



The effect of reservoir geometry on the critical submergence depth in hydroelectric power plants intake

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Abstract

The most important design index of water intakes is critical submergence depth of the intake. The depth at which the air core formed by the vortex is about to enter the intake. The emergence of a vortex and air entry into the intake increase head loss and decrease discharge coefficient. The reservoir geometric asymmetry, presence of unevenness in the bottom of the reservoir and angle of approach flow are among the factors that influence formation of the vortex and critical submergence depth. In this research, a physical model has been used to investigate the effect of reservoir geometry on the critical submergence depth. This model is designed in such a way that it can produce the strongest type of vortices with air core and with different strengths. The results showed that by creating asymmetry in the flow approaching the water intake (with side blockage in upstream), the presence of even 10% side blockage can have a great effect on the formed vortex and increase the critical submergence depth by about two times. To create uneven conditions on the reservoir bottom, blockages were created on the bottom of the reservoir upstream of the intake. The results showed that the blockage up to half of the height below the intake caused an increase of about 10–25% of the critical submergence depth, in low and high Froude numbers, respectively. However, in blockages more than half of the height below the intake, this effect increases about 60% of the critical submergence depth. In addition, the effect of the slope of the intake head wall on the order (type) of the vortex and its stability and instability was studied, and it was found that the order of the vortex decreases with the increase in the slope of the head wall toward the vertical position. Also, by increasing the slope of the head wall, the vortices form in an unstable manner. The vertical head wall can act as an anti-vortex structure and cause a reduction in critical submergence depth.

Keywords Vortex · Water intake · Physical model · Critical submergence depth · Hydroelectric power plants

Introduction

An important hydraulic phenomenon that often occurs in water intake of dams and causes problems is the circulation of water and the creation of vortex flow at the intake and the entry of air into its conduit (penstock). The vortices that form at the intake of the power plants are usually spiral and three-dimensional (Fig. 1).

In a situation where the vortex causes the entry of air and strong swirling flows into the penstock, while causing severe decreases in water intake efficiency, it will bring mechanical

damages such as increased vibrations, corrosion and cavitation, as well as operational problems (Suerich-Gulick et al. 2006; Möller et al. 2012). Due to the importance of this issue, Keller et al. (2014) and Möller et al. (2015) have investigated the amount of air influence into the intake due to vortices with air core during detailed laboratory studies in recent years. In hydroelectric power plants, at levels lower than the acceptable level, due to the formation of a vortex with the air core and the entry of air into the Penstock, the production of electrical energy faced a serious problem (Amiri et al. 2011).

The vortices formed on the water surface are physically divided into six types (levels), from 1 to 6 (Knauss 1978), as the level of the vortex increases, its strength also increases. In terms of importance and degree of risk, the six types of vortices classified into three classes A, B and C (Sarkardeh et al. 2010). The relationship between these two types of division with the appearance and physical characteristics

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Fig. 1 A view of a spiral vortex (Lugt 1983)



of the vortex shows in Fig. 2. According to Fig. 2, class A includes vortices that cause air to enter the intake, so they are at the highest level in terms of importance and degree of risk. On the other hand, class C vortices mainly have surface rotations and have the lowest degree of risk. Class B vortices are also important because they cause the transfer of floating particles into the intake. In understanding the vortex phenomenon and the effective factors on strengthening or weakening it, the contribution of laboratory studies and experimental methods is more than other ways. Guilliver and Rindles (1987) studied the mechanism of vortex formation by laboratory tests. Using an experimental method, Sarkardeh et al. investigated the effect of the geometric and hydraulic conditions of the intake and reservoir on the strength of the vortices formed at a horizontal intake (Sarkardeh et al. 2012, 2013). Azarpira et al. (2014) also investigated the flow

conditions in the reservoir in the presence of a vortex using the laboratory model of the Karun III dam.

The most important design indicator of water intakes is the critical submergence depth (S_c). The critical submergence depth is the level at which the created air core is on the threshold of entering the intake (Fig. 3). As long as the submergence depth of the intake (S_i) is greater than the critical submergence depth, air does not enter the intake. On the contrary, in the condition, that S_i is less than S_c (S_i in Fig. 3); a permanent and continuous air core is formed.

