Discharge Coefficient in Vertical Intakes with Additional Plates

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Abstract

One of the causes of perturbation at vertical intakes is the happening of vortices with an air core. The vortices with an air core occur whenever the submergence of the intake is less than a critical value. Anti-vortex devices and specially plates are used to avoid the negative effects of the air-core vortices. If plates are used, then the geometry of them should be studied experimentally. Accordingly, a precise set of experiments have been carried out using rectangular plates with different dimensions. The results showed that using the vertical plates can increase the critical submergence for the same discharge rates to 51%.

Keywords: Vertical Intake, Anti-Vortex Device, Submergence of Intake, Air-Core Vortices, Discharge Rate

1. Introduction

For various purposes water is taken from the reservoir by the structures called intake. An intake structure controls the flow into conveyance system with the help of the gate. When the submergence of an intake is not sufficient, air enters the intake through the air-core vortex and causes some hydraulic problems such as discharge reduction, loss of efficiency in turbines and water conveyance structures. The common solution for avoiding air entrainment is to provide the water head with greater critical submergence. The lowest vertical distance between the water level and upper level of the intake that is not associated with a vortex with air entrainment, is called critical submergence.

In all engineering projects, designing of the intakes is handled by two principles; minimizing the cost and maximizing the efficiency. Vortex occurrence in an intake structure can increase critical submergence and decrease discharge coefficient that both of them are not optimum hydraulic performances.

Several researchers have studied the relationship between vortex occurrence and intake submergence trying to find a good guidance for those of engineers designing any kinds of submerged intakes. They were mostly interested in air entraining vortices, as they are the source of biggest destroying occurrence in hydraulic machinery. Hecker (1987) shows that air entrainment takes place at vortex types V and VI of in total six stages (Figure 1) [1].

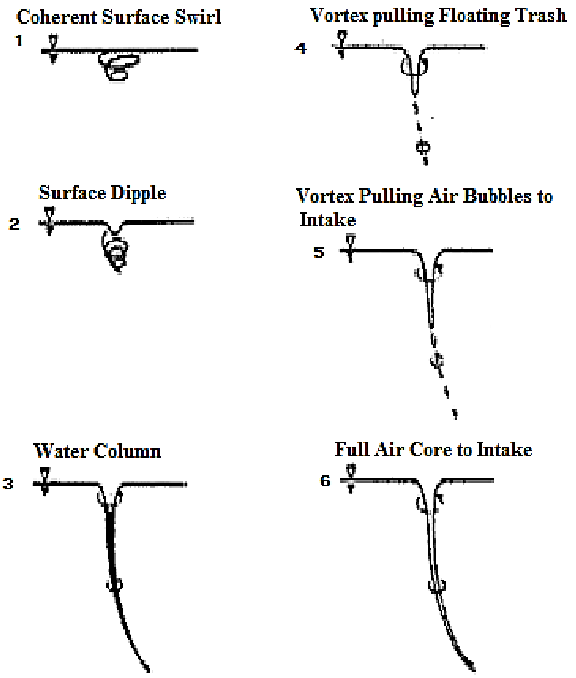

Fig .1 Vortex type classification (Hecker, 1987)

The formation of a vortex may appear at any kinds of intakes and is independent of its utilization, but the consequences and their importance differ considerably.

Rindels and Gulliver (1987) conducted studies on weak surface vortices at bell-mouth vertical intakes with headrace channel by experimental models. Guide vanes were placed to set the approach angle to the headrace, thirteen experiments were conducted with different approach angles and Froude number ranges between 0.25 and 2.2. The variations of S_C/d with Froude number were provided [2].

Yıldırım and Kocabas (1995) concentrated their studies on critical submergence determination in the intakes with air core vortex formation. To form the flow area theoretically, a point sink was superposed with a uniform channel flow. In their study, the discharge of the point sink was equated to the discharge of the uniform flow to provide continuity in the system. In their experiment, the critical submergence level was set to the radius of the imaginary point sink [3]. They showed that the critical submergence can be predicted by means of the potential flow solution for intakes in an open channel flow, reservoirs and for rectangular intakes [4, 5]. Yildirim et al. investigated the location of the impervious boundaries on the critical submergence of an intake pipe [5]. They defined the blockage effects as the loss of surface area from a CSSS of the flow boundaries on the critical submergence [7]. Yildirim and Tastan investigated the effects of the canal bottom and the dead-end wall on the critical submergence of a single circular intake [8]. Tastan and Yildirim investigated the effects of dimensionless parameters and boundary friction on air entering vortices and the critical submergence of an intake located in still water and no-circulation imposed cross-flow [9]. Eroglu and Bahadirli obtained the critical submergence for a rectangular intake by potential flow solution [10]. Rahimzadeh et al. using experimental works defined the form of the surface flow patterns [11]. Li and Chen carried out an experimental and numerical simulation to investigate the formation and evolution of the free surface vortex [12]. Zhao et al. carried out a numerical simulation of the free surface vortex in a tank with a bottom drain port [13]. Chen et al. derived the velocity expressions of the free surface vortex using RNG k-ε turbulence model [14]. Sohn et al. used the tanks with square cross section to suppress the vortex formation [15]. Sohn et al. showed that a vane-type suppressor is effective in preventing the vortex formation [16]. A circular flat plate with a porous wall was used by Mahyari et al [17]. Sarkardeh et al. have shown that by considering factors which have an effect on vortex strength, it can be concluded that the vortex formation can also be prevented if the distance between the water surface and the intake is increased [18]. Tagvaei et al. using an experimental setup showed that the horizontal plate has a better performance in comparison with other anti-vortex devices to reduce critical submergence [19].

