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Original Research Paper

Study on the Optimization of Fishway Inlet

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ABSTRACT

Fishway is the only path through which the aquatic animal fauna can smoothly pass obstruction of its upstream migration. The conventional design and study of fishway are mainly focused on the internal structure and flow conditions, while the researches on the layout of fishway inlet and the optimization of fishway structure are relatively less. That leads to difficulties or even impossibilities for fishes to enter the fishway in engineering applications. In this paper, the principles of the fishway inlet location selection were verified by numerical simulations through establishing the ecological hydraulics indexes of fishway inlet as well as combining the fish swimming performance with the flow pattern index of fishway inlet. Whatђs more, a new fishway inlet structure which can control the discharge and velocity was proposed so as to take into account the role of tempting fish and making up water. Through the above methods, the fishway inlet has been optimized and it can help fish smoothly finish migration.

INTRODUCTION

Dam, constructed on the river, will break the original continuity of the river channel, leading to changes in the environment of aquatic habitat. For migratory fish, they can not complete their life cycle, resulting in population decline. For non-migratory fish it will affect the genetic exchange between populations, leading to a reduction of genetic diversity (Li et al. 2009). In water conservancy projects, fish passage facility is a man-made channel, aiming at allowing fish to smoothly pass the obstacles. Fishway, as a common type of fish passage facilities, is a man-made water channel for fish migration via flume and dam. The structure of fishway mainly includes inlet section, channel section, outlet section, auxiliary facilities, etc. (Wang et al. 2005). Fishway is the only pathway through which the aquatic animal fauna can smoothly pass obstruction of its upstream migration. Thus, fishway has become the key facility to improve the water ecology and has significance for the restoration of free passage for fish and other aquatic species in the river.

Currently, the design and study of conventional fishway are mostly focused on the internal structure and flow conditions. The internal flow velocity can guarantee the requirements of migratory fish, based on the optimization of the internal structure of the fishway (Beach 1984). Mainly due to lack of recognition of the fish habits and migration law, researches on the location layout and structure of fishway inlet are seldomly reported. In engineering applications, it is difficult or even impossible for fish to enter the fishway. By monitoring data and some successful experience of fish passage facilities, some studies have proposed the principles of selection for fishway inlet location and also the structure of fishway inlet was improved (Bunt 2001).

One of the key factors of fishway design lies in wether fishes can quickly and accurately enter the fishway inlet. On the basis of previous studies, the eco-hydraulics indexes for the design of fishway inlet were established in this paper as well as combined the fish swimming performance with the flow state index of fishway inlet. Further more, the optimiz-ations of layout and structure of fishway inlet were studied in this paper.

ESTABLISHMENT OF ECOLOGICAL HYDRAULICS INDEXES OF FISHWAY INLET

Swimming performance is considered as the main character determining survival in many species of fish and other aquatic animals. On the entrance of fishway, the swimming performance of fish is classified into three categories: response flow speed, critical swimming speed and burst swimming speed. Response flow speed is the velocity that fish begin to react, the indication standard of the reaction is usually tend to change the flow direction of the fish swimming. Critical swimming speed is the maximum velocity that can be maintained by fish within a specific period of time and it is also the boundary velocity of fish stabilized swimming and sprint -slide style swimming. Burst swimming speed is the highest speed which fishes are capable, and can be maintained only for a short period (Beamish et al. 1978). Therefore, reverting fish swimming performance to hydraulic index, the requirements of fish migration can be better satisfied through engineering measures.

The premise condition for fish migration via fishway is that it can first pass fishway inlet and then enter fishway. Therefore, the velocity near the fishway inlet is necessary to set as “fish tempting velocity”. That is, the velocity at the fishway inlet can be perceived by fish, so that it is tempted and can continue to run smoothly in fishway. The minimum velocity for fish tempting velocity is response flow speed. The best fish tempting velocity is critical swimming speed.

Fishway inlet is also known as flow outlet. Fish will continue to run up if it is tempted into the fishway inlet by “fish tempting velocity”. Therefore, “fishway inlet velocity” should be between critical swimming speed and burst swimming speed. Critical swimming speed is the minimum velocity at the fishway inlet, while burst swimming speed is the maximum velocity at the fishway inlet.