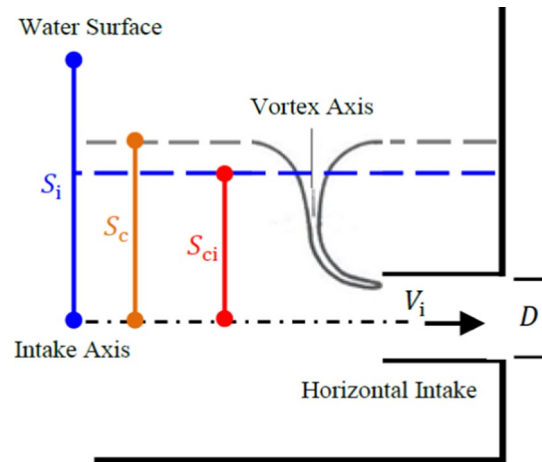


Fig. 3 Critical submergence at a horizontal intake (Knauss 1978)

Fig. 2 Vortex type visual classification

Vortex Class	Description	Appearance	Order
C	Surface rotation of water particles		1
	Surface rotation and a dimple on water surface		2
B	The formation of the vortex-rotating core		3
	Movement of floating objects towards the intake		4
A	Penetration of air bubbles into the intake		5
	Complete connection of the air core to the water inlet		6

Due to the variety of factors affecting the vortex formation, the exact determination of the critical submergence depth is associated with complications (Knauss 1978) in such a way that the general relationships presented in this field are empirical. Therefore, it is still necessary to investigate and analyze the vortex phenomenon and the factors affecting the critical submergence depth. In recent years, with the advancement of computer models, numerical methods have also been used in the study of the vortex phenomenon. As an example, we can refer to the study on the vortex flow created in a cylindrical tank containing a viscous fluid in steady state by direct numerical simulation method. In this research, it was observed that there is a direct relationship between the parameters of the flow inside the reservoir and in the intake conduit, so that with the increase in the fluid rotation in the reservoir, the flow rotation inside the intake conduit also increases (Constantinescu and Patel 1998).

Due to the importance of the subject, so far, various researches concentrated their studies to determine the critical submergence depth and several relationships have been presented with regard to effective parameters (Table 1). These influencing parameters that have been considered in the calculation of the submergence depth (*S*) are: φ direction of water intake, *V* flow velocity, Γ swirl, ν kinematic viscosity of the fluid, σ surface tension of the fluid, ρ volumetric mass of the fluid and intake diameter (*D*).

The relationships presented in Table 1 show that there is no clear trace of the geometric conditions of the reservoir on the relative critical submergence depth. This is despite the fact that based on previous research, the geometric conditions of the reservoir can have a great effect on the strength

of the vortices (Knauss 1978; Guilliver and Rindels 1987; Sarkardeh et al. 2010, 2012; Padmanabhan and Larsen 2001). Therefore, the focus of the current research is based on this issue, and the influence of the parameters such as geometric asymmetry of the reservoir, the angle of the flow toward the intake and the presence of unevenness in the bottom of the reservoir as influencing factors on the relative critical submergence depth were investigated. In the continuation of the research, the effect of changing the slope of the intake head wall as one of the methods of changing the order of the vortex and thus affecting the critical submergence depth was studied.

Materials and methods

Laboratory model

Considering that the aim of this research is to investigate the effect of the geometrical conditions of the reservoir on the intake critical submergence depth, the laboratory model should have the ability to develop a type six vortex for different submergence depths and flow rates. Achieving this requires that the flow with different Froude numbers can develop inside the water intake channel for a fixed depth. Obviously, it is not possible to achieve such a thing in the gravity flow state, because in the gravity discharge of the flow, the water depth in the reservoir and the velocity in the intake (Froude number) are directly related to each other. To solve this problem in the model, a pump was directly connected to the end of water intake tunnel. By adjusting