By increasing submergence, discharge is reduced. In the bell-mouth intakes with reducing cross sections, the flow velocity increases and pressure decreases in the centre axial of each intake. In this condition, until the pressure of the centre axial of the intake is not less than the atmospheric pressure, the air core is not formed. So the phenomenon of vortex, in effect of interaction mouth shape of intake, intake submergence and fluid properties such as viscosity and surface tension is formed. Hitherto, there are not so investigations about the discharge coefficient in tank with the vertical intake. So the aim of the present research is to study the critical submergence and discharge coefficient in a cylindrical tank with a vertical intake. In the following parts, the critical submergence is determined experimentally without any vortex suppressor and then the discharge coefficient is calculated subsequently.

2. Governing Parameters

Important dimensionless terms which should be used for experimental studies to define the discharge coefficient and the critical submergence of a vertical intake are:

$$\frac{S_C}{d}: \qquad \text{Relative Submergence (1)}$$

$$C_D=\frac{4Q}{\pi d^2\sqrt{2g\frac{S_C}{d}}}: \qquad \text{Discharge Coefficient (2)}$$

$$Fr=\frac{4Q}{\pi d^2\sqrt{gd^5}}: \qquad \text{Froude number (3)}$$

$$\mathrm{Re}=\frac{Q}{\upsilon d}: \qquad \text{Reynolds number (4)}$$

$$We=\frac{\rho v^2 d}{\sigma}: \qquad \text{Weber number (5)}$$

Where S_C is the critical submergence, d is the pipe intake diameter, Q is the discharge, g is the gravitational acceleration, υ is the kinematic viscosity, ρ is the density, σ is the surface tension and v is the flow velocity in the pipe.

According to the recommended Weber number and Reynolds number ranges that is mentioned in table 1, the effects of surface tension and viscosity could be neglected.

Table1 The ranges of the Weber and Reynolds numbers for neglecting the effect of the surface tension and the viscosity

Researcher	We	Re
Daggett & Keulegan	$V^2 \rho d / \sigma \ge 120$	$Q/(vD) \ge 3\times10^3$
Anwar et al.	$V^2 \rho d / \sigma \ge 120$	$Q/(vS) \ge 10^4$
Jain et al.	$V^2 \rho d / \sigma \ge 120$	$(gd^3)^{0.5} / v \ge 5\times10^4$

2. Materials and Methods

In this research, four different mouth shapes of vertical intake for 24 discharge rates in a cylindrical tank were tested and the corresponding critical submergences were recorded subsequently. The experiments were conducted at the hydraulic laboratory at Tabriz University in Iran. The experiments were carried out in a tank made of 2 parts. First part is a cube 1.0 meter length and 1.0 meter height and the second part is a semi-cylindrical tank, 1.0 meter in diameter and 1.0 meter in height. Figure 2 shows the schematic diagram of the tank. The circulated water was pumped from a large sump and a triangular weir was used to measure the actual discharge of the vertical intake (at the end of experimental model). The flow enters the first part of the tank horizontally and uniformly through a sand screen diffuser. The sand screen was set in the tank to make the flow further smooth using a 0.1 meter thick rock crib, which consists of rocks coarser than 0.01 meter sieve.

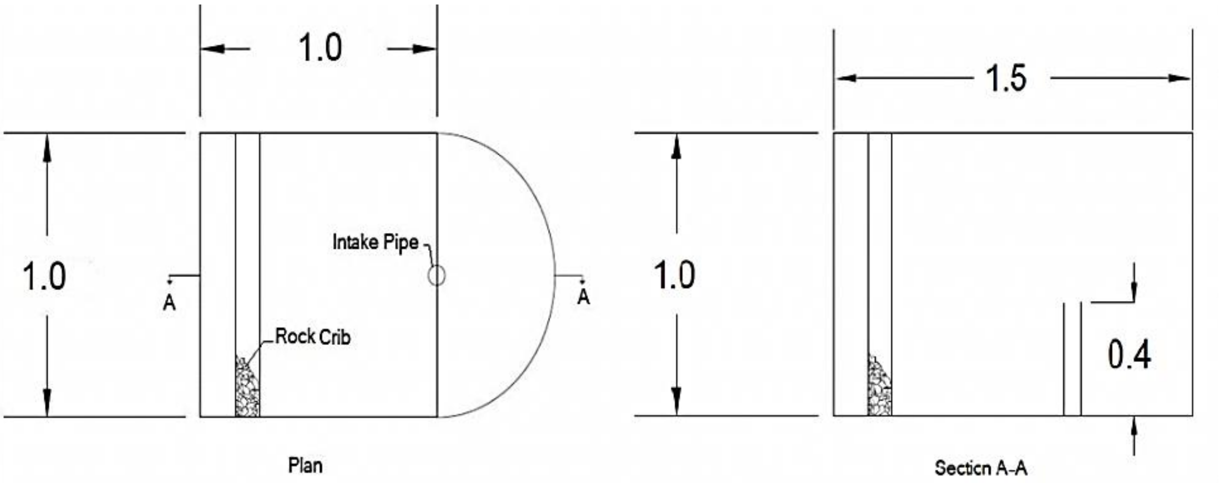

Fig. 2 Schematic diagram of the tank used in the present work

The flow discharges through a vertical pipe intake, 0.4 meter in height and 0.0704 meter in diameter at the centre of the second part of the tank. Figure 3 shows the experimental setup.

