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Analysis on Sensitivity of Parameters in Numerical Simulation of Dissolved Gas Supersaturated in Spillway Discharges

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ABSTRACT

High concentration of total dissolved gas (TDG) in the tailrace of high dam may induce gas bubble disease to the fish for lethal effect. Thus, the distribution of the TDG concentration in the plunge pool and immediately in the downstream of dam becomes critical. In order to proves to be effective and convenient, but the determination of the model parameter relies on field observed data and the calibration of the parameter is time-consuming. In this paper, the predictive relationship of the parameter in the TDG transport equation with a source term is developed. Observed field data from six spillways in China were used to fit the source parameter that the predictive relationship needed. The inclusion in the predictive relationship will allow for the estimation of the source parameter representing the mass transfer between bubble/water interfaces and may give an insight into the mitigation of high TDG concentration downstream of spillways.

INTRODUCTION

The total dissolved gas (TDG) supersaturation occurred in spillway flowing downstream of diverse hydraulic structures has been recognized as a negative environmental effect for aquatic organisms (Weitkamp 1980). The TDG concentration range of influence is a key factor to prevent the fish from gas bubble disease. It is important to determine the numerical model parameters.

The source of high TDG level is the dissolution of the entrained air under the high pressure. Orlins et al. (1999) performed experiments to forecast TDG concentration in the downstream flows of a spillway, despite effective but expensive. DeMoyer et al. (2003) studied the multivariate process including air entrainment, mass transfer between air-water interfaces through the normative testing method for gas transfer in aerated systems. Politano et al. (2009) developed a multiphase flow model which coupled a modified bubble-induce turbulence term to calculate the distribution of dissolved gas concentration. All these researches are based on the field data of low dams that limit the application of high dams. In this paper, the hydraulic field is predicted via the Renor-malization Group (RNG) $k-\varepsilon$ turbulence model providing anisotropic closure for the multiphase Reynolds Averaged Navier-Stokes (RANS) equations. The TDG concentration is predicted through the convection diffusion equation with a TDG source term using filed data.

The major goal of this study is to derive a predictive formula for the parameter (β) consisting of averaged eddy viscosity coefficient in the plunge pool, the discharge water head, and downstream river depth. In addition, field data for different type of dams under several operational conditions have been used as the foundation of numerical simulation. Sensitivity analysis is performed due to lack of research data related to this model.

Relationship between TDG generation and energy dissipation form: The energy dissipation in the plunge pool is important for the safety of high dams. Nowadays, the spillway energy dissipation mainly includes three forms: ski-jump, surface jump and hydraulic jump.

According to statistical data (Design code for spillway SL 253-2000), most large and medium-sized dams adopt ski-jump energy dissipation, which covers 75 percent of projects abroad and 85 percent in China. The relevant process includes four stages: drawing flow into the spillway ogee, passing the trajectory bucket and projecting spatially and plunging into the pool. The energy dissipation achieves through the aeration of the high-velocity flow in the air and strong collision in the plunge pool.

The fundamental of energy dissipation by hydraulic jump is realized by the enhancement of turbulent process through certain engineering measurements regulating the hydraulic jump position downstream of the hydraulic structure. In this way, the primary purpose of hydraulic jump control comes true by means of surface vortex and turbulence in the stilling basin. The advantages are obvious such as the less scour of tail water, the effective dissipation of energy and the small variation of tailrace level. Thus, the superiority of ski-jump form is definite for gravity dams with large discharge flow rate and poor geological environments despite expensive.

The principle of surface jump is the utilization of vortex (underflow and surface flow) when the water body via spillway lips and the high-speed stream skim the plunge pool.

Methods of TDG prediction: The convenient way to analyse the distribution of TDG concentration in the downstream flow during spill time is the prototype observation. The academic equipment for monitoring are valuable and need professional operation. Most research teams devote to develop effective and accurate numerical model for the practical prediction of TDG concentration,

The TDG effective saturation concentration in the plunge pool was determined based on the effective penetration depth (Hibbs et al. 1997). Geldert et al. (1998) proposed an ordinary differential equation including the transfer rate coefficient across the bubble interface and the free surface. Takemura et al. (1998) established an equation for the Sherwood number (*Sh*) of gas bubble dissolution using the velocity distribution at the bubble surface. Based on these findings, Chunli Qin (2004) derived an equation for calculating the bubble-water interface transfer coefficient which is the main focus of this study. The undetermined source strength parameter (β) of the equation is pursued through the numerical solution since no analytical solution can be usefully employed.

