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ORIGINAL ARTICLE

# Minimum Reservoir Water Level in Hydropower Dams

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**Abstract** Vortex formation over the intakes is an undesirable phenomenon within the water withdrawal process from a dam reservoir. Calculating the minimum operating water level in power intakes by empirical equations is not a safe way and sometimes contains some errors. Therefore, current method to calculate the critical submergence of a power intake is construction of a scaled physical model in parallel with numerical model. In this research some proposed empirical relations for prediction of submergence depth in power intakes were validated with experimental data of different physical and numerical models of power intakes. Results showed that, equations which involved the geometry of intake have better correspondence with the experimental and numerical data.

**Keywords** Power intake · Vortex · Critical submergence · Physical and numerical models · Empirical equations

**List of symbols**

| | |
|---|---|
| $D$ | Intake tunnel diameter |
| $Fr$ | Intake Froude Number, $Fr = V/\sqrt{gD}$ |
| $g$ | Gravitational acceleration |
| $Re$ | Intake Reynolds number, $Re = VD/\upsilon$ |
| $S$ | Intake submerged depth |
| $V$ | Intake flow velocity |
| $We$ | Intake Weber Number, $We = \rho V^2 D/\sigma$ |
| $\rho$ | Density of water |
| $\sigma$ | Surface tension of water |
| $\upsilon$ | Kinematic viscosity of water |
| $v_\theta$ | Tangential velocity |
| $r$ | Radius from the vortex axis |
| $\Gamma$ | Vortex strength |
| $N_\Gamma$ | Circulation number |

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## 1 Introduction

Vortices form at lower reservoir levels due to water withdrawal process and may cause number of problems such as decreasing the efficiency of turbines and their vibration, increasing hydraulic losses at the entrance of power intakes, entraining debris which may cause blockage of trash racks, entraining air into the power tunnel and reducing the longevity of turbines [1]. The stronger the vortex the greater will be its negative effects on power intake performance. Vortex strength is measured by its circulation in the irrotational region of the vortex defined as:

$$\Gamma = 2\text{p}rv_q, \tag{1}$$

where $\Gamma$ is the vortex circulation and $v_\theta$ is the tangential velocity at a distance $r$ from the vortex axis. Based on vortex strength, $N_\Gamma = \Gamma/2\pi g^{1/2}D^{3/2}$ parameter is defined and called circulation number, where $D$ is the diameter of the power tunnel and $g$ is the gravitational acceleration. Vortices are categorized into three classes by Sarkardeh et al. [2]. Vortices of Class C are considered to be safe. Weak rotations of flow or slight surface drop may be observed in this class. The Class B surface vortices are stronger and the rotation in water surface extends down to the intake. This extension may drag debris and trash into the intake. The strongest vortices, which should be avoided, are categorized into Class A. In this class, air bubbles are trapped and conveyed down from the water surface to the intake. In the strongest state, a stable air core is formed in the center of the vortex which allows air to steadily enter the intake (Fig. 1 [2]).

Submerged depth is defined as the distance between water surface and the axis of the intake, $S$, (Fig. 2 [3]). To prevent formation of an air core vortex, a minimum operating depth, called critical submerged depth, $S_c$, is recommended for the pipe intakes.

