partial z}) = \frac{1}{\rho} \frac{\partial p}{\partial y} + G_y + f_y,
\]

\[
\frac{\partial w}{\partial t} + \frac{1}{V_e} (uA_x \frac{\partial w}{\partial x} + vA_y \frac{\partial w}{\partial y} + wA_z \frac{\partial w}{\partial z}) = \frac{1}{\rho} \frac{\partial p}{\partial z} + G_z + f_z
\]

Where: \(\rho\) is fluid density, kg/m³; \(P\) is intensity of pressure, Pa; \(u, v, w\) is velocity component in x y z direction, m/s; \(A_x, A_y, A_z\) represents the flowable area fraction in 3 directions; \(V_e\) is the flowable volume fraction; \(G_x, G_y, G_z\) is the gravitational acceleration in 3 directions, m²/s²; \(f_x, f_y, f_z\) is the viscous force acceleration in 3 directions, m²/s².

This paper, the RNG turbulence model is used to close the Navier-Stokes equations to simulate the complex turbulent flow structure of the fishway. Similarly, the parameters including area and volume fraction are added to the model. The transport equation is expressed as:

**Turbulent kinetic energy equation:**

\[
\frac{\partial k}{\partial t} + \frac{1}{V_e} (uA_x \frac{\partial k}{\partial x} + vA_y \frac{\partial k}{\partial y} + wA_z \frac{\partial k}{\partial z}) = P_t + D_t - \varepsilon_t
\]

**Turbulent dissipation rate equation:**

\[
\frac{\partial \varepsilon}{\partial t} + \frac{1}{V_e} (uA_x \frac{\partial \varepsilon}{\partial x} + vA_y \frac{\partial \varepsilon}{\partial y} + wA_z \frac{\partial \varepsilon}{\partial z}) = 1.42 \frac{\varepsilon}{k_e} P_t + \frac{D_t}{\varepsilon} - 1.92 \frac{\varepsilon^2}{k_e}
\]

Where, \(P_t\) is the term of turbulent energy generation caused by the velocity gradient; \(D_t\) and \(\varepsilon_t\) is the term of turbulent diffusion. Its expression is:
Where,

\[ v_i \] and \[ v_e \] is the turbulent diffusion coefficient, which are determined by kinematic viscosity coefficients. Its expression is:

\[ v_e = 0.085 \frac{k^2}{\varepsilon} \] \hfill (10)

Simultaneously, the calculation process is strictly controlled to avoid causing huge turbulent kinetic energy dissipation that is not realistic.

Capture the free water surface with true-VOF method, the fluid volume function \( F \) is used to represent the Ratio of the volume of each unit to the volume of fluid that the unit can hold in the in the calculation domain, \( F = 1 \) means full, \( F = 0 \) means gas. By solving the transport equation of \( F \) to track the free water surface, the transport equation of the volume fraction \( F \) is:

\[ \frac{\partial F}{\partial t} + \frac{1}{V_F} \left[ \frac{\partial}{\partial x} (FA_u) + \frac{\partial}{\partial y} (FA_v) + \frac{\partial}{\partial z} (FA_w) \right] = 0 \] \hfill (11)

2.2. Calculation area and grid division

This study is based on an ecological barrage project[12], whose height is 1.5m. With a natural fishway the fishway, the natural fishway and the barrage are integrated into one. Unlike the characteristics of traditional vertical seam fishway, the fishway is ecologically optimized. The inlet elevation of the fishway is 77.4m high; the outlet elevation is 75m high, and the water heads of inlet and outlet are 1.5m high (the maximum). The partition walls is made up of natural pebbles, and the particle size of whose is between 0.6 and 1.2 m. Therefore, it is convenient for local material extraction and construction, and it can ensure that the similarity between the internal structure of the fishway and the natural stream bed can be as much as possible. Fish species that would pass the fishway are mainly fishes species with advantages including light-lip fish, sturgeon four large domestic fish and so on. According to the swimming ability of the fish, the maximum flow velocity of the control section of the fish passage pond room should be no more than about 1.5 ms\(^{-1}\). It requires that a generalized mathematical model of the fishway should be established. The structure of the fishway pool room and the layout of the partition wall are shown in Figure 1. The width of the single fishway is 10m; The bottom slope is designed at 1:22. Staggered, the partition walls are modeled as watertight, and there is a 1.2m wide exit across the road partition wall.