In this research, the variation range of bubble radius, assumed to be normal distribution, is divided into several intervals. Then, the discretization of exponential density function in these intervals is used to obtain the percentage of specific bubbles related to the calculation of the TDG field.

The State Key Laboratory of Hydraulics and Mountain River Engineering of Sichuan University conducted a series of TDG field observations in different river systems since 2006. The field data are important to the calibration of TDG prediction model and the numerical model for high dam projects.

With the development of computer technology, numerical simulation of supersaturated TDG is widely available. The multiphase flow of spills along with hydrodynamic and mass transfer leading to the supersaturation of TDG is complicated. Thus, the parameter analysis of multiphase numerical model of supersaturated TDG could become the theoretical basis for future work.

MODEL DESCRIPTION

TDG transportation model: The TDG flow field is simulated with a multiphase transport equation (Politano et al. 2007):

$$\frac{\partial(\rho C)}{\partial t} + \nabla \cdot (\rho \vec{U} C) = \nabla \cdot [\rho(\nu + \frac{\nu_t}{\sigma_t})\nabla C] + \rho S_C \quad ...(1)$$

Where, C denotes the TDG concentration, S_C is the TDG production source term, ν is the molecular diffusion coefficient of TDG, ρ is the density of mixture, and ν_t is the turbulent kinematic viscosity of the mixture. ν is generally several orders of magnitude smaller than ν_t and can be neglected in most turbulent flows σ_t is the turbulent Schmidt number, and the value is assumed to be 0.5~2 due to the exchange of mixture density on the scales of time and space (Zarrati et al. 1994).

TDG source term: The source term, S_C, in the TDG transport equation represents the mass transfer between bubble/water interface and at the free surface, and it can be written as:

$$S_C = K_{\mathrm{L,B}} a_{\mathrm{B}} (C_{\mathrm{se}} - C) + K_{\mathrm{L,s}} a_{\mathrm{s}} (C_{\mathrm{s}} - C) \quad ...(2)$$

Where $K_{L,B}$ is the mass transfer coefficient across the bubble interface; α_B is the specific area, the ratio of total area of entrained bubbles to the total volume of mixture; $K_{L,S}$ is the mass transfer coefficient across the water interface; α_S is the free water surface area, the ratio of total area of free surface to the total volume of mixture; C_S (=100%) is the equilibrium saturation concentration; C_{Se} is the effective saturation concentration (Heqing Huang 2002). Here C_{Se} is expressed as:

$$C_{\mathrm{se}} = C_{\mathrm{s}} \times (1 + \frac{\gamma d_{\mathrm{eff}}}{p_{\mathrm{atm}}}) \quad ...(3)$$

Where γ is the specific gravity of water; d_{eff} is the effective depth of bubble penetration; P_{atm} is the atmospheric pressure.

Cheng (2006) proposed a model to calculate $K_{L,B}$ and a_B separately based on the research of Takemura et al. (1998):

$$K_{L,B} = \beta \cdot \frac{D_m}{R_b\sqrt{\pi}} \left\{1 - \frac{2}{3}\frac{1}{(1+0.09Re^{2/3})^{3/4}}\right\} Pe^{1/2} \quad ...(4)$$

Table 1: Dissipation coefficient of typical river system.

Project	River	Dissipation coefficient (h^{-1})	Correlation coefficient
Tongjiezi	Dadu	0.2013	0.9694
Gongzui	Dadu	0.1599	0.9838
Manwan	Lantsang	0.0955	0.9608
Pubugou	Dadu	0.1599	0.9838

Where R_b is the bubble radius; P_e ($=2R_b v_r/D_m$) is Peclet number: ($= 2R_b\sqrt{2k/3}/\nu_t$) is Reynolds number; β is an undetermined coefficient, the main point of this study.

For mass transfer coefficient of surface water, Zarrati et al. (1994) established a correlation:

$$K_{L,s} = 0.002436u^{(-5/3)}k^{(4/3)} \quad ...(5)$$

In this application, the dissipation coefficient obtained through field observation is given in Table 1.