Table 1 Relationships of the critical submergence depth in intakes

Formula	Intake type	Researcher/s
$(S/D)_{cr} = (0.151 + .0305 V - 0.01 V^2)$	Vertical downwards	Denny and Young (1957)
$(S/D)_{cr} = 3.3Fr^{0.5} + 0.25$	Vertical upwards	Berge (1966)
$(S/D)_{cr} = 2.3Fr$ (asymmetric intake)	Horizontal	Gordon (1970)
$(S/D)_{cr} = 1.7Fr$ (symmetrical intake)		
$(S/D)_{cr} = M_R + Fr)(0.5 \leq M_R \leq 1.0)$	Horizontal	Reddy and Pickford (1972)
$(S/D)_{cr} = 300c/Fr\sqrt{gD^{3/2}} = 300N_\Gamma$	Vertical downwards	Keulegan and Daggett (1974)
$(S/D)_{cr} = 3.3\sqrt{Fr} - 1/2$	Vertical upwards	Amphlett (1976)
$(S/D)_{cr} = -0.567 + 6.41Fr - 3.051Fr^2$	Vertical upwards	Chang (1977)
$\frac{0.86(.054(S/D)_{cr}+0.139)^2}{((S/D)_{cr}+0.5)^{1/2}} = c/\sqrt{gD^{3/2}}$	Horizontal	Anwar et al. (1978)
$(S/D)_{cr} = 88Fr^{0.139}(c/\sqrt{gD^{3/2}})^{0.724}$	Vertical upwards	Jain et al. (1978)
$\frac{0.86(.06(S/D)_{cr}+0.139)^2}{((S/D)_{cr}+0.5)^{1/2}} = c/\sqrt{gD^{3/2}}$	Vertical upwards	Amphlett (1976)
$(S/D)_{cr} = 48\Gamma/Fr\sqrt{gD^3}$	Vertical downwards	Odgaard (1986)
$S_{cr} = 0.076\Gamma(V/g\nu)^{0.5}$	Horizontal	Hite and Mih (1994)

S is the submergence depth of the intake, *D* is the Penstock diameter, *S/D* is the relative submergence depth, *V* is the velocity in the penstock, $Fr = V/\sqrt{gD}$ is the Froude number, M_R is the shape factor of the intake, and $N_\Gamma = \Gamma/VD$ is the circulation number

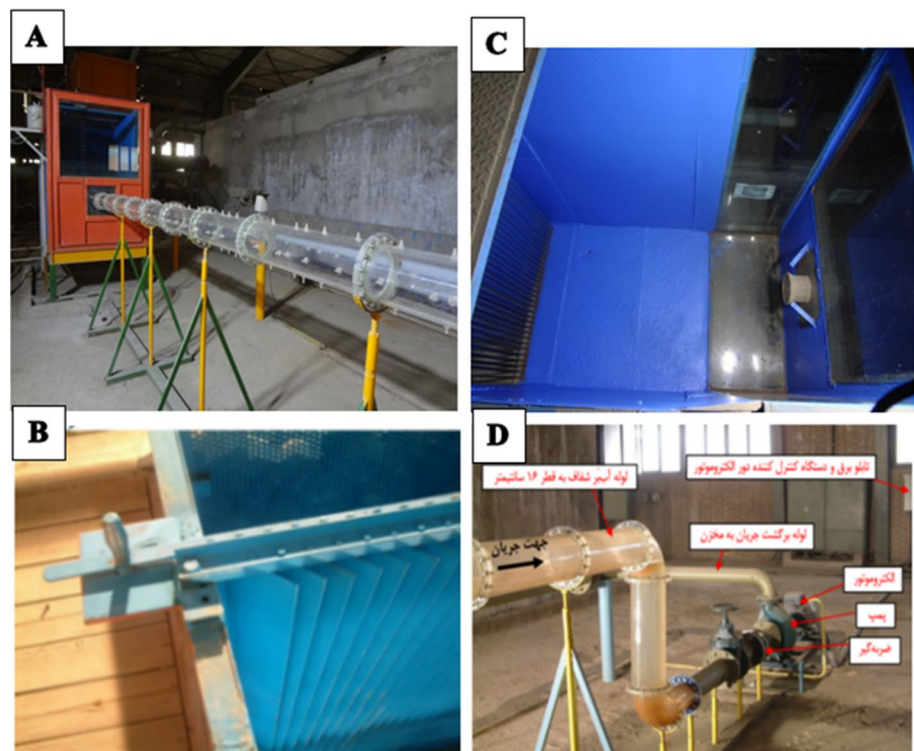
the speed of the pump electromotor, flow velocity can be adjusted independently of the water depth in the reservoir. In addition, to keep the water depth of the reservoir constant, at different flow rates, the return pipe was directed to the model reservoir, so there is always a constant amount of water circulating in the system. In this way, it is possible to fill the reservoir with water to a certain depth at the beginning and then, by changing the speed of the electromotor, different discharges and as a result different Froude numbers can be created in the Penstock. The main components of the laboratory model are reservoir, water-carrying pipe (Penstock), pump and a device to control electromotor rotation, which are shown in Fig. 4.