Recently, hydraulic model studies have served as one of the principal approaches for vortex modeling and many studies have been carried out by different researchers to detect and discover its behavior [4–14]. Some attempts were made to understand the flow field in the presence of vortices by using experimental models. To define swirling flow characteristics within the pump sumps, Ansar and Nakato [15] measured three-dimensional (3D) flow field within a rectangular single pump bay using an Acoustic Doppler Velocimeter (ADV). They studied the flow pattern where strong free surface vortices were presented in the vicinity of the pump intake. Carriveau et al. [16] investigated the formation mechanisms of vortices at deep hydraulic intakes. They found that vortices can be formed at submerged intakes in different distinct manners depending on the magnitude of the submergence. Camnasio et al. [17] experimentally studied the velocity fields in rectangular shallow reservoirs by ultrasound velocity profiler to evaluate the effect of geometry on the flow fields. Sarkardeh et al. [3] also studied the velocity field in a reservoir in the presence of surface vortices experimentally. They observed a downward conical flow over and an upward one below the intake axis in the reservoir. Besides the experimental studies, some numerical models were also developed to investigate vortex formation in the reservoirs [18–22]. Moreover, some researchers have also carried out studies to find out a relationship for $S_c$ based on the prototype and physical model studies [1, 2, 23–25]. Generally, relationships correlate relative critical submerged depth $S_c/D$, to flow velocity in the tunnel $V$ and some have correlated it to the intake Froude number defined as $Fr = V/\sqrt{gD}$. For estimating the critical submerged depth at horizontal intakes, a number of empirical equations were presented.

$$\text{Gordon [23]}: (S_c/D) = 2.3 \times Fr, \quad (2)$$

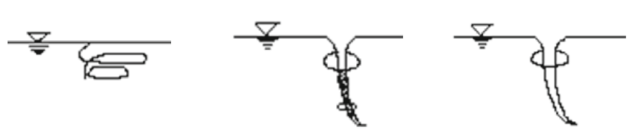



**Fig. 1** Different classes of vortices

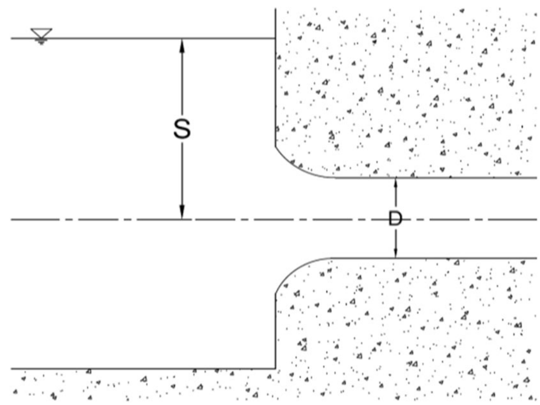



**Fig. 2** Submerged depth in pipe intakes

$$\text{Amphlett [24]}: (S_c/D) = c \times Fr^{0.5} - 0.5, \quad (3)$$

$$\text{Knauss [1]}: (S_c/D) = 1.5 \text{ for } Fr < 0.5 \text{ and } (S_c/D) = 2 \times Fr + 0.5 \text{ for } Fr > 0.5, \quad (4)$$

$$\text{Moller et al. [25]}: (S_c/D) = -2.5 \times Fr^{-0.45} + 5.3, \quad (5)$$

where $c$ is an empirical coefficient between 3.3 to 3.95. As it can be seen in these empirical equations, only the effect of $Fr$ is considered and some effective parameters are not considered. Sarkardeh et al. [2] suggested a formula considering the intake head wall slope as a geometry which has a meaningful effect on vortex formation [26]. The next section focuses on the experimental setup and the formula for prediction of submergence depth proposed by Sarkardeh et al. [2].

Despite all these previous works, there is no comprehensive study on the validity of the proposed equations for predicting critical submerged depth at intakes. In the present study using experimental data of different physical and numerical models, five more applicable equations in intakes design were validated and compared.

## 2 Experimental Setup and Development of the Equation

Schematic side view of the reservoir model built by Sarkardeh et al. [2] is shown in Fig. 3. As can be seen, the intake tunnel diameter was 16 cm and had a rounded entrance. The viscosity and surface tension can affect the formation of free surface vortices in experimental models. To avoid these effects Reynolds number ($Re = VD/\upsilon$) and Weber number ($We = \rho V^2 D/\sigma$), where $\upsilon$ is the kinematic viscosity, $\sigma$ is the surface tension and $\rho$ is the water density, must be large enough in the model: $Re \geq 5 \times 10^4$ [27], $Re \geq 7.7 \times 10^4$ & $We > 600$ [28], $Re \geq 1.1 \times 10^5$, $We > 720$ [29] and $We > 120$ [30]. They showed that the minimum $Re$ and $We$ values in their work are greater than

