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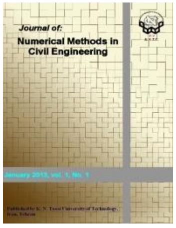

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Numerical Investigation of Bottom Intake Structure for Desalination Plants

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Abstract:

One of the most important hydraulic structures used to divert flow is lateral intake. Different methods can perform it, such as channels, pipes, orifices. This study investigates the effects of various geometric and hydraulic parameters on bottom intake, which is widely used as seawater intake for desalination plants. Observation shows that the flow velocity is higher in the square shape than the circular shape in front of the velocity cap, while it is more at both sides of the velocity cap in the circle type. The correlation of various factors on the discharge coefficient was analyzed based on 180 physical tests using Python code. Results show that the discharge capacity of the circle-shaped intake velocity cap is about 2% to 4% higher than that of the square-shaped intake cap. In addition, the discharge coefficient of intake is affected by the approach flow Froude number and area of intake, while the height of the velocity cap has less effect on discharge through the intake. Furthermore, numerical investigation invests in the flow patterns around velocity caps. Observation shows that the separation zone at the back side is more prominent in the square shape than in the circular shape.

ANOVA	Analysis of Variance	A	Area of velocity cap (m^2)
B	channel width, (m)	D	Diameter of the orifice, (m)
DOE	Design of Experiment	Fr	Froude number
h	height of the velocity cap, (m)	H	Head of water above the centerline of the orifice, (m)
MTs	Model trees	N	Number of blades
P	water pressure, (N/m^2)	Q_{in}	Discharge through the intake (m^3/s)
Q_m	Discharge in the main channel (m^3/s)	Re	Reynolds number
V	Velocity in main channel, (m/s)	w	the distance of opening of intake from the channel bed, (m)
Y_m	Water depth in the main channel, (m)	Z	The height of the point relative to the base level, (m)
ρ	Mass density (kg/m^3)		

1. Introduction

The study of intake structures has a long history in the field of hydraulic engineering. It is considered one of the most important hydraulic structures diverting a portion of the flow. Selecting the type of water intake depends on various factors, including the discharge of intake, the topography of regions, and the type of resource (river, channel, or sea).

Large numbers of investigations have been conducted on channel intake. The same ideas can be considered for seawater intakes since few studies have been performed in marine environments. Many researchers have focused on lateral intake up to now. Large numbers of investigations have been conducted on lateral channel intake. Neary et al. (1999) showed that separation zones in the main and diversion channels are formed because the flow diversion makes a complex flow structure [1]. Barkdoll et al. (1999) investigated sediment control at lateral diversions and considered vane to limit the sediment entrance[2]. Rahmani Firozjaei et al. (2019) studied lateral channel

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intake. They simulated different lateral intake angles and introduced a 60o angle as an appropriate angle [3]. Many studies have been conducted that can be mentioned such as Zhao et al. (2022), Yang et al. (2022),and Band et al. (2022) [4~6]. Moghadam et al. (2010) experimentally studied flow patterns in a 30-degree intake. The results reveal that the separation zones are directly related to the lateral intake elevation [7]. Lateral orifice and lateral pipe intake are other methods for water intake. The discharge coefficient of sharp-crested circular side orifices in open channels was experimentally studied by Hussain et al. (2010) [8]. They stated that the Froude number, water elevation, and orifice shapes are important in the discharge coefficient. Alwan et al. (2020) studied experimentally and numerically on the sharp-crested rectangular weir and presented an equation for the discharge coefficient [9]. Rahmani Firozjaei et al. (2020) studied lateral pipe intake flow patterns and sediment transport. Their results indicate that pipe intake with a 90o angle has high performance. Also, they presented the discharge coefficient for lateral pipe intake[10]. Critical submergence for a horizontal pipe intake was studied by Taştan (2020) [11]. He stated that similarities between Froude, Reynolds, and Weber numbers are unimportant to evaluate. Sarkardeh and Marosi (2022) studied vortex at vertical intakes with an analytical model. They determined and verified a relationship for critical submerged depth by experimental data [12]. Xianbei et al. (2022) studied the air entertainment to vertical pipe intake. They declared that the natural asymmetry makes air-entrainment formation more easily and quickly [13].