Bubble distribution: Based on the previous prototype observations and general theory of statistics, the assumption of normal distribution is adopted in this study (Wang 2012). Fig. 1 shows the distribution and the discretization of density function with the hypothesis on r (mm) ~ N (2.5, 0.52) and the range between 0.45~ 4.45mm. The calculating equation of specific area a_B is generated by the normal distribution:

$$a_B = \sum_{i=1}^{n} 4\pi r_i^2 \bullet (N \bullet \varepsilon_i) N \quad ...(6)$$

Where N is the bubble number of per mixture volume; n is the interval number of bubble radius; r_i is the average bubble radius of interval i ; ε_i is the bubble number density of interval i.

SENSITIVITY ANALYSIS OF PARAMETER β

The model was calibrated using the field data of TDG in the tail-water from Tongjiezi spillway discharges. The Tongjiezi dam fracture zone and discharge are depicted in Fig. 2.

The source parameter β was calibrated to be 3 when the standard error between field data and simulation result is 0.5% of saturation. Lots of bubbles entrained into the pool lead the increase of gas volume fraction during spills. The dissolved gas concentration gradually rises due to the mass transfer at bubble/water interface 90 to 120 m downstream of the dam. The TDG concentration reaches 147% in the strong collision area with higher gas volume fraction and dissolved gas concentration in the pool, and the characteristics of the vertical average value increase eventually even after the second dam. Sensitivity analysis is used to investigate the impact of β on the downstream TDG level of Tongjiezi dam. For each β, the trend of TDG concentration is similar with respect to the distance. Quite evidently, averaged TDG level and peak TDG concentration grow higher with the increase of β.

DETERMINATION OF DIFFERENT SPILLWAY DISCHARGES

The focus of this study is the development of the source strength parameter associated with other characteristic parameters through six operating conditions for different spillways. Three types of energy dissipation are available for two discharge cases each: ski-jump, hydraulic jump and surface jump. Case 1 and case 2 are discussed above. It is assumed that the air entrainment within turbine flow is seldom and the residence time in the spillway is short so that the forebay TDG concentration measured can be used as

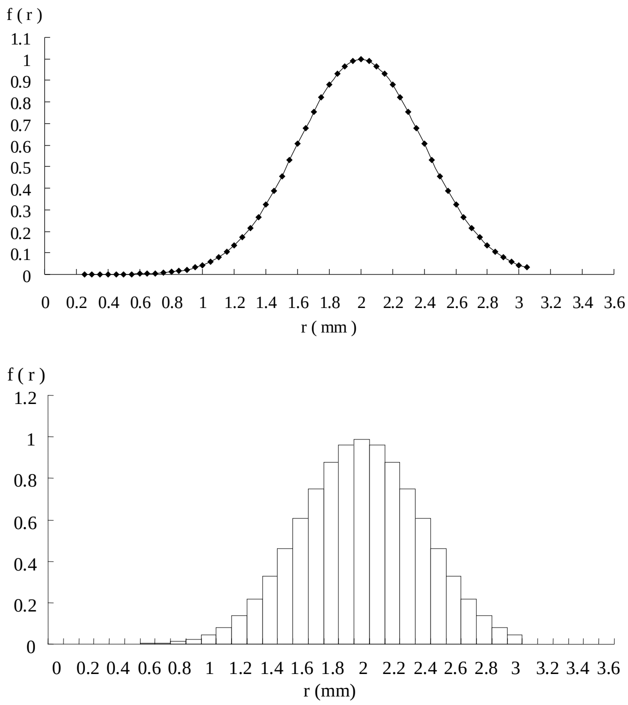


Fig. 1: Normal distribution and the discretization of exponential density function.

inlet condition. The free surface computations are performed using the VOF model with a pressure outlet boundary condition. All cases are calibrated.

Two operating conditions of Gongzui dam are employed. The results indicate that the turbulent viscosity of surface water is greater than the bottom water owing to the severe turbulence on the top region about 300m away from the spillway. In this domain, the turbulent kinetic energy reaches a peak when the aerated jet is drawn into the rolling region and causes turbulent diffusion. The turbulent viscosity becomes uniform at cross section as the flow moves downstream. Compared with case 3, high turbulent area is much longer because of large spill in case 4. The TDG concentration of vertical average falls into decline longitudinally after the degassing of bubbles at the end of the rolling area.