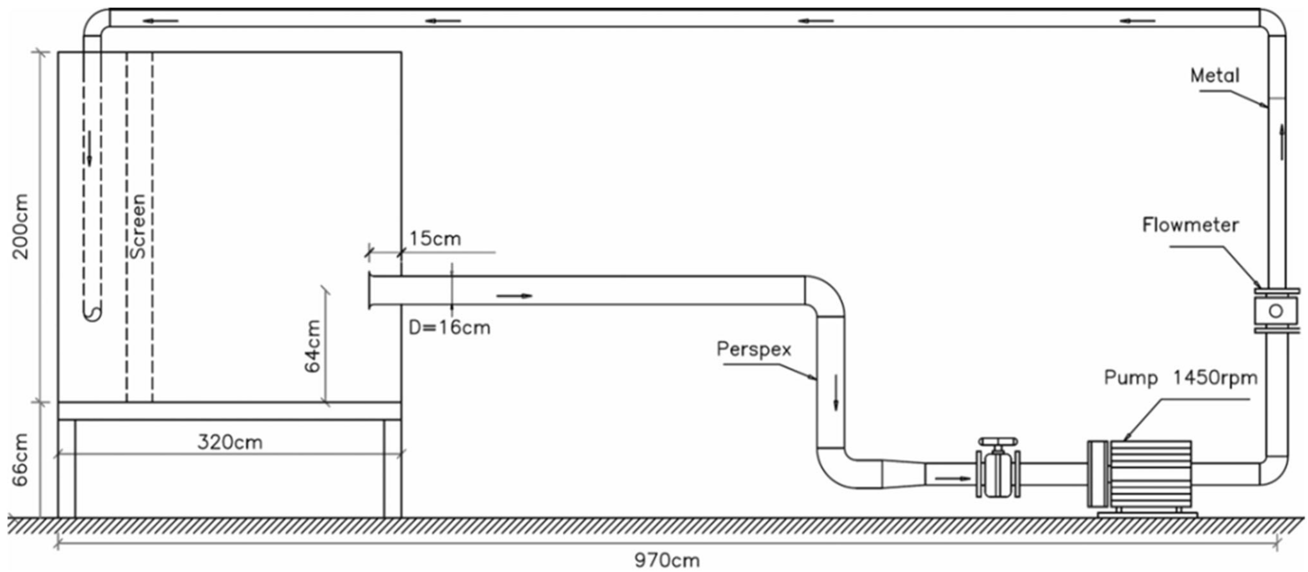



**Fig. 3** A schematic side view of the reservoir model of Sarkardeh et al. [2]

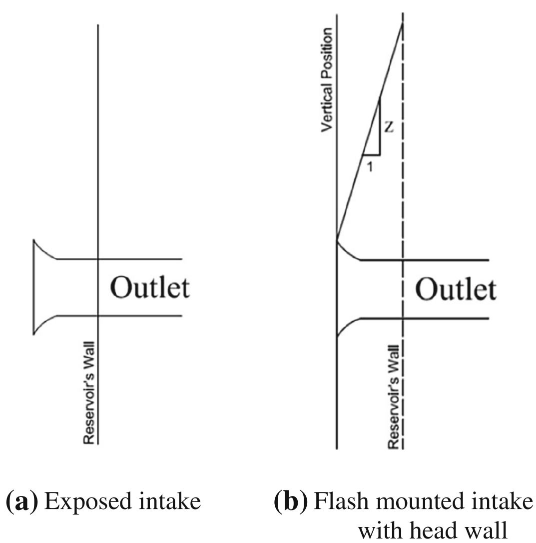



**Fig. 4** Intake with different head wall slopes [2]

the minimum values suggested by different researchers. Moreover, side walls and bed of the reservoir were more than '4$D$' distance away from the intake axis to eliminate their effects on vortex formation.