One of the biggest global social problems is that about one-third of the world's population does not have access to clean water, and this rate will continue to rise. Ocean water intake has recently been considered a large water reservoir. There are different seawater intake types, such as surface water intake and offshore intake structure. Each type has its design and environmental considerations. Generally, seawater intakes are divided into two main groups: direct and indirect. Figure 1 shows different possible marine intake types (Toorang et al., 2013 [14]). Greenlee et al. (2009) stated that an open intake structure is better than other seawater intake methods due to the high water supply capacity. One of the intake structures that can be used for this purpose is the so-called velocity cap [15].

As shown in Figure 2, these intakes are usually located on the sea floor and mounted at a water depth ranging between 10 and 20 meters. The specific geometry of the velocity cap curbs the formation of a surface vortex and protects it from bed sediments taken in. This change in the flow pattern (from vertical to horizontal), performed by velocity caps, aids in declining marine life impingement.

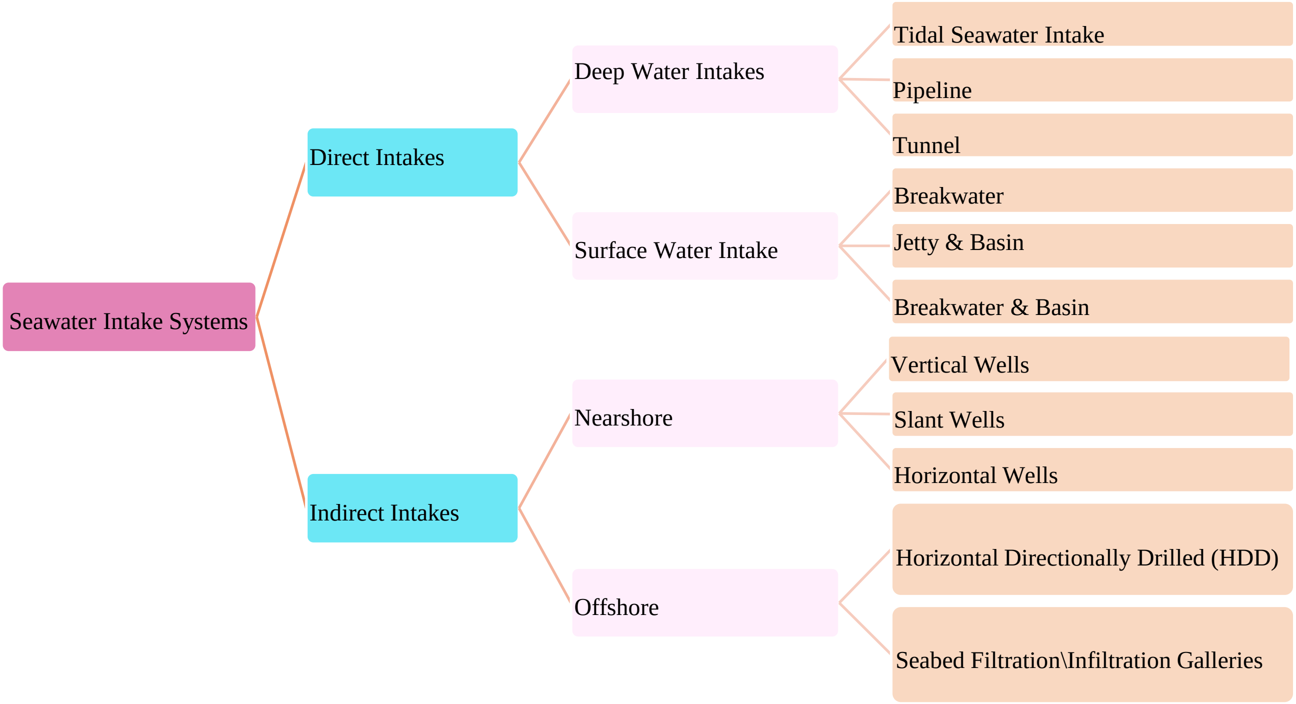


Fig. 1: Different possible marine intake types (Toorang et al., 2013) [14]