THE LOCATION SELECTION OF FISHWAY INLET

At present, there is less information about how to look for fishway inlet as well as efficiency and attracting water, and internationally there have been no study results of fish clearly responding to micro-flow condition yet. In spite of this situation, certain experience in inlet location arrangement of fish passage facility and attracting water construction has been accumulated based on the fish’s getting back observation of more than 100 years, and also some successful fish passage facilities have been constructed. Generally, fish would swim up as soon as possible if water flowed out from the dam or power station tailrace with high velocity, and therefore, the inlet locations of already-established and successful fish passage facility are always closer to the dam or power station tailrace as much as possible, and also the open direction of the inlet could ensure fish directly access to it. It is difficult for fish to find out the inlet if fish passage facilities are too far away from the dam or power station tailrace and the flowing water from the inlet do not have enough attraction in contrast to the river’s flow conditions. Besides, the velocity gradient is not enough in the central section of river channel so that fish is not attracted to be there, thus, the inlet should be set at the bank as close as possible.

When selecting the location arrangement of fishway inlet, it need numerical simulation and model experiment to verify. Rely solely on experience and engineering examples are far from enough. In this paper, the principles of the fishway inlet location selection were verified by numerical simulations. The standard 3d $k-\varepsilon$ model was used for the calculation in a practical project (Wang 2004), and two fishway inlets were established in the calculation: inlet 1 was set at the left side close to the outlet of the power station tail water channel and its angle with the mainstream direction was 25°. At the same time, fish is very likely to continue up running after passing the power station tail water channel area, and in order to let more fish pass the river channel, inlet 2 was set at the location about 100m downstream from the left band of the auxiliary weir and its angle with the mainstream direction was 45°. The net width of fishway was 1m, water depth was 1m, and the discharge was 1m^3/s. The control equations are as follows (Li et al. 2004, Mao et al. 2010).

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad ...(1)$$

Momentum equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial \rho}{\partial x}+$$

$$\left(\nu+\nu_t\right)\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial x\partial y}+\frac{\partial^2 u}{\partial x\partial z}\right) \qquad ...(2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial \rho}{\partial y}+$$

$$\left(\nu+\nu_t\right)\left(\frac{\partial^2 v}{\partial x\partial y}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial y\partial z}\right) \qquad ...(3)$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial \rho}{\partial z}+$$

$$\left(\nu+\nu_t\right)\left(\frac{\partial^2 w}{\partial x\partial z}+\frac{\partial^2 w}{\partial y\partial z}+\frac{\partial^2 w}{\partial w^2}\right)+g \qquad ...(4)$$

Turbulent kinetic energy equation *k* and dissipation rating equation *e*:

$$\frac{\partial k}{\partial t}+u\frac{\partial k}{\partial x}+v\frac{\partial k}{\partial y}+w\frac{\partial k}{\partial z}=\frac{\partial}{\partial x}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x}\right)+$$

$$\frac{\partial}{\partial y}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial z}\right)+\frac{G_k}{\rho}-\varepsilon \qquad ...(5)$$

$$\frac{\partial \varepsilon}{\partial t}+u\frac{\partial \varepsilon}{\partial x}+v\frac{\partial \varepsilon}{\partial y}+w\frac{\partial \varepsilon}{\partial z}=\frac{\partial}{\partial x}\left(\frac{\nu_t}{\sigma_z}\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}$$

$$\left(\frac{\nu_t}{\sigma_z}\frac{\partial \varepsilon}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\nu_t}{\sigma_z}\frac{\partial \varepsilon}{\partial z}\right)+\frac{\varepsilon}{k}C_{1\varepsilon}\frac{G_k}{\rho}-C_{2\varepsilon}\frac{\varepsilon^2}{k} \qquad ...(6)$$

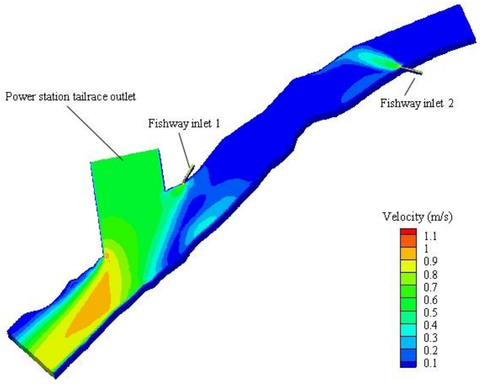


Fig. 1: The calculation result of the three-dimensional flow field.