They measured discharge by an electromagnetic flow meter, water surface elevation by scales marked on the reservoir wall and 3D velocity components of flow by a 25 Hz ADV. Any disturbance or obstacle in the path of the vortex could increase internal friction and therefore reduce the vortex strength as well as $(S/D)_{cr}$. It can therefore be concluded that proximity of the adjacent walls, for example the intake head wall, could reduce vortex strength. In Sarkardeh et al. [2] experiments, an intake with different head wall slopes (Fig. 4) was considered to study the effect of head wall slope as a geometry factor on class of vortices.

They studied the effect of wall vicinity on the vortex strength, with three different slopes of 1H:2V; 1H:3V; 1H:4V and a vertical wall as well as an exposed intake by installing in the model (Fig. 4a, b) and measuring vortex strength and class in four different $Fr$ and three different $S/D$ of 1.5, 1.75 and 2. Measured $N_\Gamma$ in these experiments is plotted versus $Fr$ and $S/D$ in Fig. 5.

From Fig. 5 it can be stated that along with increasing $Fr$, $N_\Gamma$ increases in all wall slopes and submergences. Increasing $N_\Gamma$ in relation to $Fr$ is less with walls of different slopes compared to the exposed intake, showing the preventing effect of wall friction on flow circulation. This figure also shows that the rate of increase in $N_\Gamma$ with $Fr$ is more pronounced in lower submergences in all wall slopes. This observation means that in lower submergences, increase in $Fr$ has a greater effect on the increase in $N_\Gamma$. Moreover, when $Fr$ is constant, as the wall slope increases to vertical position, $N_\Gamma$ decreases for all submergences.

Regarding the experiments carried out by Sarkardeh et al. [2], the critical submergence for Class A vortices can be found as follows:

$$(S_c/D)_\mathrm{A} = 2(1/Z)^{0.008} Fr^{0.334}. \tag{6}$$

It should be noted that in Eq. (6) to have reliable results, the upper limit for $Z$ (i.e., in vertical position) is a large number in order of $10^6$ and lower limit for $Z$ (exposed position) is a small number in order of $10^{-6}$.

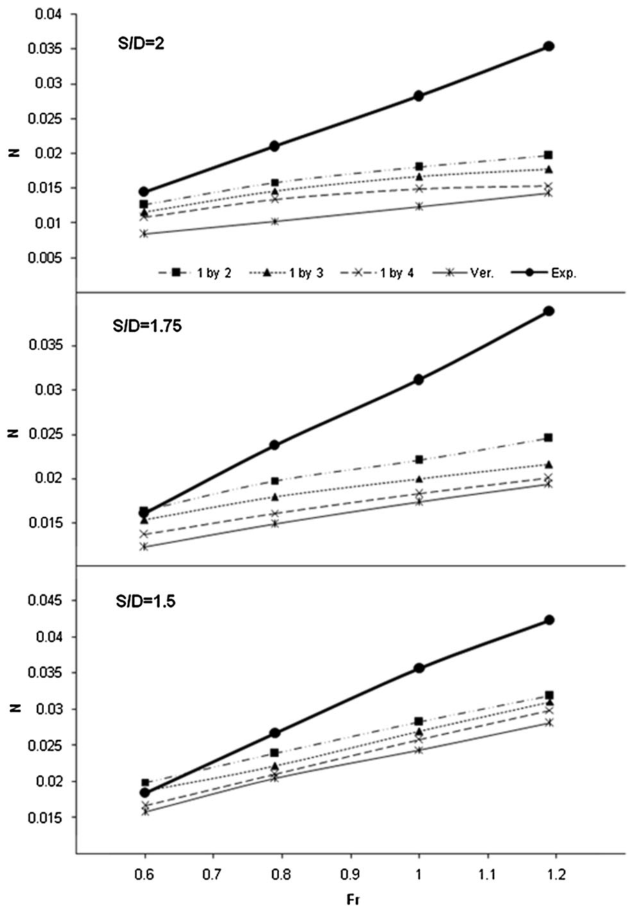



**Fig. 5** $N_\Gamma$ versus *Fr* and *S*/*D* in different intake head wall slopes (Ver. means Vertical, Exp. means Exposed)