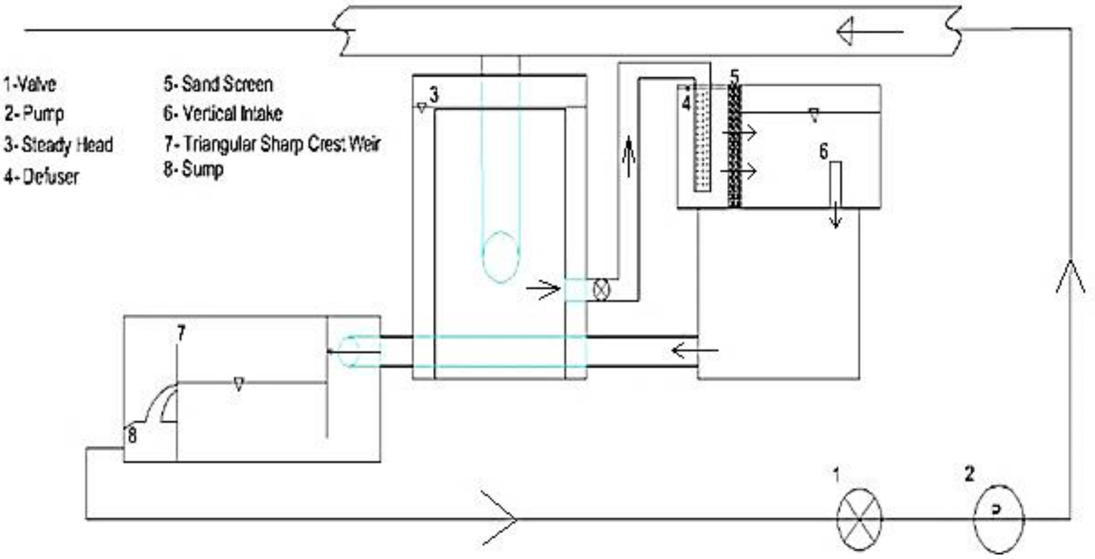

Fig. 3 Schematic diagram of the experimental setup

Two ultrasonic point gage level meters were used to measure the depth of the flow on the upper level of the intake mouth and behind of the triangular weir. The dimensions of the plates used in the present work are given in Table 2.

Table2 Variables used in present work

Dimensions of anti-vortex plates	Discharge rates (Lit/s)
2.5d×d, 2d×d, 1.5d×d, 2.5d×d/2, 2d×d/2, 1.5d×d/2, 2.5d×d/4, 2d×d/4, 1.5d×d/4	2 to 9.5 (10 different rates)

The test variables were the degree between the vertical nets and the diameter of the net orifice. The degree between the vertical plates was 90 and the diameter of the net orifice was 0.11d. Figure 4 shows the schematic diagram of three different types of vertical plates and Figure 5 shows the vertical intake used in the present work.

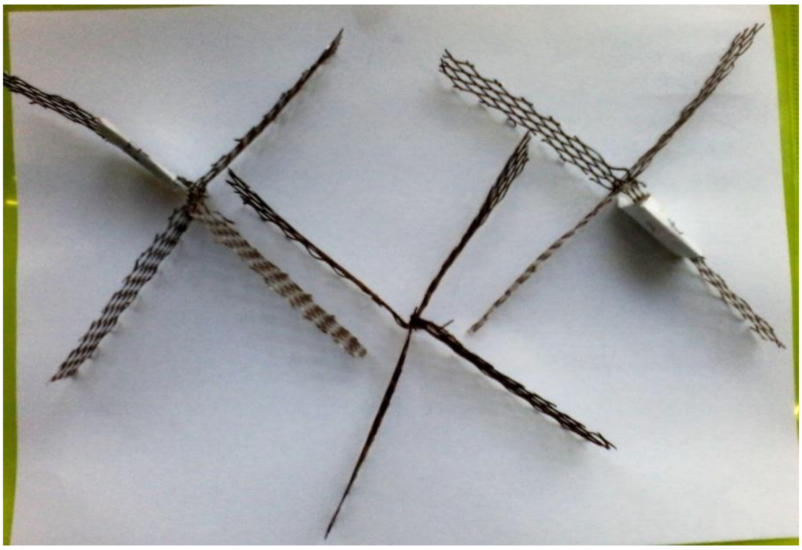

Fig. 4 Schematic model of 4 different types of vertical nets

Each test included feeding the test tank using the pump. With 15 minutes delay, the experiment was started and liquid was drained from the test tank and the flow rate and the reservoir submergence was controlled by a gate valve which was connected to the lowest level of the vertical intake. The free surface of the liquid in the tank was recorded by an ultrasonic point gage level meter. After the air entered the vertical intake, the submergence in the tank was recorded and drained flow was measured by triangular weir and then the experiment was finished.