Where,

$$G_k = \rho v_t \left\{ 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2 \right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 \right\} \quad ...(7)$$

$$v_t = C_\mu \frac{k^2}{\varepsilon} \quad ...(8)$$

u, v, w - the velocities in the directions x, y, z (unit: m/s);

ρ - the density of water body (unit: kg/m^3);

p - the time average intensity of pressure (unit: Pa);

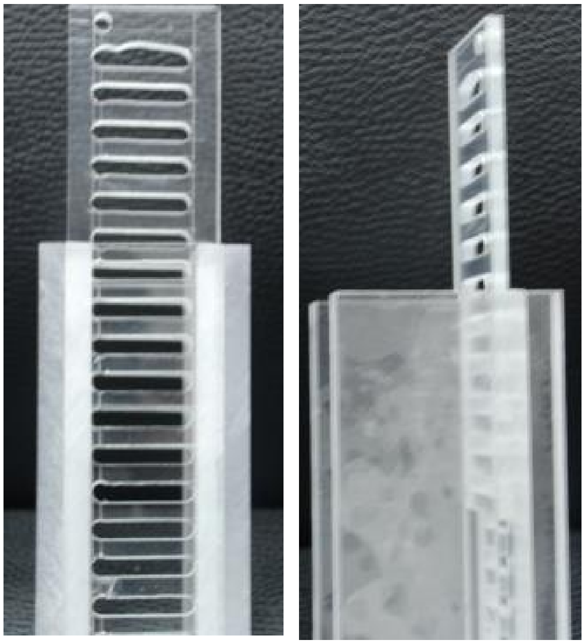
v, v_t - the water molecules viscous coefficient and turbulent eddy viscosity coefficient, respectively;

g - the gravitational acceleration (unit: m^2/s);

k [m^2/s^2], e [m^2/s^3] - the turbulent kinetic energy and turbulent kinetic energy dissipation rating;

σ_k, σ_ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ - the empirical constants (C_μ = 0.09, =1.44, =1.92, =1.0, and =1.3, in this model);

Fig. 2: The device of tempting fish and making up water at fishway inlet.



(a) (b)

Fig. 3: The flow control fence at fishway inlet: (a) front view; (b) side view.

The calculation result is shown in Fig. 1. The discharge of fishway flow is small in comparison with the river flow, and also the size of fishway inlet is very small in comparison with the whole river channel. Therefore, it featured "the hole of needle". So the location of fishway becomes the key to success. From result of the numerical simulation (Fig. 1), we can get that in the whole calculation range the maximum flow velocity, which was about 1.1m/s, appeared at the power station tailrace outlet and the intersection with the downstream river way. The flow velocity at the power station tailrace outlet and its downstream river area was higher, which was in the range of 0.5~1.0m/s. Fishway inlet 1, close to the power station tailrace outlet, could affect a wider area in comparison with fishway inlet 2. Fishway inlet 2 was at the area 100m downstream from the auxiliary weir, and there existed a long "dead zone" when fish migrated along the river way, making the migration of fish disadvantageous. According to the simulation results, the most suitable position of fishway was usually the same side with power plants of the hydropower station in the river. Power station tailrace outlet is the main way to the downstream discharge and the most direct area to lure the fish. It could make the "dead zone" formed between the barrier and the fishway inlet reduce to minimum when the fishway inlet is close to the dam or power station tailrace outlet. This is very important, because the anadromous migratory fish may not

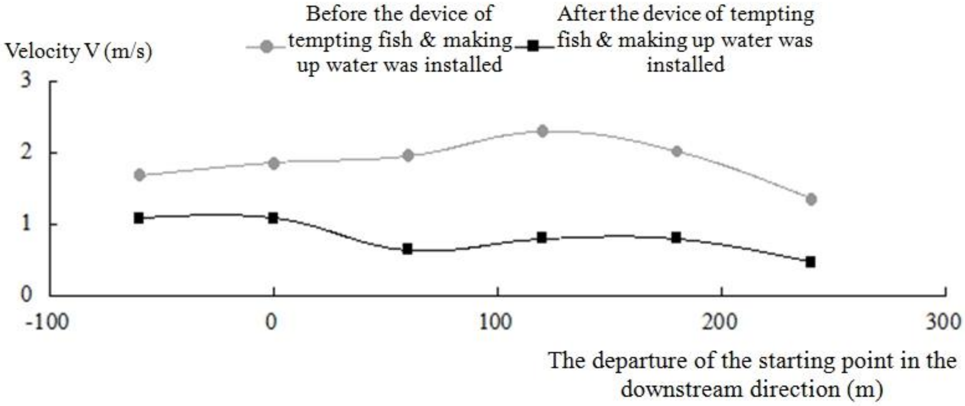


Fig. 4: The curve about the change of the velocity near the local downstream side.

perceive the inlet and still remain trapped in the dead zone.