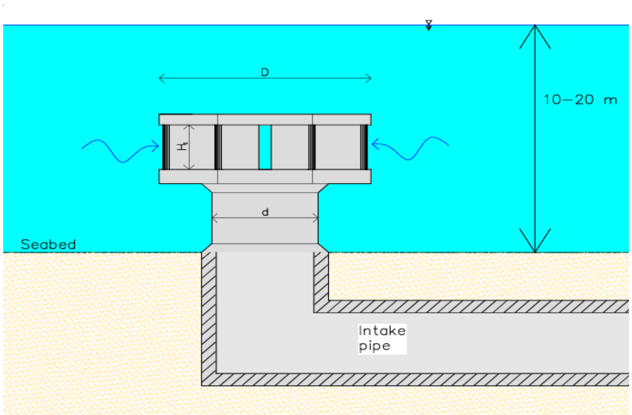


Fig. 2: Schema of a velocity cap intake structure in prototype

Lee and Wahab (2019) studied the performance of various turbulence models on an open offshore intake. They used Delft3D and FLOW3D software in their studies. Their observations showed that among turbulence models, RNG k-Ɛ has excellent accuracy compared to other turbulence models for predicting flow velocity and water level [16] . Chie and Wahab (2020) numerically investigated the design criteria for the flow field around the velocity cap. They used FLOW-3D software for simulation. They showed that a velocity cap increases the velocity of flow upstream and reduces it downstream [17]. Using a computational fluid dynamics model, Christensen et al. (2014) studied a velocity cap structure's hydraulic performance [18]. Cornett et al. (2015) studied seawater intake structures in shallow water under wave conditions [19]. They developed empirical relationships to describe loads on submerged intake structures. To sum up, the conducted investigations show numerous studies on water intake, each examining the issue from a specific point of view. Although attention to bottom intake for various purposes is increasing due to the unlimited water resources and the high quality of water, until now, little investigations have been conducted on effective parameters of the discharge coefficient of seawater intakes underflow, which was mainly numerical. This study will discuss effective parameters on discharge coefficient and observations during experiments. The presented experimental investigation complements previous works and aims to investigate the nature of the effective parameters on the discharge coefficient of bottom intake under flow conditions.

2. Analytical considerations

2.1 Discharge equation

The hydraulic study of these structures is performed based on the energy equation and continuity equation of the system. Therefore, considering all the losses caused by friction and connections, the energy between the two points is compared. This balance ensures the continuity of the flow .Bernoulli's equation expresses the principle of energy for incompressible flows. Since the outlet level is lower than the input level of the intake cap, the form of Bernoulli's equation is as follows (Equation 1):

$$\left(\frac{p}{\rho g}+\frac{V^2}{2g}+\mathrm{z}\right)_1=\left(\frac{p}{\rho g}+\frac{V^2}{2g}+\mathrm{z}\right)_2+H \qquad (1)$$

Points 1 and 2 are related to sea and outlet levels, respectively. In the above relation, H indicates the losses of the whole system, which contain friction losses, minor losses, entrance losses, bend losses, and transition losses. Finally, the intake discharge is extracted from Equation (2). This is a general of lateral intake [20].

$$Q_{in}=C_d\sqrt{2gH}\cdot\frac{\pi}{4}\ D^2 \qquad (2)$$

2.2 Dimensional analysis for Cd

By reviewing the previous intake research, it was found that the parameters affecting the discharge coefficient or Cd in the side intake from the open channel include V, B, Ym, w, h, ρ, μ, g. which is ρ, μ, and g are mass density, viscosity and acceleration due to gravity, respectively [8].

$$C_d=f_1(\mathrm{V}،Y_m،\mathrm{B}،\mathrm{w}،\mathrm{h}،\mathrm{A}،\rho،g،\mu،\mathrm{N}) \qquad (3)$$

ρ, V, and Y_m are considered the repeating variables,Taking ρ, V, and Y_m as the repeating variables, Cd could be written as the following functional relationship based on non-dimensional parameters:

$$C_d=f_2\left(\mathrm{Fr}=\frac{V}{\sqrt{gY_m}}،\frac{\mathrm{B}}{Y_m}،\frac{\mathrm{w}}{Y_m}،\frac{\mathrm{h}}{Y_m}،\frac{\mathrm{A}}{{Y_m}^2}،\mathrm{Re}=\frac{VY_m\rho}{\mu}،\mathrm{N}\right) \qquad (4)$$

Parameters B and A can be ignored because they are constant in all experiments. Reynolds number is insignificant in open channel flows [20]. Hussain et al. (2010) stated that evaluating the Reynolds number for Cd of lateral intake is unnecessary. Therefore, Cd could be expressed as the following functional relationship [8]:

$$C_d=f_2\left(\frac{V}{\sqrt{gY_m}}،\frac{\mathrm{w}}{Y_m}،\frac{\mathrm{h}}{Y_m}،\frac{\mathrm{A}}{{Y_m}^2}،\mathrm{N}\right) \qquad (5)$$

2.3 Experimental and numerical work and procedure

As shown in Figure 3, a rectangular channel was used with 3.5, 0.5, and 0.5 m in length, width, and height, respectively. In order to regulate the depth of the f low and measure the discharges from the main, a sharp-crested rectangular weir was provided at the end of the main channel. An intake was considered at 2 meters from the beginning of the main channel. Experiments were performed for velocity cap area A= 0.020 m^2, velocity cap heights h= 0.08 and 0.016m, and crest heights of intake w=0.08, 0.12 and 0.016m. In this study, two shapes of velocity caps, which are commonly used in prototypes, have been investigated. The caps have fixed and movable blades. During the test, the purple color blades were removed from the cap if necessary. Discharge through the velocity cap was passed into a pipe of 75mm diameter, then to a return channel.