According to Anwar et al. (1978), the minimum distance of the reservoir bed and wall from the axis of the penstock intake should be more than $4D$, where D is the diameter of the penstock conduit. Therefore, in this research, the width of the reservoir is 130 cm and the distance of the intake axis from the bottom of the reservoir is 64 cm. Also, the height and length of the model reservoir are 2 and 3.5 m, respectively. As mentioned before, the diameter of the Penstock conduit plays a key role in the laboratory model and other parameters are determined based on it. This diameter should be able to: (1) provide reasonable dimensions and acceptable velocities compared to the original sample (prototype), (2) considering the usual scales in modeling (1:30 to 1:50), it covers a wide range of power plants, and (3) for the desired submergence depths and discharges, scale effect in

the model can be ignored. In large and medium-sized dams, the diameter of the Penstock is usually between 4 and 10 m and the flow rate in it is between 100 and 400 m^3/s . Also, the flow velocity in the Penstock is limited to 4–10 m/s. According to this information, in order to determine the diameter of the model penstock in the present study, several diameters are first considered. Then, for different discharge and model scale from 1:30 to 1:60, the relevant hydraulic parameters were calculated and these values were compared with the data of several hydropower plants in Iran. Finally, the diameter of 16 cm has been considered for the water intake of the model due to the inclusion of a more appropriate range of relevant parameters and a wider range of scale ratios. In the prototype, as shown in Fig. 5a, in order to allow the installation of the trash racks, head wall of the water intake is made with a slope. Therefore, a dead zone is created above the intake (Fig. 5b). This zone helps the fluid to circulate more easily on top of the water intake and create a more stable vortex. To simulate this phenomenon and to form stable vortices in the laboratory model, about 0.15 m for the projecting of the intake into the reservoir was considered. As a general result, the projection is to simulate the dead zone of flow area above the water intake.

The length of the penstock pipe is 4.5 m, and its inside diameter is 0.16 m. At 2 m upstream of the intake in the reservoir, there are vertical blades that can change the angle of the incoming flow toward the intake. This makes it possible to strengthen the upstream circulation to reach stronger

Fig. 4 **a** Reservoir, transparent flow pipe; **b** blades installed to create geometric asymmetry in model; **c** glass walls of the reservoir and intake; **d** pump and electromotor speed controller in laboratory model