OPTIMIZATION OF FISHWAY INLET

The device of tempting fish and making up water: In order to induce fish into the fishway inlet, it need to set water pipes, if necessary, in the previous design of fishway inlet. If making up water was simply relying on water diversion addition, the effect of tempting fish was difficult to meet the requirements and the cost necessarily increased, and also the energy dissipation measures for flowing water from the pipes should be taken. Then, via locally water drop, a new fishway inlet structure was proposed, making use of the upstream flow for tempting fish and making up water, and simultaneously the way of implementing flow control was more reasonable.

The device of tempting fish and making up water mainly included the functions of gathering fish and retaining wall, for the purpose of tempting fish into the inlet and then making them stay near the inlet. The purpose of flow control fence and energy dissipation section was to increase wetting and produce the flow of tempting fish, and simultaneously the velocity of making up water was ensured to be lower than the turbulent swimming speed of fish. A control gate was established at fishway inlet, and block was set before the energy dissipation section. Its structure is shown in Fig. 2.

The flow control fence at fishway inlet was to implement the control of flow rate and flow velocity by adjusting the relative positions of two pieces of orifice plates. If the pieces of orifice plates were well overlapped, the pass water flow was the maximum so that only one piece of orifice plate was equivalently in existence. However, the pass water flow was the minimum if the two pieces of orifice plates were alternatively arranged and also their relative positions were the maximum (Wu 2008). The velocity at fishway inlet was lowered in coupling with the energy dissipation section, and the disorderly and intense water from the flow control fence became more quietly, so that the velocity at fishway inlet was controlled, and also the requirements on velocity were fulfilled. The flow control fence at fishway inlet is shown in Fig. 3; the single orifice plate was composed of uniform transverse cracks.

Separation net was installed in the downstream direction of flow control fence for mainly blocking fish. Thus, the fish into the gathering and retaining wall could only swim toward fishway inlet, but smaller fish in migration was likely to run from the flow control fence, while separation net could ensure fish not to enter the control fence location. To let fish easily find the fishway inlet, a section of wall was extended from the downstream of the inlet for generating a section of tempting fish in fishway, while the measures of actively tempting fish could be added through setting lights and rushing shoot water at the section of tempting fish.

Experiment of tempting fish and making up water: The device was installed in the hub model of another practical project to implement the test of tempting fish and making up water, and a particular fish was selected for the study. Water releasing test was conducted with 2 sets, 3 sets, 4 sets and 6 sets respectively, for the discharge of 679.4m^3/s, 1105.1m^3/s, 1579.8m^3/s and 2750.6m^3/s. The velocity near the local downstream side of the device of tempting fish and making up water and the velocity at the area of fishway inlet were measured, and also the control method of completely overlapping two orifice plates was used for the flow control fence in measuring velocities. The water releasing test was conducted with 4 sets running at the same time, and the discharge is 1579.8m^3/s, which was used as the typical working condition. The curve about the change of the velocity near the local downstream side of the device of tempting fish and making up water is as shown in Fig. 4. Combined

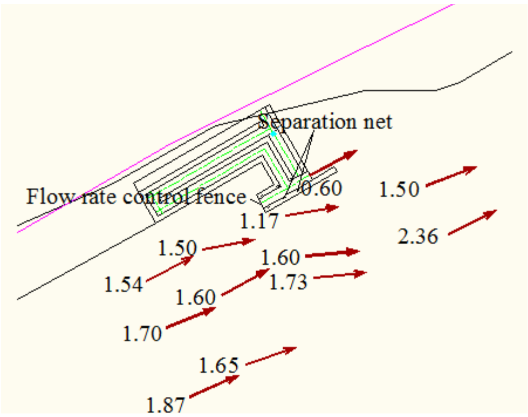


Fig. 5: The velocity distribution near the local fishway inlet area of 2 sets running (m/s).

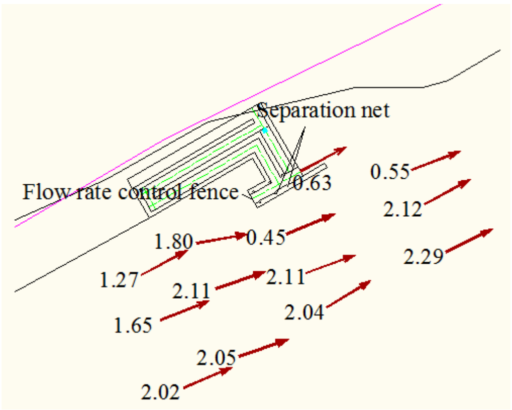


Fig. 6: The velocity distribution near the local fishway inlet area of 3 sets running (m/s).