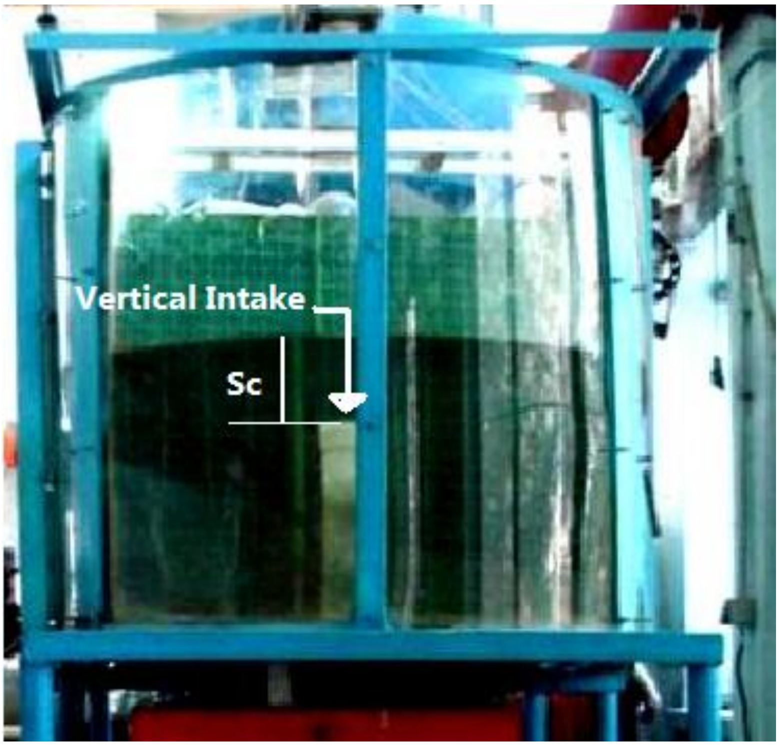

Fig. 1 The vertical intake used in the present work

3. Results and discussion

In the experimental model, the geometry was fixed and the Reynolds and Weber numbers were high enough to neglect. For a comparison of using the vertical plates on a vertical intake data with a reference, the first experiments were carried out on a simple vertical intake named intake number 1. The intake number 1 results are shown in figure 6.

By experimental findings, the critical submergence for a simple vertical intake is formulated as:

$$\frac{S_C}{d} = 3Fr^{0.248} \qquad (6)$$

Where the Froude number is limited from 0.68 to 2.86 and the R^2 from the equation 7 is 0.95.

Four different types of plates were installed on the simple vertical intake and the relevant results are shown in figures 7 to 9.

As can be seen in figures 7 to 9, the changes of the submergence ratio against the Froude number, is uptrend and with increase in submergence ratio, the discharge coefficient increases too as it is shown in figure 10.

As it is shown in figure 10, in the constant discharge coefficient, using the anti-vortex plates, the critical submergence reduces and for the same critical submergence with a simple vertical intake, the discharge coefficient increases.

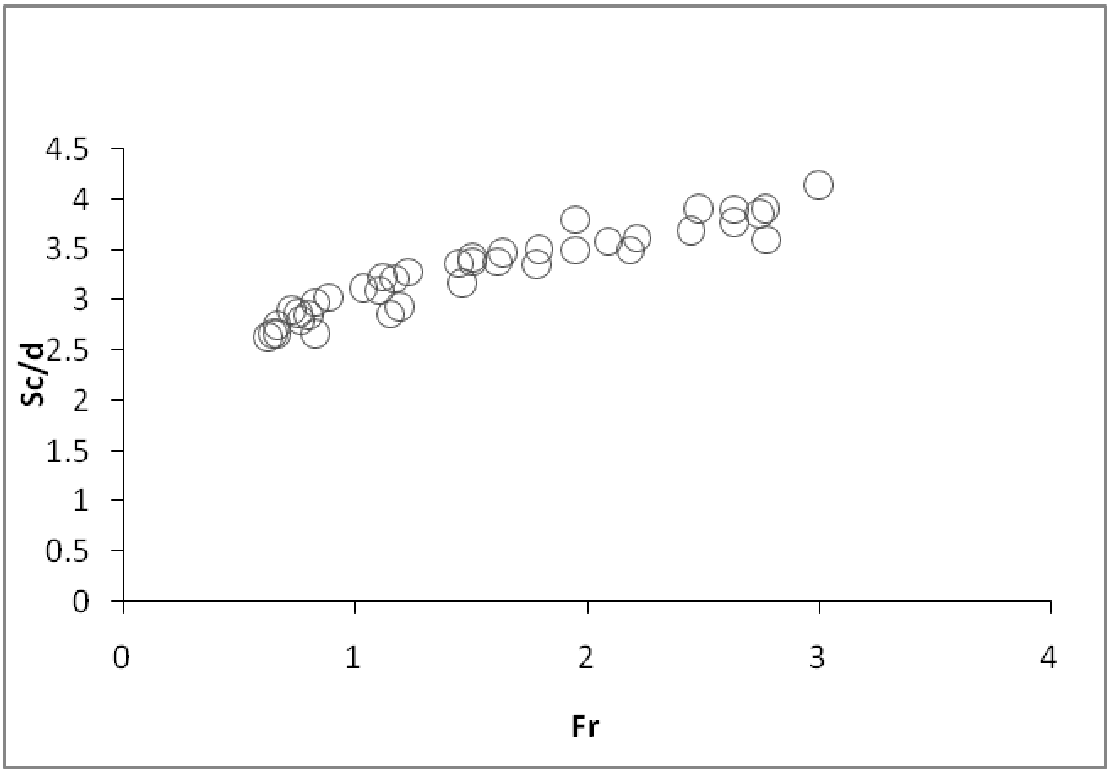

Fig. 2 The experimental results of the critical submergence at various Froude numbers (Intake No.1)