One operating condition of Manwan dam is discussed (Case 5). The spillway energy dissipation in the form of ski-jump makes the turbulence violent in the plunge pool. The entrained bubbles involved in the water jet dissolve into the spills in the plunge pool and the TDG concentration increases rapidly. On the other side, the TDG concentration is relatively low for less residence of bubbles and less hydraulic pressure. The water depth turns into deeper before the second dam resulting in high total pressure and the TDG concentration grows up gradually. The averaged TDG concentration in vertex is plateau downstream of the second dam.

One operating condition of Pubugou dam is available (Case 6). Unlike Manwan dam, the spillway tunnel was designed for flood discharges. In the scour hole, the turbulent kinetic energy of upside is evidently higher than the downstream zone since the impact of bubble coalescence and breakup. Thus, the curve of TDG concentration longitudinally appears to be “M” shape. The summarization is presented in Table 2.

PARAMETER ANALYSIS

With certain temperature and salinity in the plunge pool, the water depth and turbulent intensity have proved to be the direct and significant factors in the production of TDG concentration. Based on the previous study, a qualitative relationship between the source strength parameter β and the characteristics of spillway discharge (Fig. 3) is established. Here, the mean turbulent viscosity μ_t in the pool, the steady water depth h_d in the downstream riverbed and the fluctuation of reservoir water level, H, and tail-water depth h_d. Two dimensionless variables, $(H-h_d)/H$ and μ_t/η, are introduced to represent the discharge characteristics.

There is no distinct relationship between $\beta \sim (H-h_d)/H$ (Fig. 4) and $\beta \sim \mu_t/\eta$ separately. Then, the source strength parameter together with two dimensionless variables is analyzed through the fitting curve. The error between calibrated and fitted parameter β is acceptable (Table 3).

CONCLUSIONS

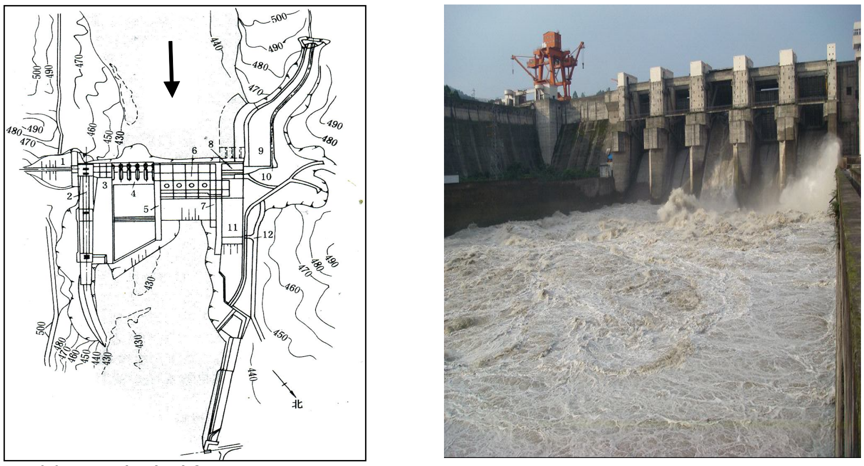
A multiphase, unsteady-state model is performed for predicting TDG levels in the downstream flow after the spillway. The model integrates relationships proposed in the

Table 2: Operating conditions of different discharge flow rate.

	Case	Spillway discharge (m^3/s)	Power discharge (m^3/s)	Reservoir Water surface (m)	depth of Tail-water(m) (m)	Forebay TDG (%)	TDG of Tail-water (%)
Tongjiezi	Case 1	629	1930	469.99	16.34	129.2	138.9
	Case 2	1080	2150	470.52	17.06	129.6	143.8
Gongzui	Case 3	1960	1320	524.53	28.23	112.2	125.3
	Case4	1430	1480	523.73	23.75	112.6	124.6
Manwan	Case 5	1810	1930	990.49	21.25	106.0	121.0
Pubugpu	Case 6	2570	1920	844.13	13.61	111.0	125.0

Table 3: Results of Numerical simulation.