## 3 Numerical Models

To show the ability of numerical models in parallel with physical models, numerical simulations of vortex phenomenon and critical submergence were performed by solving 3D Navier–Stokes equations of fluid motion based on Finite Volume Method (FVM) in Flow 3D Software. Turbulence effects were modeled by Large Eddy Simulation (LES) model. Cartesian grid also was used to mesh computational domain. By implementation of Fraction Area/Volume Obstacle Representation (FAVOR) method, walls, bed, and vertical intake defined as obstacles in the flow domain. The free surface was simulated by Volume Of Fluid (VOF) method. Based on VOF method cells without fluid have a value of zero, cells filled by water assigned value of one and partially filled cells have a value between zero and one [31, 32]. The general governing Navier–Stokes, continuity and kinematic of volume fraction equations for incompressible fluid, including the VOF and FAVOR variables are given below:

$$\partial(u_i A_i)/\partial x_i = 0, \tag{7}$$

$$\begin{aligned}\partial u_i/\partial t &+ (1/V_F)\left(u_j A_j \partial u_i/\partial x_j\right)\\ &= g_i - (1/\rho)(\partial P/\partial x_i) + [1/(\rho V_F)]\left[\partial\left(A_j \tau_{ij}\right)/\partial x_j\right],\end{aligned} \tag{8}$$

$$\begin{aligned}\partial F/\partial t &+ (1/V_F)[\partial(F A_i u_i)/\partial x_i] =\\ &(1/V_F)[\partial(\upsilon_F A_i \partial F/\partial x_i)/\partial x_i].\end{aligned} \tag{9}$$

The variable $u_i$ ($i = 1, 2, 3$) represent the *i*-component of the velocity; $x_i$ is the *i*-coordinate in the Cartesian coordinate system; $V_F$ is volume fraction of fluid in each cell; $A_i$ is fractional areas open to flow in the *i*-coordinate of Cartesian system; $\rho$ is density; $P$ is defined as the pressure; $g_i$ is gravitational force in the subscript direction; $\nu_F$ is diffusion coefficient; F represents the volume of fluid per unit volume and $\tau_{ij}$ represents the Reynolds stresses for which a turbulence model is required for closure. The LES turbulence model has been suggested in Refs. [18–22] instead of other turbulence models which do not represent the highly unstable and intermittent phenomenon such as a vortex in a realistic way.

Regarding free surface vortex formation, air entrainment should be simulated. In order to air entrainment occurs, the turbulent kinetic energy per unit volume, $P_t$, must be larger than surface stabilizing forces of surface tension and gravity, $P_d$. The volume of air entrained per unit time, $\delta V$, is given below:

$$\begin{aligned}\delta V &= 0.5A_s[2(P_t - P_d)/\rho]^{1/2}\\ &= 0.5A_s[2(\rho k_T - \rho g_i L_t - \sigma/L_t)/\rho]^{1/2}.\end{aligned} \tag{10}$$

The variable $k_T$ is turbulent kinetic energy; $A_s$ is surface area; $L_t$ is a characteristic size of turbulence eddies, and $\sigma$ is coefficient of surface tension.

## 4 Results and Discussions

To compare the empirical equations which were proposed by Gordon [23], Amphlett [24], Knauss [1], Sarkardeh et al. [2], and Moller et al. [25], the experimental data from six large physical models were used. Characteristics and properties of each dam are summarized in Table 1 and Fig. 6 [33].