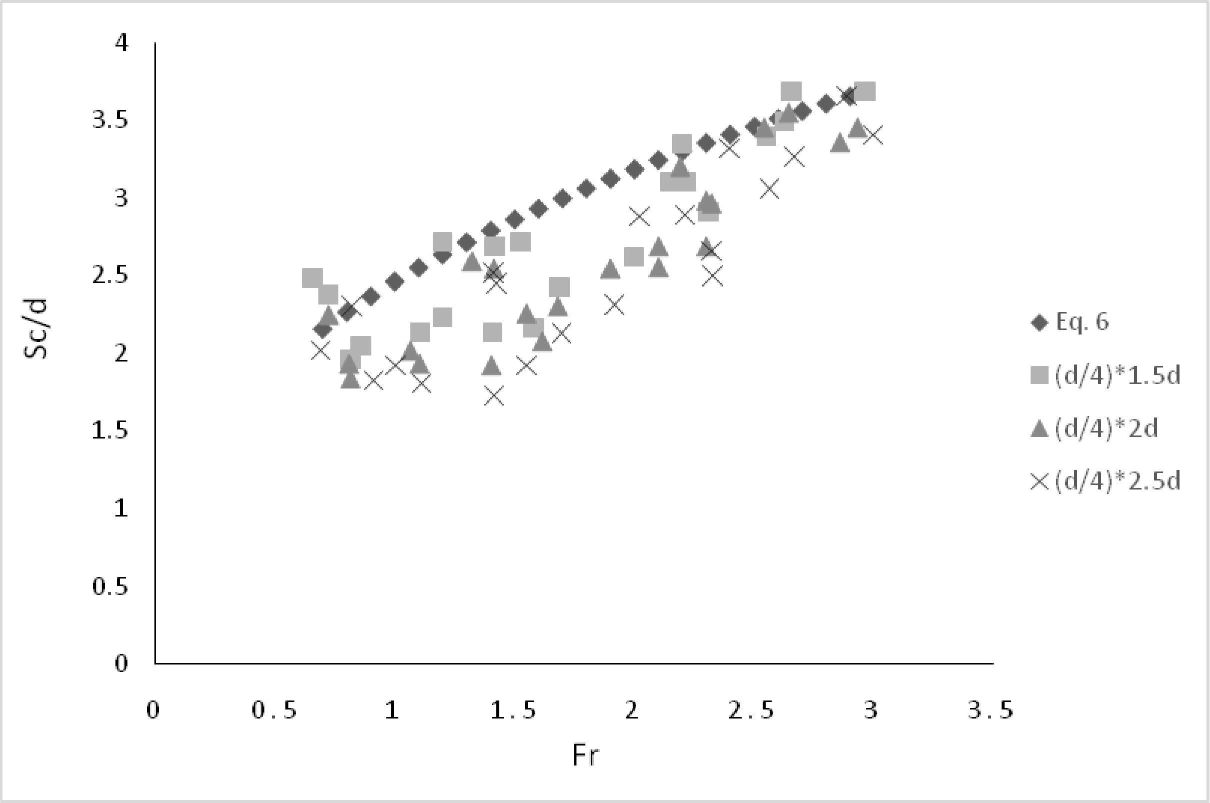

Fig. 7 The experimental results of the critical submergence at various Froude numbers. (Plates with height of d/4)

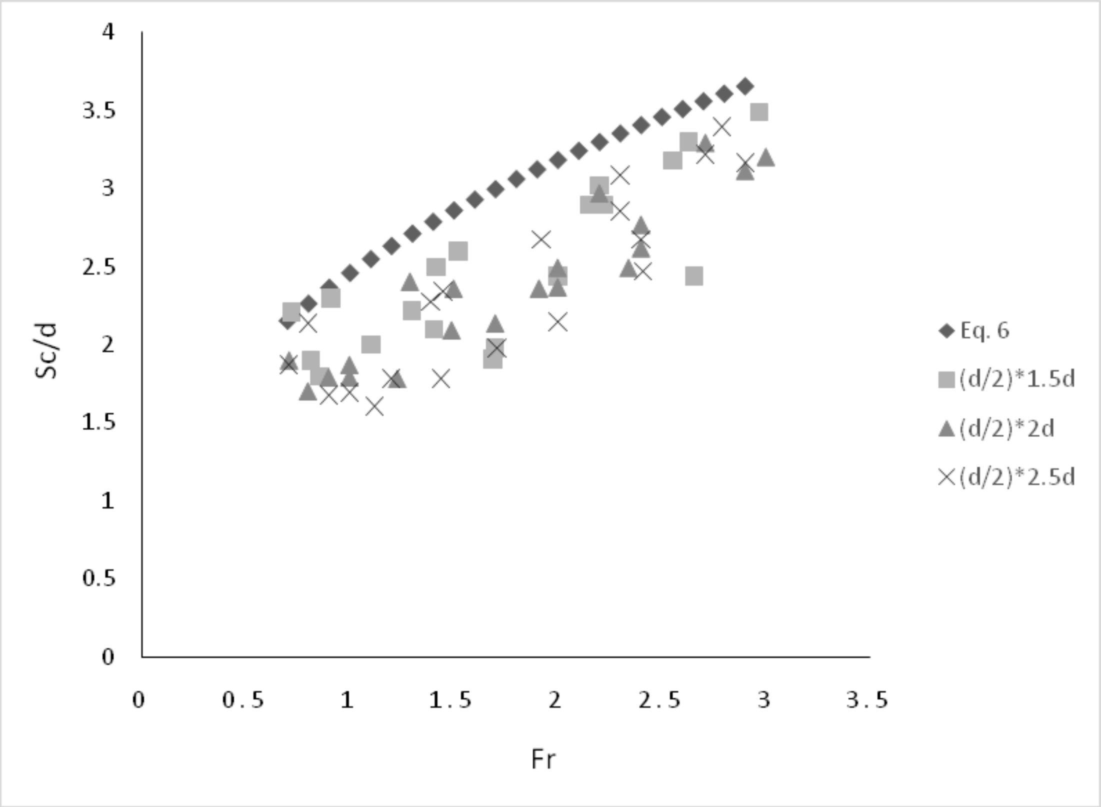

Fig. 8 The experimental results of the critical submergence at various Froude numbers. (Plates with height of d/2)