In order to be convenient in adjusting the profile of the fishway section according to the actual terrain and geological conditions during the arrangement of the fishway, it would be better to understand and more importantly to optimize the water flow conditions of fishway pool rooms like this. According to the above descriptions of the fishway structure, the slope and bottom width were changed, and the bottom hole of the slope was blocked. Five calculation conditions are listed, as shown in table 1 below.

\[
\begin{align*}
P &= \frac{\mu}{\rho V_F} \left[ 2A_i \frac{\partial u}{\partial x} + 2A_i \frac{\partial v}{\partial y} + 2A_i \frac{\partial w}{\partial z} + \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \left( A_i + \frac{\partial w}{\partial z} \right) \right] \\
D_x &= \frac{1}{V_F} \left[ \frac{\partial}{\partial x} (v_i A_i) + \frac{\partial}{\partial y} (v_i A_i) + \frac{\partial}{\partial z} (v_i A_i) \right] \\
D_y &= \frac{1}{V_F} \left[ \frac{\partial}{\partial x} (v_i A_i) + \frac{\partial}{\partial y} (v_i A_i) + \frac{\partial}{\partial z} (v_i A_i) \right]
\end{align*}
\]
Table 1. Number of different working conditions of low-head ecological fishway structure

| Species | Bottom slope, \( i \) | Number of partitions (n) |
|---------|-----------------|--------------------------|
| 0       | 1:22            | 16                       |
| 1       | 1:30            | 22                       |
| 2       | 1:35            | 26                       |
| 3       | 1:40            | 30                       |

In order to reduce the influence of the boundary of the inlet and outlet on the flow field of the pool chamber, the length of the flat section of the pool chamber takes 20m, with the simulation range includes the flat section of the fishway and the upstream and downstream sections. The hexahedral structured grid was used to mesh the model. The grid that was used in the fishway part was 0.2m, with a local encryption of 0.1m, a flat section grid size of 0.4m, and a total grid of 1.5 million.

2.3. Definite solution conditions and calculation methods

Both the inlet and the outlet of the three-dimensional mathematical model adopted pressure boundaries. The prototype water level at the inlet and outlet of the fishway is set to 78m, and the top is set to be the atmospheric pressure boundary condition. At the same time, the fluid volume fraction is set to 0, indicating that the fishway is full of air. The partition and bottom of the fishway are fixed boundary walls, whose surface is rough, and the rough height of the model is set to 0.01m. The model is set to the initial water level and initializes it with hydrostatic pressure to make the model converge faster. With the GMRES implicit algorithm for calculation applied, the calculation accuracy of the model is high. Besides, in this way the convergence becomes fast and it is not easy to diverge. The calculation uses an adaptive step size, with the initial step size set to 0.0001s, and the minimum step size set to 1E-05 s.

2.4. Model validation

The measured data of the established fishway was used to verify the efficacy of the model, and the flow velocity at the most important vertical joint of the fishway was also verified. With the maximum flow velocity is 1.42 ms\(^{-1}\) and 1.43 ms\(^{-1}\), respectively, the mathematical model measured that the average velocity at the vertical joints of the first and second partition walls were 1.32 ms\(^{-1}\), and 1.26 ms\(^{-1}\). The actual current measured at the vertical joints of the first and second partition walls were 1.4ms\(^{-1}\) and 1.35ms\(^{-1}\), with the maximum flow velocity at 1.41 ms\(^{-1}\), and 1.45 ms\(^{-1}\), respectively. Therefore, it is safe to say that the velocity calculated by the mathematical model is basically consistent with the measured data, which in turn indicates that this mathematical model is reasonable.

3. Results and Discussion

3.1. Analysis of the flow regime and velocity

The water flow of the low-head ecological fishway is obviously three-dimensional. The flow velocity cloud diagrams of the four groups of working conditions are simulated as shown in Figure 2, from which one can see that the water flow structure of each pond room in the fishway is similar. The only difference lies in the relative positions of the vertical seams and the position of the bottom holes in the fishway. This difference contributes to the difference in the positions of the mainstream of the fishway and the similar characteristics the hydraulic force. In order to analyze the flow characteristics of the fishway, the contracted section and the flow velocity, the observation points of number 2, 4, 6, and 8 and the intermediate third-level pool room were used as the representative pool room for analysis. The
observation points and areas are shown in Figure 3.

Figure 2. Distributions of flow velocity in bottom layer (ms⁻¹)

Figure 3. Arrangement of observation points on the fishway

According to the literature review [2], the vital factors that affect fish to upstream are the flow velocity of the contraction section of the fishway and the flow pattern of the pond chamber. It is required that the water flow velocity at the vertical seam of the fishway should be less than the design limit flow rate, so that the fish can complete upstreaming by passing through the contraction section smoothly. At the same time, the requirements for the interior of the fishway ponds should be clear. The ponds can be indoors, but they should not be too large. The backflow of excessively high velocity values can exist which helps fishes to avoid losing directions, especially for small-scale fish, because if fishes lose their direction, the efficiency of fish passing can be affected.