	Case	Calibrated parameter β	Fitted parameter β	Absolute error(%)	Relative error(%) error(%)
Tongjiezi	Case 1	3	3.3	0.3	10.0
	Case 2	5	4.4	-0.6	12.0
Gongzui	Case 3	5	4.8	-0.2	4.0
	Case 4	4	4.5	0.5	12.5
Manwan	Case 5	9	9.0	0	0
Pubugou	Case 6	1	1.0	0	0



(a) Geological fracture zone (b) Discharge of Tongjiezi Dam

Fig. 2: Tongjiezi Dam fracture zone and project discharge.

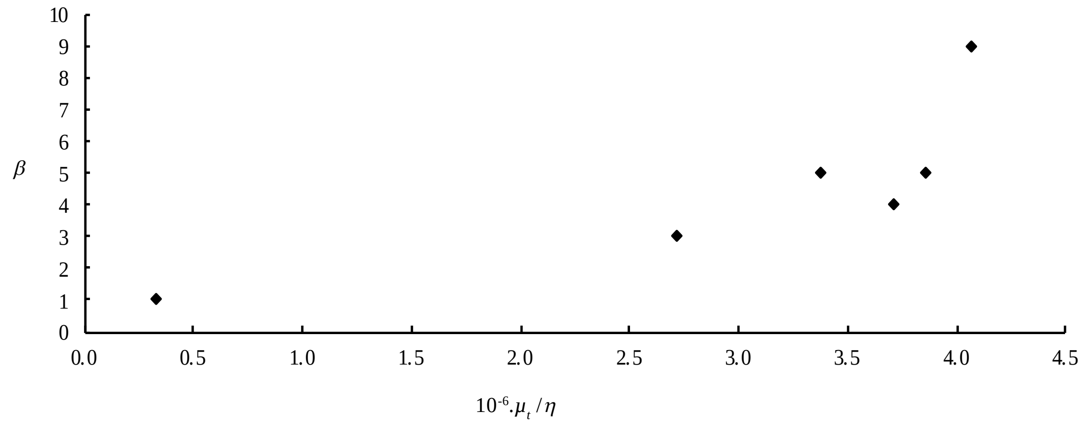


Fig. 3: Relationship between parameter β and dimensionless variable μ_t/h.

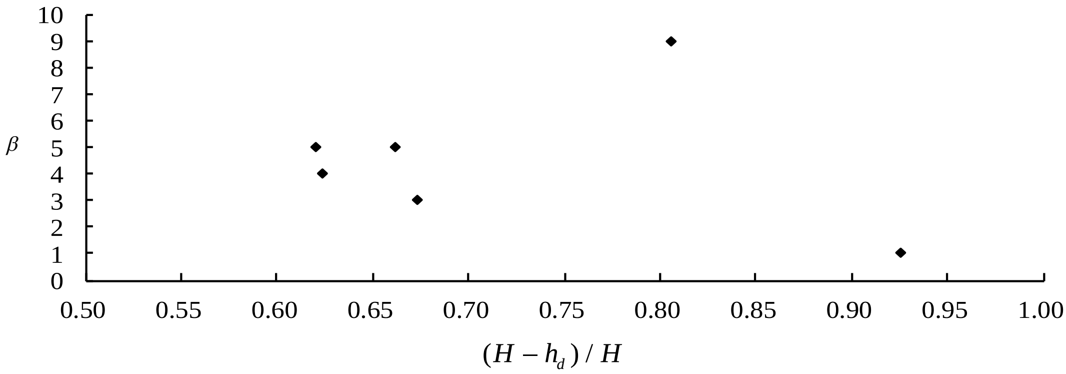


Fig. 4: Relationship between parameter β and dimensionless variable $(H-h_d)/H$.

literature that describe mass transfer between bubble and surface, turbulence decay and bubble distribution, and was calibrated with field data measured by the State key laboratory of Hydraulics and Mountain River Engineering of Sichuan University at different river system. Sensitivity analysis was presented to prove the importance of the source strength parameter in the numerical model for predicting TDG concentrations. The main conclusions are summarized as follows:

1 The hypothesis on the bubble normal distribution can efficiently reflect the process of bubble transfer and declassification at free surface.

2 Projects with different geometry, project head, discharge and upstream TDG levels are necessary in determining the parameter relationship.

3 The deduced parameter relationship reduces the steps of model calibration, and improves the efficiency of model simulation.

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