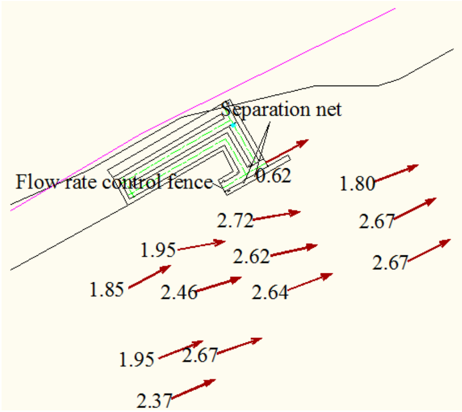


Fig. 7: The velocity distribution near the local fishway inlet area of 4 sets running (m/s).

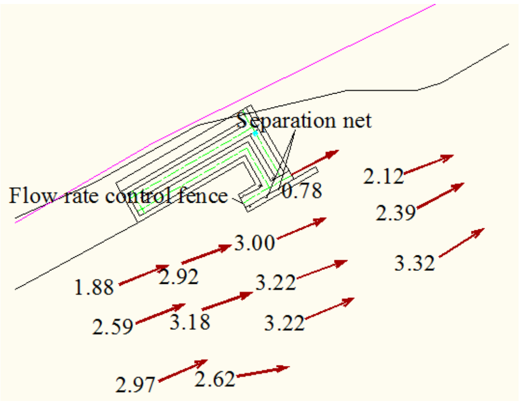


Fig. 8: The velocity distribution near the local fishway inlet area of 6 sets running (m/s).

with the results of the other three experiments, it is concluded that the velocity near the downstream side can be well reduced by this device, to meet the requirement on the velocity which is higher than the response flow speed and close to the critical swimming speed of the target fish, and finally help fish find the fishway inlet.

According to the measurement result, the velocities near fishway inlet were 0.60m/s, 0.63m/s, 0.62m/s, and 0.78m/s under 2 sets, 3 sets, 4 sets and 6 sets running respectively. The distributions of the fishway inlet velocity in the four working conditions are shown in Figs. 5, 6, 7 and 8. In contrast to the nearby high-velocity, the flow velocity near the inlet was significantly lower, which could meet the requirements of the fishway inlet flow velocity (higher than the critical swimming speed and lower than the burst swimming speed of the target fish). Even after the operation monitoring, the velocity of fishway inlet exceeds the fish burst swimming speed; it is only need to adjust the gap flow control fence rate to control the fishway inlet velocity.

CONCLUSION

Through the study, the conclusion can be drawn up as follows.

Firstly, the previous fishway inlet design did not give a better reflection to fish swimming performance indexes in terms of flow pattern. In this paper, the ecological hydraulics indexes of fishway inlet were established, and fish swimming performance was reverted to hydraulic index, and then the requirements of fish migration were better satisfied through engineering measures.

Secondly, fishway inlet in practical engineering must be located in the place where fish is concentrated during its upstream migration, and the concentrated place is decided by the characteristics of the downstream water and hydropower station structure. In this paper, the 3d flow field of the whole watercourse added with a fishway was simulated using the standard 3d k-model (Mao et al. 2012). The principles that the concentration area of fish is at the power station tailrace, the fishway inlet location should be chosen near the power station tailrace and is in the same side to the tail water of the power station have been verified.

Thirdly, the purpose of tempting fish and making up water was achieved by generating power and discharging flow at upstream, optimizing the structure of fishway inlet, introducing river water locally, and referring to the local flow difference, so that the energy dissipation problem caused by the reservoir pressure piping water diversion was prevented, and then the cost of fishway operation was reduced.

Fourthly, the optimized fishway inlet can achieve the control on flow discharge and velocity by adjusting the relative position of two orifices of the discharge-controlled fence. The fishway inlet system can generate a locally higher flow velocity of tempting fish if the discharged flow of the power station is reduced and the flow velocity at left bank is low. When the full-work of plants or higher power flow discharge make the velocity in the section of river generally higher than the burst swimming speed of fish, the fishway inlet system similar to wing dam at the left bank can provide a certain range of low-velocity rest area, and the effect of tempting fish and inducing fish to enter fishway can be played for different target fish, and then complete the migration.

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