In all presented physical models in this research, Froude similarity was considered as the basis of the model studies [34, 35]. As mentioned before, to avoid scale effects in physical model studies of vortices and eliminate the effects of viscosity and surface tension, *Re* and *We* numbers in all

**Table 1** Characteristics and properties of dams [33]

| Dam name | Dam type | Height (m) | Power generation capacity (MW) | Tunnel diameter (m) | Discharge ($m^3/s$) | Scale of the model |
|---|---|---|---|---|---|---|
| Karun I | Double arch concrete | 203 | 1000 | 9 | 375 | 1:30 |
| Karun III | Double arch concrete | 205 | 2000 | 12.6 | 750 | 1:33.33 |
| Gotvand | Gravity with clay core | 180 | 2000 | 11.5 | 360 | 1:25 |
| Seymareh | Double arch concrete | 180 | 480 | 11 | 460 | 1:50 |
| Siyah Bisheh | Clay core Earth dam | 82 | 1040 | 5.7 | 130 | 1:20 |
| Goder-e-Landar | Gravity | 177 | 2000 | 10 | 375 | 1:66.66 |

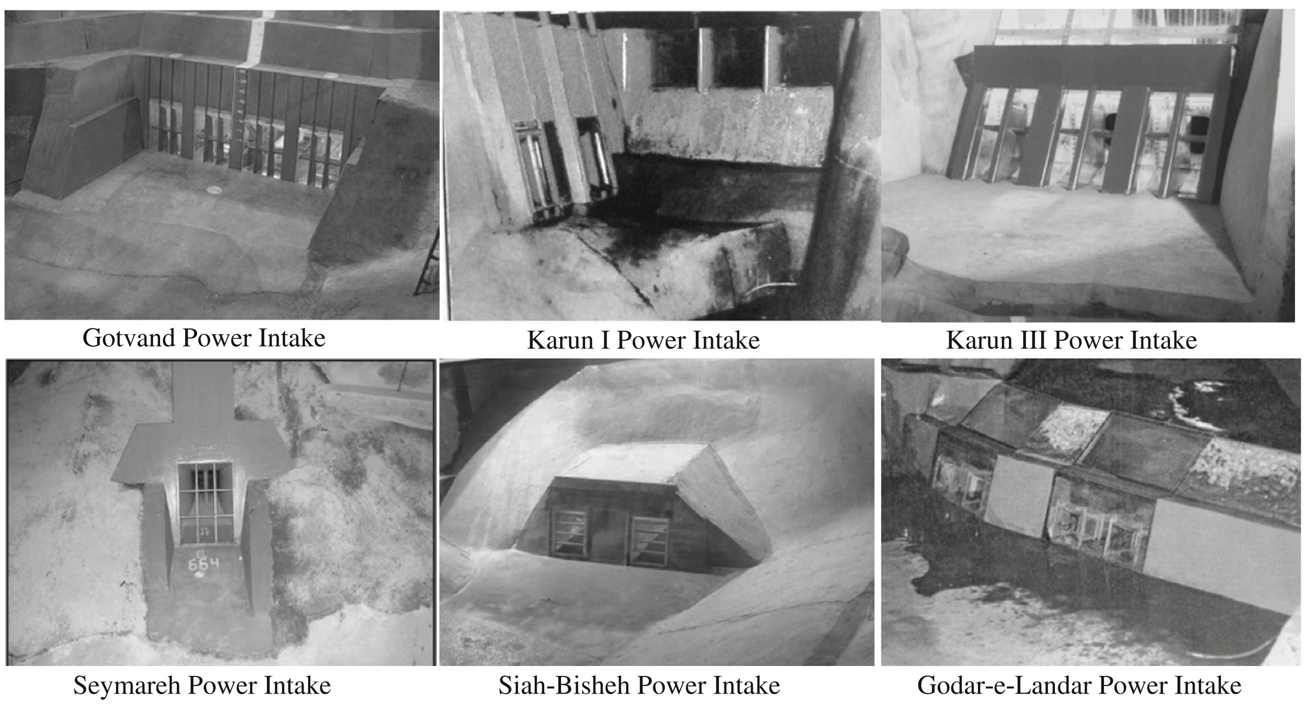



**Fig. 6** Physical model of different power intakes (Courtesy of Hydraulic Structures Division, Water Research Institute, Tehran, IRAN)

physical models were kept more than the minimum values suggested by different researchers.