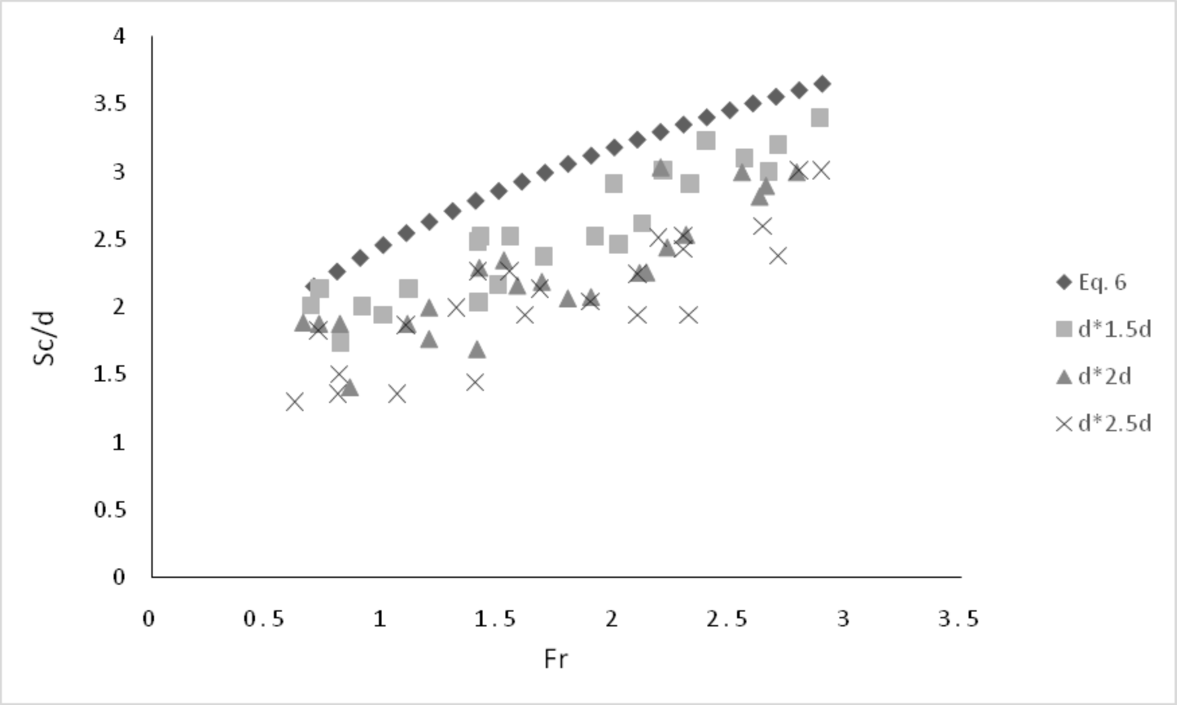

Fig. 9 The experimental results of the critical submergence at various Froude numbers. (Plates with height of d)

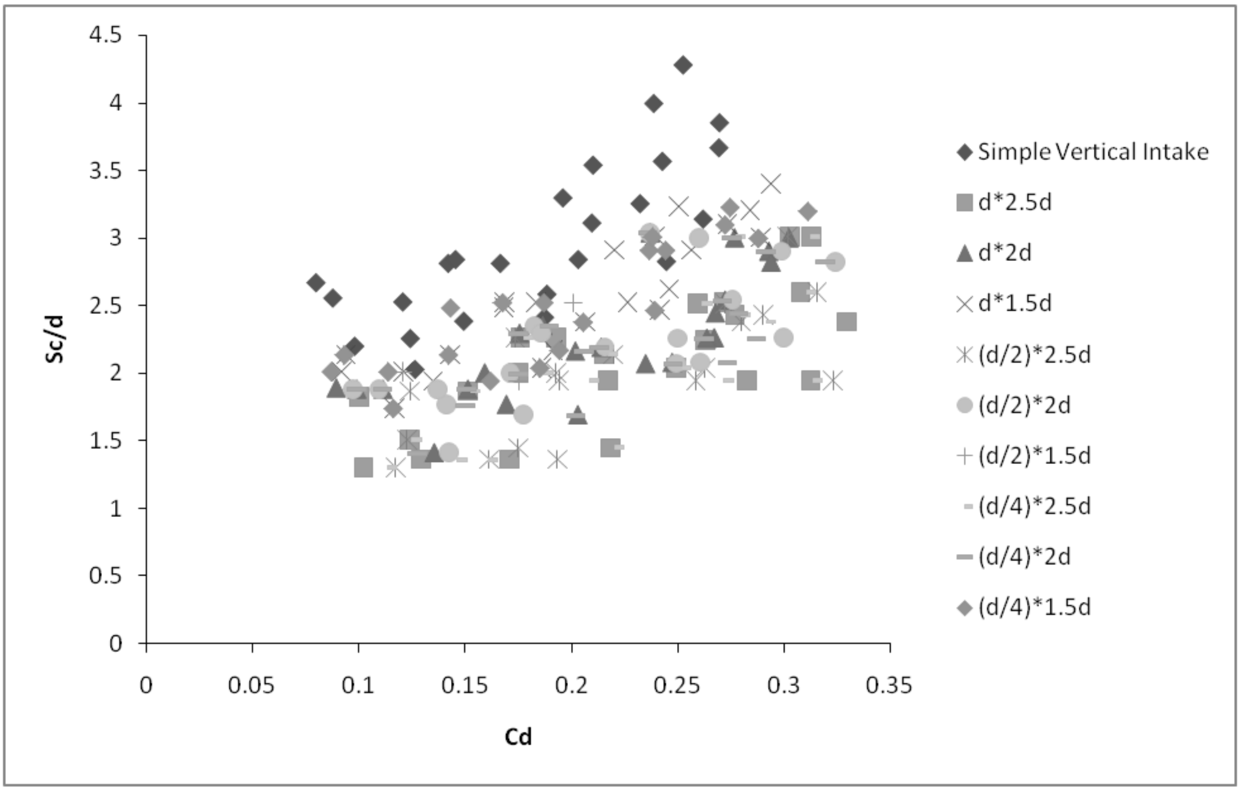

Fig. 3 Variation of discharge coefficient against the critical submergence ratio

Increasing the dimensions of the vertical meshed plates, the critical submergence rate decreases. The existence of the vertical plates on the simple shape of the intake makes the flow with lower critical submergence to reach the higher discharge coefficient. According to the results, it can be mentioned that with increasing discharge of the intake, the effect of vertical nets to reduce the critical submergence in higher discharge rates of intake will be more than the low discharge rates. This fact shows that using vertical meshed plates on the

