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Research paper

Forebay hydraulics and fish entrainment risk assessment upstream of a high dam in China

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Abstract

Hydropower operations can induce significant variation of velocity field upstream of intakes and may lead to fish entrainment into turbines. In this study, the flow fields upstream of a high dam in China under different intake and spillway operation patterns were investigated theoretically using potential flow solution and computational fluid dynamic modeling, and experimentally in a 1:50-scale physical model. Flow fields induced by multiple intakes and by a line sink tends to be the same at about two times of the distance of adjacent operating intake upstream of the intakes. Different operation scenarios were analyzed to improve the general understanding of characteristics of upstream flow and to reduce the risk of fish entrainment. The extent of the risk zone for fish entrainment defined by specified thresholds of velocity and acceleration indicate that smaller water depth over submerged intake means a higher risk of fish entrainment.

Keywords: CFD modeling; Fish entrainment; Forebay hydraulics; Physical modeling; Potential flow solution

1. Introduction

The construction of hydropower dams will modify river hydrological behaviors and affect flow velocity field upstream and downstream of a dam. Hydropower operations can prominently influence the flow patterns upstream of the intakes and spillways, thus risk the fish entrainment into turbines and impact the ecological environment in the reservoirs. On the other hand, the better understanding of intake-induced flow field can allow the hydropower operators to optimize their operations, reduce the risk of intake-induced fish entrainment, and minimize adverse environmental impacts.

At low flow velocities, fish can swim at their ease and orient towards any direction. However, a high flow velocity, strong shear stress and turbulence could dramatically influence fish movement, which may cause fish to be sucked into the turbines and lead to fish mortality. The fish entrainment mechanism is not only associated with the natural biological features of different fish species, but also the velocity and acceleration distribution of flow field (Cada et al., 1997; Coutant and Whitney, 2000). Therefore, to reduce fish entrainment risk, it is important to understand velocity fields upstream of power intakes. In addition, studies of fish entrainment can also provide important information for developing fish protection technologies such as fish collection system, fish diversion system, physical barrier and behavior barrier (Taft, 2000). Limited researches have been done to minimize fish morality by repelling fish from the zone of entrainment (Edinger and Kolluru, 2000; BC Hydro, 2006). Cada et al. (1997) and Meselhe and Odgaard (1998) proposed

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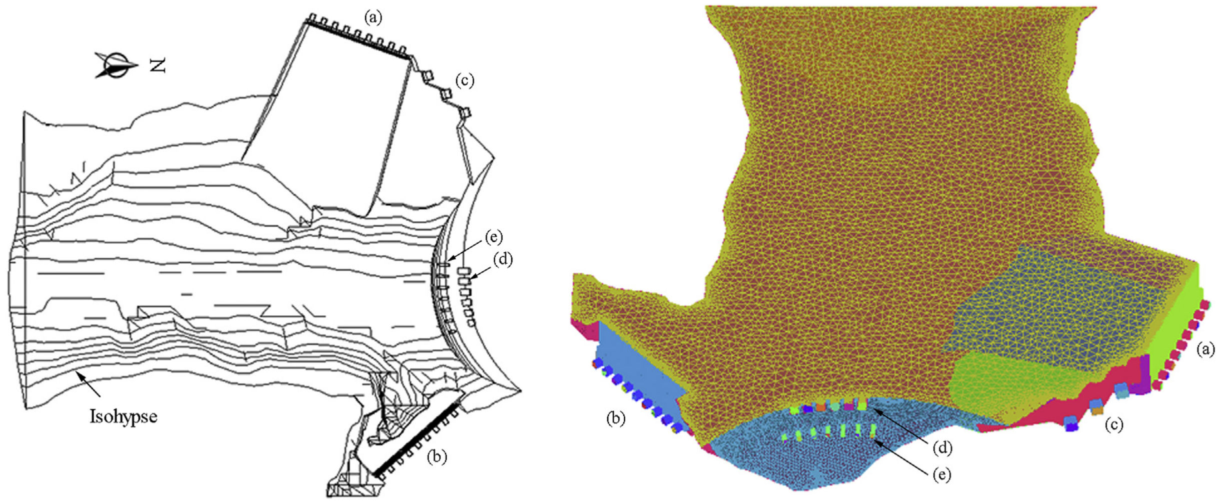