Many experiments were performed on each model for different *Fr* values and submerged depths in Hydraulic Laboratory of Water Research Institute, Tehran, IRAN. In each test, *S*/*D*, *Fr* and vortex class were measured and recorded. Experimental results are summarized in Table 2 [33].

For all the cases, vortex classes, *Fr* and *S*/*D* are plotted and shown in Fig. 7. In this figure, equations proposed by Gordon [23], Amphlett [24], Knauss [1], Sarkardeh et al. [2] and Moller et al. [25] for predicting formation of an air core vortex are presented and compared with all experimental and numerical data, too.

As it can be seen from Fig. 7, Gordon Equation is not in agreement with physical model data and for vortices in Class A, the observed submerged depths were higher than the submerged depths predicted by this equation. Amphlett Equation predicts higher depths than what observed in the physical models. In the other words, the submerged depth prediction by this equation is on the safer side but it may not provide an economical feasible solution. Equations presented by Knauss and Moller et al. predict the critical submergence good but a rational safety factor seems be necessary in use of them. Equation presented by Sarkardeh et al. is more compatible with different experimental data and therefore could be proposed to hydraulic engineers for designing power intakes.

It was observed that, almost of empirical equations predict critical submergence more than numerical simulation results. In numerical models different experimental

Table 2 Vortex class in different physical models [33]

| Siyah Bisheh | | | Seymareh | | | Karun I | | |
|---|---|---|---|---|---|---|---|---|
| Vortex class | *S*/*D* | *Fr* | Vortex class | *S*/*D* | *Fr* | Vortex class | *S*/*D* | *Fr* |
| Class A | 1.34 | 0.68 | Class B | 2.29 | 0.47 | Class A | 1.1 | 0.31 |
| Class A | 1.69 | 0.68 | Class C | 2.75 | 0.47 | Class A | 1.6 | 0.63 |
| Class B | 2.04 | 0.68 | Class C | 3.2 | 0.47 | Class B | 2.43 | 0.63 |
| Class B | 2.39 | 0.68 | – | – | – | – | – | – |
| Class B | 2.74 | 0.68 | – | – | – | – | – | – |
| Class B | 3.09 | 0.68 | – | – | – | – | – | – |
| Karun III | | | Goder-e-Landar | | | Gotvand | | |
| Vortex class | *S*/*D* | *Fr* | Vortex class | *S*/*D* | *Fr* | Vortex class | *S*/*D* | *Fr* |
| Class A | 1.59 | 0.54 | Class B | 2.2 | 0.48 | Class B | 1.82 | 0.33 |
| Class B | 1.59 | 0.54 | Class C | 2.65 | 0.48 | Class B | 2.25 | 0.33 |

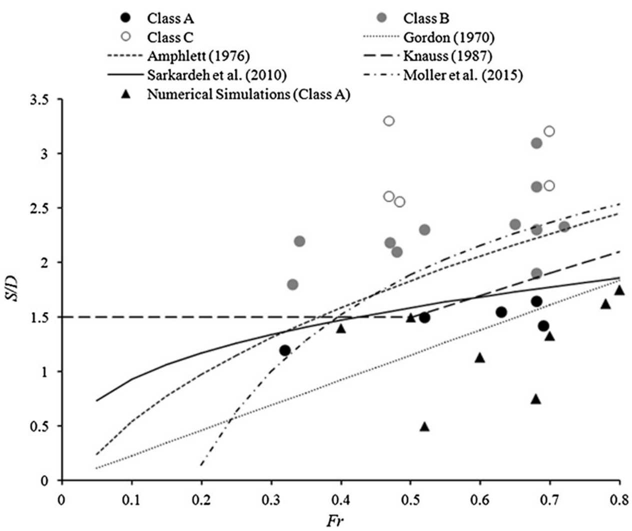



Fig. 7 $(S/D)_{cr}$ versus *Fr* for different experimental and numerical data and empirical equations