Figure 4. Distribution of water flow velocity in the chamber (i = 1:22)
a. 0.2h  b. 0.5h  c. 0.8h

Figure 5. Distribution of water flow velocity in the chamber ($i = 1:35$)

Existing engineering studies have shown that\cite{5,11}, the water permeability of a natural fishway’s partition wall should be less than 0.25, and it would be more appropriate if the size of the low head fishway be limited within the above range. In general, the four schemes have similar flow patterns, and their mainstream is clear. They are basically in the center of the pond room. With small return flow velocity, reflows occur on the left and right sides of the pond room, which can be used as a short rest place for fish. The mainstream should not be curved to a large extent, which is conducive to fish passing upstream.

Figure 6. Comparison of flow velocity at different measurement points of different species

The water flow of the low head natural fishway is also obviously three-dimensional, but in order to compare different bottom slopes’ influence on the water flow conditions of the fishway pond room, 0.2h, 0.5h and 0.8h (h is for the depth of the fishway) are analyzed in three representative layers, namely the bottom, middle, and surface layers of the fishway. The velocity distributions of different water layers in simulation conditions 0 and 2 are shown in Figures 4 and 5. From the figures one can see that the mainstream of the water flow in each water layer of the fishway is still clear, and the difference lies in the flow field's structure of each water layer. The maximum flow velocity at the bottom of the contraction section is slightly larger than that of the upper and middle layers. A "large and small flow velocity zone" has been created, which is more conducive to the target fish of different species and different water layers to pass upstream. What’s more, the energy dissipation effects of different bottom slopes are clearly different, and the flow velocity of the tank chambers is vastly different. Comparing the calculation results of working conditions of 1 and 2, the study finds that the indoor flow field structure of the fishway ponds under each simulation working condition are basically the same. Therefore, related information will not be mentioned repeatedly here.

Among the schemes, there are two schemes that are when the bottom slope are $i = 1:22$ and $i = 1:30$, both of whose flow velocity at the contraction section of the fishway exceeded 1.5 ms$^{-1}$, which do not meet the energy dissipation requirements. Therefore, under the condition that other parameters remain unchanged, the slope of the bottom slope should be reduced. When the slope is changed to $i = 1:35$,
the maximum flow velocity of the contracted section is less than 1.5 m s\(^{-1}\), which means that it can meet the design requirements. This article compares the flow velocity of different measuring points of the four schemes in detail. It can be known from figure 6 that it would be more appropriate to set the bottom slope of the low-waterhead fishway to 1:35 in this design. What’s more, continue to slow down the bottom slope is not only of little significance but also can greatly increase the scale of the project.

3.2. Analysis of turbulent kinetic energy

The turbulent dissipation of water flow during the fishway operation has a certain amount of turbulent energy\(^{[7]}\). If the turbulent energy is too high, that means fishes need to overcome the turbulence obstacles and consume more energy. This can reduce the fish’s swimming and balance ability, making it unable to complete the retrospection smoothly. Therefore, the construction of appropriate turbulent kinetic energy provides good and stable water flow conditions for fish, which is one of the basic prerequisites to ensure the fish’s traceability. Literature review\(^{[6,10]}\) suggest that when the turbulent energy of the fishway ranges from 0.02 to 0.035 m\(^2\)s\(^{-2}\), the energy consumption of fish going backward is less, and at this interval it is favorable for fish to go upstream.

The numerical calculation results suggest that the rule of the turbulent energy change of the mainstream area is similar to that of the flow velocity. After the water flow passes through the contraction section, the turbulence energy would gradually decrease, and it would also gradually increase before the next contraction section. When the bottom slope is sent to \(i = 1:22\), 88% of the systolic kinetic energy of the contraction segment is beyond the range of fish preference. From this perspective, the body shape cannot meet the requirement of the fish upstreaming. Besides, when the bottom slopes is set to \(i = 1:22\) and \(i = 1:30\), 88% and 64% of the systolic kinetic energy of the contraction section are beyond the range of fish preference. From the perspective of turbulent kinetic energy, these two types of slopes cannot meet the fish’s upward passing. However, when the bottom slope is set to \(i = 1:35\) and \(i = 1:40\), the turbulent kinetic energy of the contraction section is basically within the range of fish’s preference, and only a small fraction exceeded the range. Therefore, from the perspective of turbulent kinetic energy, the bottom slope \(i\) should be set less than 1:35 which can basically meet the fish’s preference.