Fig. 1. Plan view (left) and schematic view of the dam intakes and spillways with CFD Model mesh (right): (a) intakes on the left bank; (b) intakes on the right bank; (c) spillway tunnels; (d) surface orifices/spillways; (e) deep flooding orifices.

that flow acceleration has implication for fish habit and migration through affecting body orientation and swimming mode of fishes. Studies by NPP (2005) and BC Hydro (2006) showed dangerous regions of fish entrainment could be described by two thresholds: 0.1 m/s for flow velocity and 0.0001 m/s^2 for acceleration.

Flow field upstream of intakes can be analyzed using potential flow theory. Treating an intake as an orifice, the flow field upstream of a single or multiple intakes was investigated by Shammaa et al. (2005). Bryant et al. (2008) incorporated pressure gradient effects at the intake in their solutions. A closed-form solution of the potential flow in a contracted flume was given by Belaud and Litrico (2008). Islam and Zhu (2011) studied hydrodynamic components of flow upstream of two-dimensional intakes with different sizes and locations.

Due to the three-dimensionality of the dam geometry and flow field upstream of hydropower intakes, three-dimensional (3D) computational fluid dynamics (CFD) model have been used to capture the complex flow features. Meselhe et al. (1998, 2000) presented studies of numerical modeling for Wanapum dam. Khan et al. (2004) developed a 3D CFD model of a turbine unit in Dalles dam to investigate the impact of the proposed blocked trash rack on the turbine intake hydraulics. Bhuiyan et al. (2009) modeled the flow upstream of Revelstoke and Mica dams in British Columbia in Canada, using numerical code to assess the risk extents of fish entrainment. In some of those studies, numerical model results were validated by physical model and/or field data. As flow patterns vary with reservoir depth, flow rate and various operating conditions, application of the CFD model is expected to be efficient for assessing entrainment risk for fish utilizing different water depths upstream of the intakes.

In this study, the flow field upstream of a high dam in China under different operational conditions was investigated and the associated entrainment risk for the purpose of operational optimization was assessed. This hydropower station has a total installed capacity of 12 million kW and an average annual energy output of 51.5 billion kWh. Its reservoir has a total capacity of 20.6 billion m^3 and an average annual inflow rate 4140 m^3/s. The dam has nine powerhouse intakes on the left and the right banks (initial design), three spillway tunnels next to the intakes of the left bank (looking downstream), six surface-orifices and seven deep-orifices in the dam (Fig. 1). The normal reservoir water level is 825 m and the dead water level is 765 m, with a corresponding discharge at each intake of 427 m^3/s and 386 m^3/s, respectively. The discharge of each spillway tunnel is about 4084 m^3/s. The intakes on the left bank are located near the bottom of the approach channel, while the intakes on the right bank, having the same size as the left intakes, are located at the same elevation but their upstream bathymetry is different. One trash rack is placed in front of the intakes of each bank.

To predict flow characteristics under various operation scenarios and to assess fish entrainment risk, a combination of theoretical analysis, CFD modeling and physical model testing have been employed in this study. Scenarios under different operating conditions are listed in Table 1. Scenario 1 has the nine left intakes in operating under the normal reservoir level. Scenario 2 has the same condition as in Scenario 1 but with three spillways also in operation. Scenario 3 has the nine left intakes in operation under the dead water level. Scenarios 4 and 5 both have four left intakes but with different

Table 1
List of operation scenarios.

Scenario number	Name	Left intakes	Water level (m)	Discharge per intake (m^3/s)
1*	825L9	All	825	427
2*	825L9p	All + 3 spillways	825	427/4084
3*	765L9	All	765	386
4	825L4a	1,2,3,4	825	427
5	825L4b	1,3,5,7	825	427

Note: * represent that it was also carried out by physical model experiments.