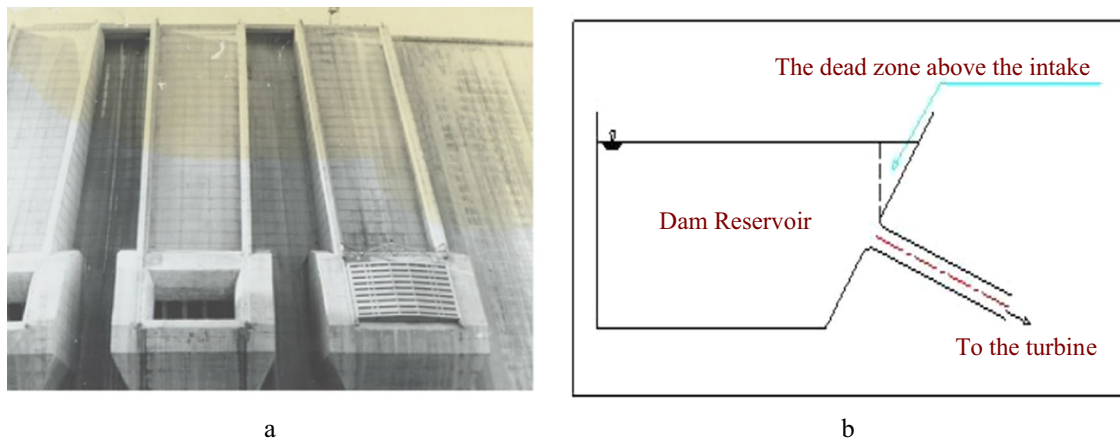


Fig.5 a Water intakes of the Karun I dam power station, b general view of a power plant water intake

Table 2 Range of hydraulic and geometric characteristics of flow and laboratory model

Specifications	Parameters	Signs and measure units	Variation range
Hydraulic	Flow discharge	Q (m ³ /s)	$0.015 \leq Q \leq 0.030$
	Flow velocity	V (m/s)	$0.75 \leq V \leq 1.5$
	Submergence depth	H or S (m)	$0.24 \leq S \leq 0.48$
	Froude number	Fr_r	$0.6 \leq Fr \leq 1.2$
	Reynolds number	Re	$120,000 \leq Re \leq 240,000$
	Relative submergence	S/D	$1.5 \leq S/D \leq 3.0$
Geometric	Reservoir Height	H_{res} (m)	2.0
	Penstock diameter	D (m)	0.16
	Blades angle	θ (°)	$0 \leq \theta \leq 20$

Froude and Reynolds numbers are defined as $Fr = V/\sqrt{gD}$ and $Re = VD/\nu$ where ν is the kinematic viscosity of the fluid

vortices. This model was made in the Water Research Institute of the Ministry of Energy. Since in all conditions of the experiments, the Reynolds number was much more than 2000 (Table 2), and the prevailing flow can be considered turbulent and independent of the Reynolds number.

To prevent scale effects caused by viscosity and surface tension of the fluid, minimum values of $Re \geq 5 \times 10^4$ (Daggett and Keulegan 1974); $Re \geq 7.7 \times 10^4$ and $We > 600$ (Padmanabhan and Larsen 2001); $Re \geq 1.1 \times 10^5$ and $We > 720$ (Odgaard 1986) and $We > 120$ (Jain et al. 1978) should be observed in the construction of the model. The minimum values of Reynolds number and Weber number in the model are 1.2×10^5 and 1.2×10^3 , respectively, which are more than the above values. The sidewalls and the floor were placed at a distance of $4D$ from the water intake so as not to affect the flow conditions in the water intake.

Various tools and equipment have been used to measure the hydraulic characteristics of the flow. For flow discharge measurements, an electromagnetic flow meter



Fig. 6 Flowmeter installed in the model

(MAGFLO2500) with an accuracy of 1% installed in the path of the water return pipes into the reservoir was used (Fig. 6).

To measure the water level, the right wall and the front wall of the reservoir are graduated. In Fig. 7, the level of the water level is considered in relation to the center of the intake. The accuracy of reading the reservoir water level is within ± 1 mm. A protractor has been used to measure the angles of the vanes (to give an angle to the flow approaching the water intake).

Results and discussion

One of the important and effective parameters in the vortex formation is the topography of the reservoir and conditions of the approach flow. In reservoirs of dams due to various reasons (such as the geometric asymmetry, the angle of approach flow into the reservoir or the presence of unevenness in the bottom of the reservoir), vorticity occurs in the fluid elements. It increases in the mouth of the intake. The collection of these rotations can help as an important and auxiliary factor in the vortex formation process. As mentioned before, the critical submergence depth is the minimum depth above the intake below which the vortex forms with an air core. Therefore, in each of the test conditions, the depth was reduced to the point where the intake is exposed to the occurrence of the vortex type 6.