Figure 8 presents the distribution of turbulent kinetic energy at different positions on different bottom slopes, from which it can be seen that as the \(i\) value of the bottom slope becomes smaller as the turbulent kinetic energy decreases, which is beneficial for fish to trace back. However, the amplitude of turbulent energy decreases as the bottom slope decreases to \(i = 1:35\), and the amplitude of turbulent energy also falls within the range of fish preference. Therefore, in order to reduce the investment on this project and the scale of land occupation, setting \(i = 1:35\) on the bottom slope of the low head weir can basically meet the fish’s retrospective requirements.

![Figure 7. Distributions of turbulent kinetic energy (m\(^2\)s\(^{-2}\))](image-url)
4. Conclusion

Based on a certain low-head ecological weir project’s requirement of the fishway construction and fish migration, a three-dimensional mathematical model of a natural fishway was established. This study analyzes the influence of changes in the structure of the pool room, such as the bottom slope and the number of partition walls, on the flow conditions in the pool room. The research finds that:

1) The low-head natural fishway has an obvious three-dimensional hydraulic characteristic. Its mainstream is clear; the turbulent kinetic energy is overall reasonable; if a suitable bottom slope is selected it can basically meet the design hydrodynamic conditions and thus fish can pass upward smoothly.

2) The flow patterns of the surface, middle and bottom layers of the natural fishway pond are different, which means that one can increase the path for different layers of fish and effectively improve the efficiency of fish passing.

3) The low head natural fishway can be well integrated with the ecological weirs and has a certain promotion and application value.

The mathematical model applied in this article made some generalizations on the natural fishway. In fact, the natural fishway is made of natural pebble materials and the shape of the pebbles are different, which makes it difficult to achieve a uniformity in the cross section of the water. The shape of the cross section are all quite different, and this requires a further study.

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References

[1] Zhonnong Chang, Xiaohong Cao, Huaifeng Ge.Status and prospection of fish pass construction in China[J]. Journal of Hydraulic Engineering: 2012,43(02):182-188+197.
[2] Jinchao Xu, Xiaogang Wang, Xuan Guoxiang et al. Physical model test study on nature-like fishways[J]. Advances in Water Science: 2017,28(06):879-887.
[3] Wang Siying, Yang Wenjun,Huang Minghai et al. Fish Passage and Habitat Restoration Techniques in China: State of the Art[J]. Journal of Yangtze scientific research institute.:2017,9(19):11-17.
[4] Li Shengqing, Ding Xiaowen, Liu Daoming. Overview of nature-simulating fishway [J]. Yangtze River: 2014, 45 (21): 70-73 + 96.
[5] Zhiping Guo, Xihuan Sun, Zhiyong Dong. An Experimental Study of Turbulent Structures in a Flat-Crested Weir-Type Fishway[J]. MDPI, 2019, 9(19).

[6] Bingqian Wei, Lei Huang, Haishi Yuan et al, Hydraulic characteristics and optimization of fishway combined with vertical slot and nature-like section [J]. Hydro-Science and Engineering: 2019 (04): 9-16.

[7] Marta Puzdrowska, Tomasz Heese. Turbulent Kinetic Energy in Bolt Fishway[J]. MDPI, 2019, 1(2).

[8] Guangning Li, Shuangke Sun, Ziqi Guo et al. Physical model test of hydraulic and fish passing performance of natural fish channel [J]. Transactions of the Chinese Society of Agricultural Engineering, 2019, 35(09): 147-154.

[9] J.M. Duguay, R.W.J. Lacey, J. Gaucher. A case study of a pool and weir fishway modeled with OpenFOAM and FLOW-3D[J]. Elsevier B.V., 2017, 103.

[10] Keiko Muraoka, Satoru Nakanishi, Yuich Kayaba. Boulder arrangement on a rocky ramp fishway based on the swimming behavior of fish[J]. Elsevier GmbH, 2017.

[11] Bryan A. Marriner, Abul B.M. Baki, David Z. Zhu, Steven J. Cooke, Christos Katopodis. The hydraulics of a vertical slot fishway: A case study on the multi-species Vianney-Legendre fishway in Quebec, Canada[J]. Elsevier B.V., 2016, 90.

[12] Qiaoyi Hu, Long Zhu. Numerical study on flows in nature-like fishway combined with slot and orifice[J/OL]. China Rural Water and Hydropower, 2020, 1-8.