Table 3 Sc/d values for different anti-vortex plates at the same coefficients of the discharge

	Simple	d*2.5d	d*2d	d*1.5d	d/2*2.5d	d/2*2d	d/2*1.5d	d/4*2.5d	d/4*2d	d/4*1.5d
Cd	Sc/d	Sc/d	Sc/d	Sc/d	Sc/d	Sc/d	Sc/d	Sc/d	Sc/d	Sc/d
0.07	2.029	1.193	1.45	1.589	1.077	1.415	1.461	0.99	1.401	1.651
0.09	2.243	1.347	1.604	1.781	1.234	1.57	1.651	1.158	1.556	1.832
0.11	2.431	1.484	1.739	1.95	1.375	1.706	1.82	1.313	1.691	1.99
0.13	2.599	1.609	1.86	2.103	1.504	1.828	1.974	1.457	1.813	2.133
0.15	2.752	1.724	1.97	2.244	1.625	1.94	2.116	1.593	1.924	2.263
0.17	2.893	1.831	2.071	2.375	1.739	2.043	2.249	1.723	2.027	2.383
0.19	3.025	1.932	2.166	2.498	1.847	2.139	2.374	1.847	2.123	2.495
0.21	3.148	2.028	2.255	2.614	1.949	2.23	2.492	1.966	2.213	2.601
0.23	3.265	2.119	2.339	2.724	2.047	2.316	2.605	2.081	2.298	2.701
0.25	3.375	2.206	2.419	2.828	2.141	2.397	2.713	2.192	2.38	2.796
0.27	3.481	2.289	2.495	2.929	2.232	2.474	2.816	2.3	2.457	2.886
0.29	3.582	2.37	2.567	3.025	2.32	2.549	2.915	2.405	2.531	2.973
0.31	3.679	2.447	2.637	3.118	2.405	2.62	3.012	2.508	2.602	3.056
0.33	3.772	2.522	2.704	3.207	2.488	2.689	3.104	2.608	2.671	3.136

intake mouth, effectively prevents the vortex forming and can cross flow with high efficiency. The values of ratio of the critical submergence using different dimensions of anti-vortex plates at the same discharge coefficients are given at Table 3. As can be seen from Table 3, the minimum values of the ratio of critical submergence happens when using d/4*2.5d for $C_d<0.19$ and d/2*2.5d for $C_d>0.19$.

Equation 7 is used to calculate the performance of the anti-vortex plates with respect to the simple shape of the vertical intake.

$$\text{Performance (\%)}=\frac{\frac{S_{C1}}{d}-\frac{S_{Cn}}{d}}{\frac{S_{C1}}{d}}\times 100 \qquad (7)$$

Where S_{c1}/d is the ratio of the critical submergence of the simple vertical intake at a given discharge coefficient and S_{cn}/d is the ratio of the critical submergence of the anti-vortex plates on the simple vertical intake at the same discharge coefficient. The best performance of the anti-vortex plates is shown in figure 11.

As can be seen from the Figure 11, the best performance of the anti-vortex plates happened when the d/4*2.5d anti-vortex plates were used and is 51%.