The effect of upstream side blockage on the critical submergence depth

In this part, in order to model the presence of a natural convexity such as a mountain or a high unevenness inside the reservoir, the parameter of the upstream side blockage (SB) is defined. In order to measure the effect of upstream side blockage on the critical submergence depth, the side blockage is created at a distance of about 13 times of the penstock



Fig. 7 Graduated wall of the reservoir in order to measure of the water level

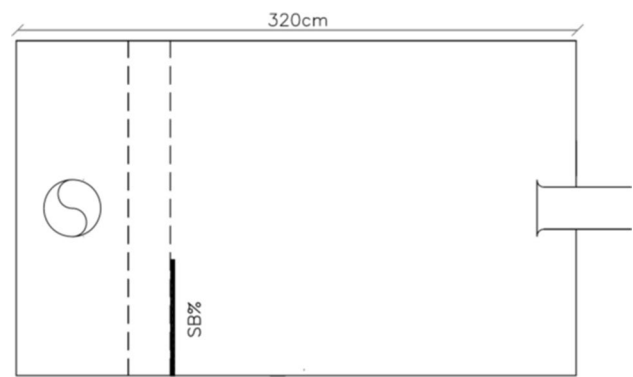


Fig. 8 Side blockage in the upstream of the physical model

diameter. Five different percentage of the reservoir width from the bottom to the water surface is covered. The experiments were carried out in four Froude Numbers (Fig. 8).

In Fig. 8, SB is the closing rate of the reservoir width. The results of these tests are shown in Table 3 and Fig. 8. It is worth mentioning that the closure for SB is dimensionless with the reservoir width.

What can be seen in Fig. 9 is the very large effect of the presence or absence of blockage in the upstream. The presence of even 10% blockage in the upstream can increase the critical submergence depth by about two times.

The reason for this severe change in the strength of the formed vortex is the increase in vorticity in the upstream and its collection at the intake and finally the formation of a stronger vortex. Following the increase in the percentage of blockages, it is obvious that for a 20% increase in SB, the depth of critical submergence increases by 10% to 15%. Another point is that, the trend of increasing the critical submergence depth in contrast to increasing the Froude number is seen in all blockages.

The effect of bottom blockage (BB) in upstream on the critical submergence depth

To model another type of asymmetry for the approach flow to the intake, a percentage of the reservoir bottom to the axis of the intake was closed in upstream (Fig. 10). This geometry indicates the presence of a slope in the valley leading

Table 3 Sc/D in upstream closures (SB) and different landings

Fr	SB				
	0%	10%	25%	50%	70%
0.6	1.31	2.19	2.25	2.31	2.38
0.8	1.50	2.44	2.56	2.69	2.75
1.0	1.63	2.75	2.81	2.88	2.93
1.2	1.81	2.88	2.93	3.0	3.06

Fig. 9 Changes in relative critical submergence depth (Sc/D) versus Froude number for different upstream side closure (SB)