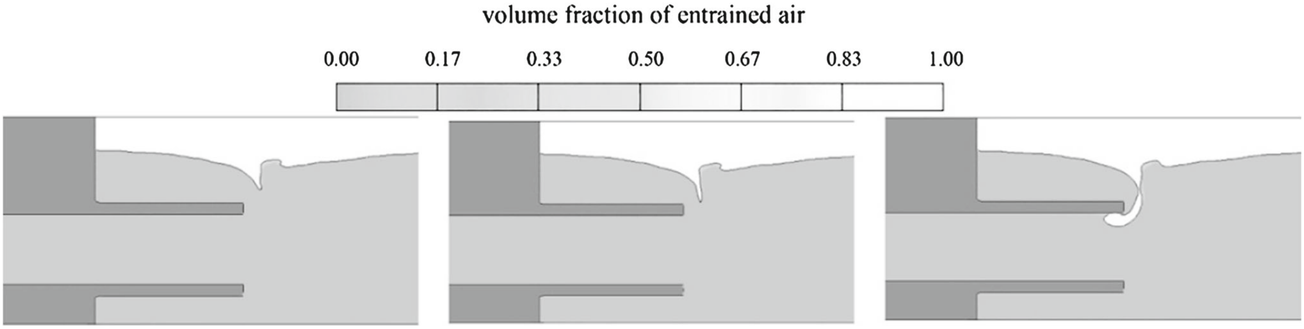
apparatuses were simulated. In these simulations both horizontal and vertical intakes considered. Vertical and horizontal intake conditions were implemented and validated with related experimental data [20–22]. Figure 7 shows also that numerical models can reasonably determine $(S/D)_{cr}$.

Typically, $(S/D)_{cr}$ is determined by observation of the vortex formation, see Fig. 8. In this figure, steps of forming an air-core vortex were presented [22].

Numerical simulations show that formation steps of a free surface vortex at an intake and its class can be suitably simulated and therefore, predicted which it is very helpful inside of physical modeling.

## 5 Conclusions

Formation of vortex in power intakes is an undesirable phenomenon, which causes a number of problems. There are some parameters which are effective in increasing the strength of vortex. Geometry of the intake structure is one of the most important parameters influencing the vortex formation in hydropower intakes. In this research five empirical equations for predicting of the critical submerged depth were validated and compared with different types of experimental data collected on power intake physical models. Numerical simulations of different experimental setups were also performed to obtain the critical submerged depth. Results showed that Gordon Equation was not in agreement with experimental data for vortices belonging to Class A, wherein the observed submerged depths were higher than the submerged depths predicted by this equation. Amphlett Equation predicts higher depths than those observed in experiments. In otherwise, critical submerged depth which predicted by this equation is on the safe side but it cannot provide an economical feasible solution. Predicted critical submerged depth equations presented by by Knauss and Moller et al. were good but a rational safety factor seems be necessary in using of them. Equation which proposed by Sarkardeh et al. wherein considered the intake head wall slope as the intake geometry, is more compatible with different experimental data. Therefore, it could be proposed to hydraulic engineers for designing power intakes. Numerical simulations in parallel with physical modeling concluded suitable results in predicting critical submerged depth and can be helpful in design procedure.




**(a)** Vortex Class C **(b)** Vortex Class B **(c)** Vortex Class A

**Fig. 8** Steps of forming an air-core vortex [22]

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