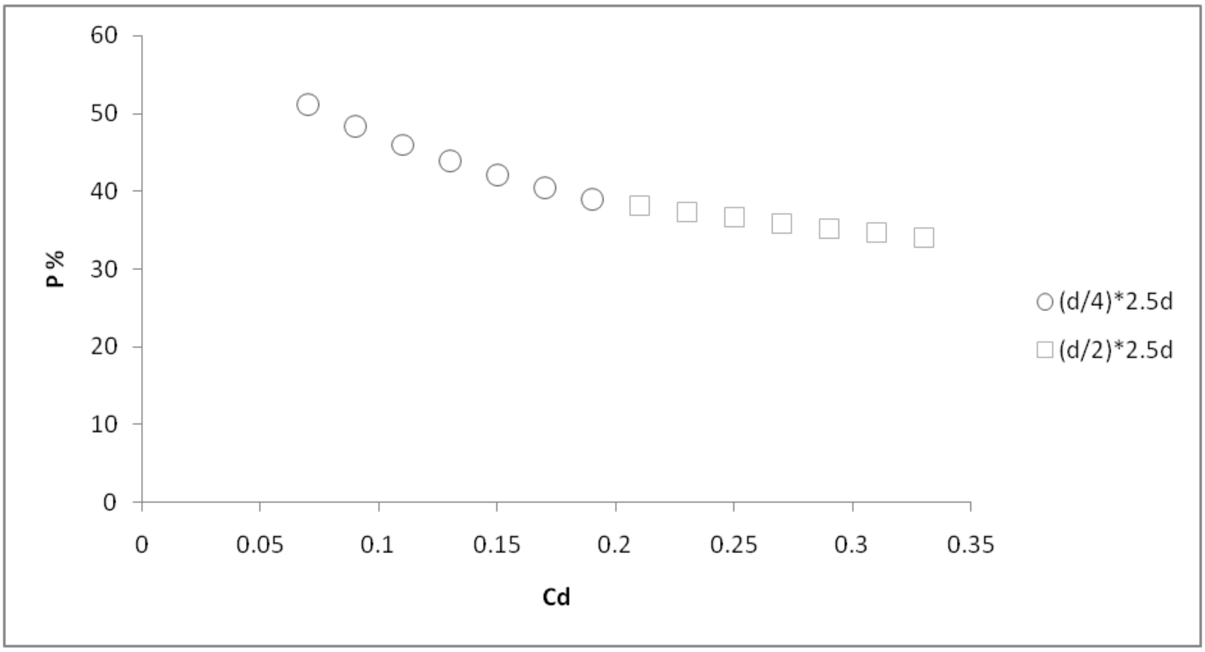

Fig. 3 The best performance of the anti-vortex plates used in present work

4. Conclusion

The vertical intake is one of the drain ports and is used in the present work. The main problem with all intakes is the development of strong vortices in their mouth. In this study, the critical submergence of the vertical intake was investigated in a reservoir tank. Developed equation can be used to predict the critical submergence ratio for a simple vertical intake while knowing hydraulic conditions. The results showed that using vertical meshed plates on the intake, the critical submergence occurs in a higher discharge rate and also the maximum discharge coefficient with a bigger dimension of the vertical meshed plates on the intake mouth is created. Analyzing the results showed that extending the length of the vertical plates is more effective than height extending to reduce the critical submergence and increase the discharge coefficient. It should be mentioned that the proposed conclusion is made with the present experimental setup and many more experimental models is needed in order to achieve a generalized sequel.

References

1 Hecker GE (1987). Fundamentals of vortex intake flow. Swirling flow problems at intakes. IHAR Hydraulic structures design manual 1, J. Knauss Ed. Balkema, Rotterdam, The Netherlands, pp.13-38.

2 Rindels AJ and Gulliver JS (1983). An experimental study of critical submergence to avoid free-surface vortices at vertical intakes. Saint Anthony Fall Hydraulic Laboratory. Project Report No. 224.

3 Yildirim N and Kocabas F (1995). Critical submergence for intakes in open channel flow. Journal of Hydraulic Engineering, ASCE, 121(12): 900-905.

4 Yildirim, N. and Kocabas, F., Prediction of critical submergence for an intake pipe [J]. J. Hyd. Res., IHAR, 2002, 121(12): 900-905

5 Yildirim, N., Critical submergence for rectangular intake [J]. J. Engrg. Mech., ACSE, 2004, 130(10): 1195-1210

6 Yildirim, N., Kocabas, F. and Gulcan, S.C. Flow boundary effects on critical submergence of intake pipe [J]. J. Hyd. Engrg., ASCE, 2000, 126(4): 288-297.

7 Yildirim, N., Kocabas, F. and Gulcan, S.C. Errata for flow boundary effects on critical submergence of intake pipe [J]. J. Hyd. Engrg., ASCE, 2007, 133(4): 463-472.

8 Yildirim, N. and Tastan, K. Comparison of Flow-Boundary Effects on Critical Submergence of an Intake [J]. Journal of Teknik Dergi, Turkey, 2009, 20(3): 4779-4792.

9 Tastan, K. and Yildirim, N. Effect of dimensionless parameters on air-entraining vortices. [J]. J. Hyd. Res., 2010, 48(1): 57-64.

10 Eroglu, N. and Bahadirli, T., Prediction of critical submergence for a rectangular [J]. J. Energy. Engrg, ASCE, 2007, 133(2): 91-103.

11 Rahimzadeh, H., Fathi, N. and Asoodeh, M.H., An experimental model of flow surface patterns at vertical downward intake with numerical validation, Int. Conf. on water resources, Hydraulics & Hydrology. Chalkida, Greece, May 11-13, 2006, pp:111-118

12 Li, H. and Chen, H. Experimental and numerical investigation of free surface vortex [J]. Journal of Hydrodynamics, 2008, 20(4): 481-491

13 Zhao, Y. et al. Numerical analysis of structure and evolution of free water vortex [J]. Journal of Xi'an Jiaotong University, 2003, 33(3): 85-88.

14 Chen, Y., Wu, C. and Ye, M., hydraulic characteristics of vertical vortex at hydraulic intakes [J]. Journal of Hydrodynamics, 2007, 19(2): 143-149.

15 Sohn C. H., Ju N. G. and Gowda B. H. L., PIV study of vortexing during draining from square tanks [J]. Journal of mechanical science and technology, 2010, 24(4): 951-960.

16 Sohn C. H., Ju N. G. and Gowda B. H. L. Draining from cylindrical tanks with vane-type suppressors, a PIV study [J]. Journal of Visualization, 2009, 12(4): 347-360.

17 Mahyari M. N., Karimi H., Naseh H. and Mirshams M. Numerical and experimental investigation of vortex breaker effectiveness on improvement in launch vehicle ballistic parameters [J]. Journal of Mechanical Science and Technology, 2010, 24(10): 1997-2006.

18 Sarkardeh, H., Zarrati, A.R., Jabbari, E. and Roshan, R., Discussion of prediction of intake vortex risk by Nearest Neighbor Modeling [J]. Journal of Hydraulic Engineering, 2012, 137(6): 701-705.

19 Tagvaei, S.M., Roshan, R., Safavi, Kh. And Sarkardeh, H., Anti-vortex structures at hydropower dams [J]. International Journal of the Physical Science, 2012, 7(28): 5069-5077.

20 Daggett LL and Keulegan GH (1974). Similitude conditions in free-surface vortex formation. Journal of Hydraulic Engineering, ASCE, 100(11):1565-1580.

21 Anwar HO, Weller JA and Amphlett MB (1978). Similarity of free-vortex at horizontal intake. Journal of Hydraulic Research, 16(2):95-105.

22 Jain AK, Ranga Raju KG and Garde RJ (1978). Vortex formation at vertical pipe intakes. Journal of Hydraulic Engineering, ASCE, 104(10):1429-1445.

23 Odgaard AJ (1986). Free-surface air core vortex. Journal of Hydraulic Engineering, ASCE, 112(7): 610-620.