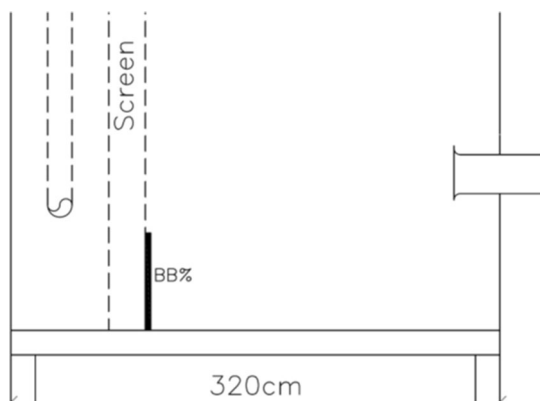
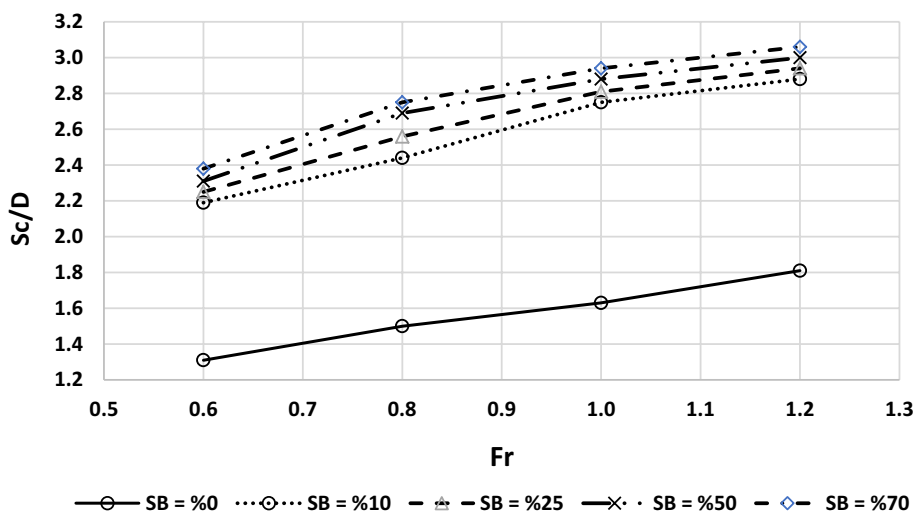


Fig. 10 Bottom blockage in the upstream of the physical model

Table 4 Sc/D values in blockage from the floor in the upstream (BB) and different landings

Fr	BB			
	0%	20%	40%	70%
0.6	1.30	1.33	1.44	2.39
0.8	1.51	1.69	1.81	2.58
1.0	1.62	1.99	2.16	2.68
1.2	1.80	2.15	2.24	2.81

to the intake or the presence of mounds in the bottom of the reservoir, which can be natural or the result of the formation of sedimentary islands. In this regard, the areas below the intake were closed at a distance of about $13D$ in upstream.

In Fig. 10, BB is the degree of closure from the bottom of the reservoir to the axis of the intake. It is worth mentioning that the closure for BB is dimensionless with the height below the intake (the distance from the intake axis to the bottom of the reservoir). (Table 4).

Figure 11 shows that blockages in the bottom of the reservoir up to half ($< 50%$) of the height below the intake have

caused an increase of about 10–25% of the critical submergence depth in low and high Froude numbers, respectively. However, in the blockages of more than half of the height under the intake ($> 50%$), this effect increases significantly so that for 70% of bottom blockage, the submergence depth increases 60% compared to 40% of bottom blockage in the lower Froude numbers. This is while the percentage of increase in high Froude numbers is about 25%. The reason for this increase is the contribution of the incoming flow to the vortex (which is fed from the surface).

The effect of intake head wall on the critical submergence depth

By studying the existing normal dams, it is clear that the slope of the upper wall of the intake in them varies from 1:2 to almost vertical. Therefore, in the model walls with slope of 1:2, 1:3, 1:4 and vertical were tested. For each wall the type of the vortex was determined, then, it was compared with the intake projecting into the reservoir (present model). At first, projected intake (with $1D$ projection) was tested. Then, the effect of the wall slope (z) was studied in four different Froude numbers ($Fr = 0.6, 0.8, 1.0$ and 1.2) and three relative submergence depths ($S/D = 1.5, 1.75$ & 2.0). The results of Table 5 show that the order (type) of the vortex decreases with the increase in the wall slope.

In addition, the results show that the vortices are unstable by increasing the wall slope to the vertical state. As can be seen in Table 6, the slope of the wall has a great effect on the instability of the vortices, especially at lower Froude numbers. For example, in $Fr = 0.6$ and the intake projecting to the reservoir at all relative submergence depths, the vortex type 6 (class A) is formed, while class B and unstable vortices are formed due to the vertical wall above the water intake.

Fig. 11 Changes in relative critical submergence depth (Sc/D) versus Froude number for different bottom closure (SB)

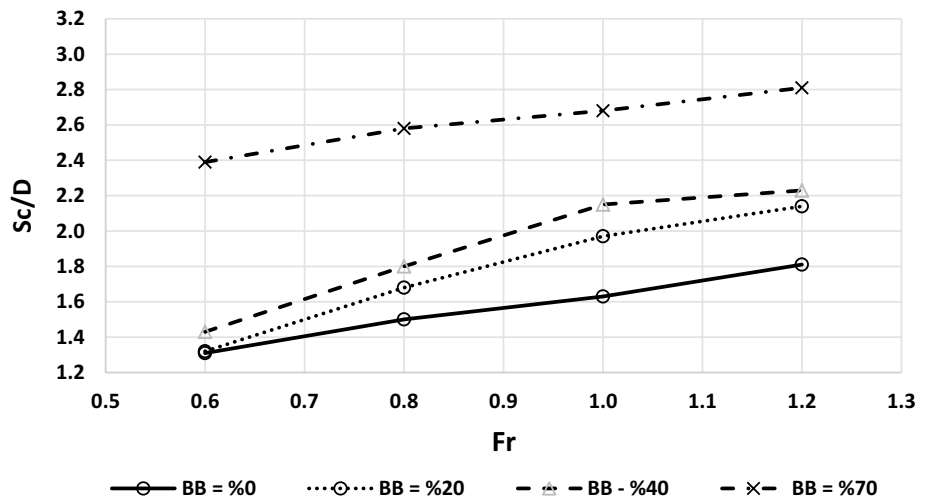


Table 5 Order of eddies in different flow conditions and different slopes of the upper wall of the water intake

S/D	2.0				1.75				1.5				
	Z	1:2	1:3	1:4	Vertical	1:2	1:3	1:4	Vertical	1:2	1:3	1:4	Vertical
Fr													
0.6	3	3	2	2	5	4	3	3	5	5	5	3	
0.8	4	4	3	2	5	5	4	4	6	6	5	5	
1.0	5	5	4	3	6	5	5	5	6	6	6	6	
1.2	6	5	4	4	6	6	6	5	6	6	6	6	

Table 6 Stability of eddies with different classes (A, B and C) in different flow conditions and different slopes of the upper wall of the water intake

S/D	2.0			1.75			1.5			
	Z	Projected	2:1	Vertical	Projected	2:1	Vertical	Projected	2:1	Vertical
Fr										
0.6	A	B	–	A	B	–	A	A and B	C	
	Stable	Unstable		Stable	Unstable		Stable	Unstable	Unstable	
1.2	A	A	B	A	A	B	A	A	B and C	
	Stable	Unstable	Unstable	Stable	Unstable	Unstable	Stable	Unstable	Unstable	

In fact, it can be said that because the presence of the wall above the intake and changing its slope to a vertical state reduces the order or type of vortex, it acts like an anti-vortex structure and will reduce the depth of critical submergence depth.

Conclusion

Studies have been carried out in the form of a large-scale laboratory model. It was tried to study the effect of reservoir geometry and asymmetry of the approach flow on the critical submergence depth by conducting detailed tests. In total, the following results have been obtained from this research:

- Determining the critical submergence depth by considering the asymmetry of approach flow toward the water intake (side blockage—SB—in the upstream) in different hydraulic conditions showed that even the presence of 10% blockage in the upstream can have a great effect on the vortex type and increase the critical submergence depth by about two times.
- Blockages in the bottom (BB) of the reservoir up to half of the height below the water intake cause an increase of about 10–25% of the critical submergence depth in low Froude numbers. In higher blockage, e.g., for 70% BB, the submergence depth increases 60% compared to 40% of bottom blockage in the lower Froude numbers. The reason for this increase is more contribution of the approach flow to the vortex, which is fed from the surface.

- The effect of the slope of the intake head wall on the type of the vortex and its stability and instability was studied. The results show that the type of the vortex decreases with the increase in the head wall slope. In addition, by increasing the slope of the head wall to the vertical state, the vortices are formed unstable.
- The presence of the head wall above the intake and changing its slope to a vertical state reduces the order or type of vortex. Therefore, the structure acts as an anti-vortex, and its establishment will reduce the depth of critical submergence depth in the reservoir.

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Declaration

Conflict of interest Not applicable.

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