As shown in Figure 3, the channel was fed by a pipeline that transferred water from the reservoir. Then, the flow entered a small tank at the beginning of the main channel to calm down. To decrease large-size eddies and to eliminate surface disturbances, splitter plates were considered upstream of the main channel to attain stable conditions. An ultrasonic flowmeter was used to calibrate the rectangular sharp-crested weir, which was located at the end of the main channel, to measure the discharge rate. A digital point gauge of accuracy of 0.1 mm was used to measure water levels and head over the weir crests. Experiments were carried out in free flow and no vortex formation conditions through the lateral intake. The collected experimental parameters in this study are summarized in Table 1. A total of 180 experiments were conducted using the full-factorial design method.

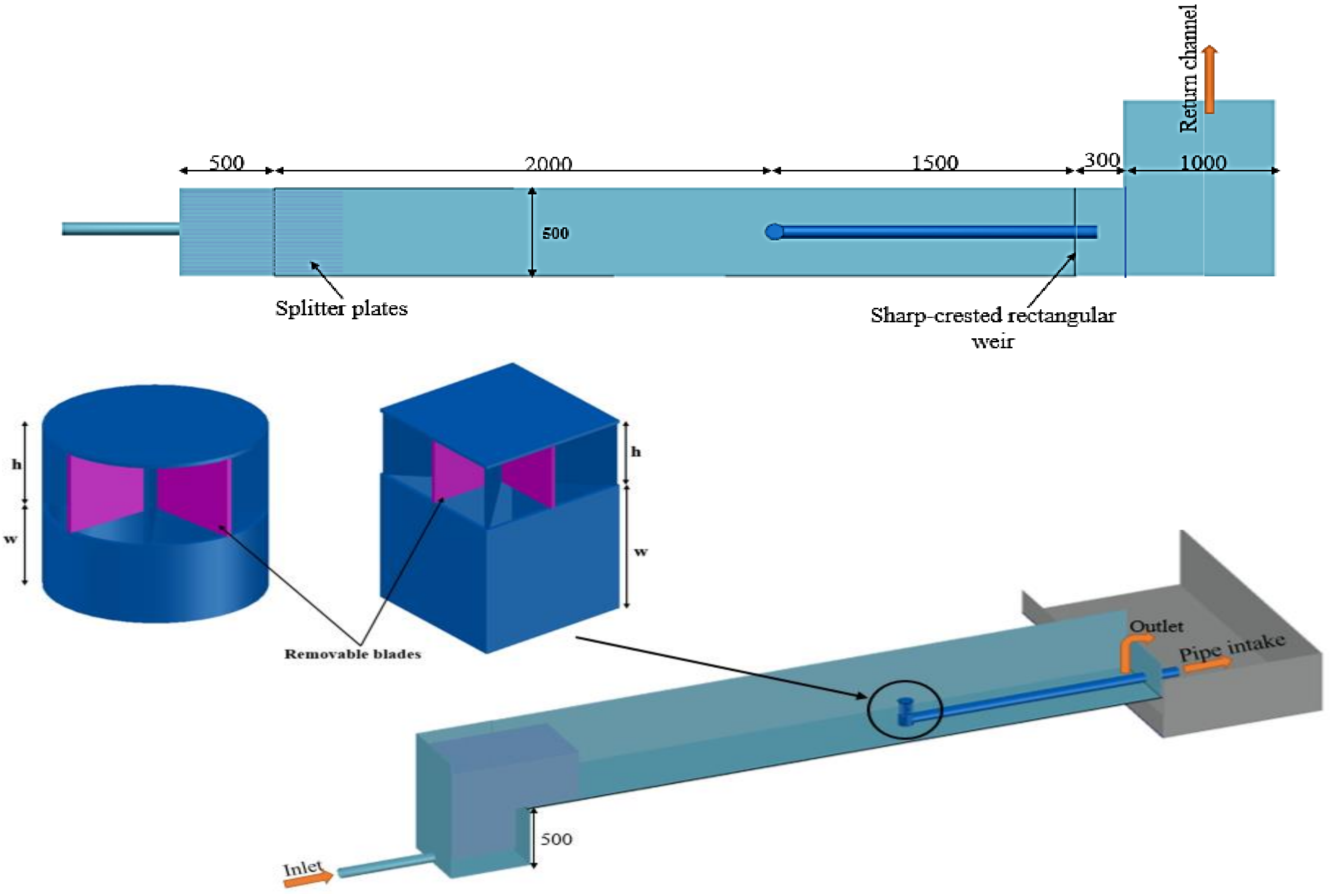


Fig. 3: scheme of the experimental setup

Table 1: Overview of the datasets used in the present study

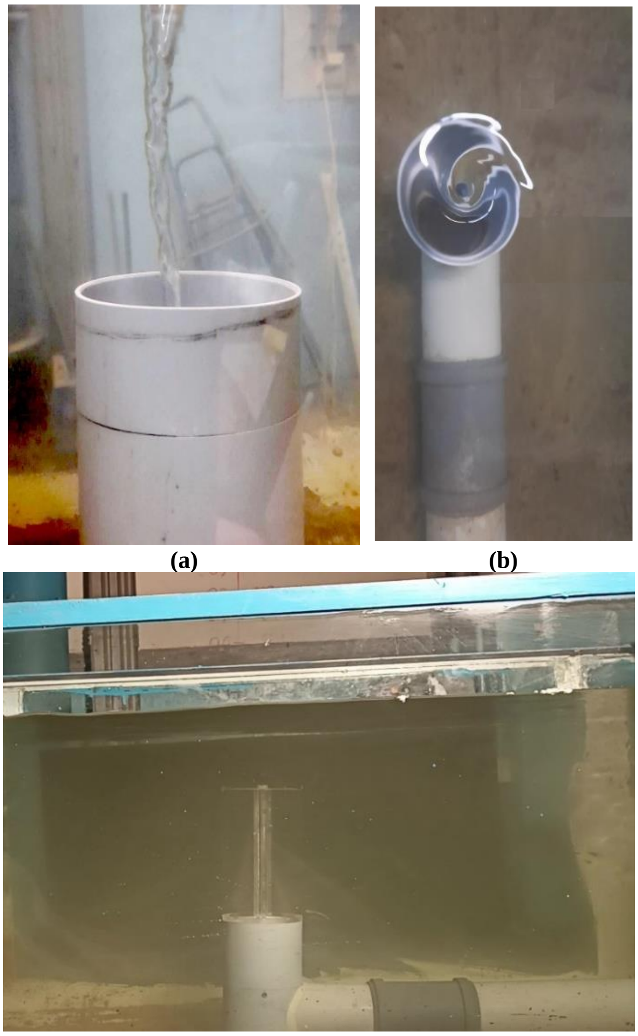
Parameter	Unite	Range of data	
		Minimum	Maximum
Q_m	m^3/s	0.006	0.016
Q_{in}	m^3/s	0.003	0.009
h	m	0.08	0.016
w	m	0.08	0.016
A	m^2	0.0064	0.020
Y_m	m	0.2910	0.4180
V	m/s	0.0319	0.1004
Fr	Dimensionless	0.016566	0.056516

Various ways have been used to detect the current velocity in hydraulic phenomena, such as ADV and LIF. In recent years, LIF (Laser-Induced Fluorescence) has widely received attention in hydraulic engineering to investigate flow characteristics because it does not affect current, unlike ADV (Acoustic Doppler velocimetry). In the LIF system, a continuous laser with an output power of 150 MW with a wavelength of 532 nm is used. Also, the camera used has a CMOS sensor and the ability to record pictures with a resolution of 800*600 pixels and a rate of 200 frames per second. In This study, PIVlab software was used to process and analyze images. Also, analyzing the experimental data has been done using Python code.

3. Results and Discussion

3.1 Observations during experiments

As mentioned before, one of the most significant roles of a velocity cap is to prevent the formation of a vortex from the surface. Figure 4 shows that the absence of the velocity cap causes the vortex problems. As seen in Figure 4, vortex formations and their progress are challenging for seawater intake. A velocity cap with numerous blades is applicable significantly because it turns vertical flow into horizontal flow. During the tests, a vortex was formed around the velocity cap when the water level above the velocity cap was relatively less. However, no experiments for discharge through the seawater intake were performed under this condition. Future studies will investigate in detail the parameters affecting vortex formations.



(a) **(b)**

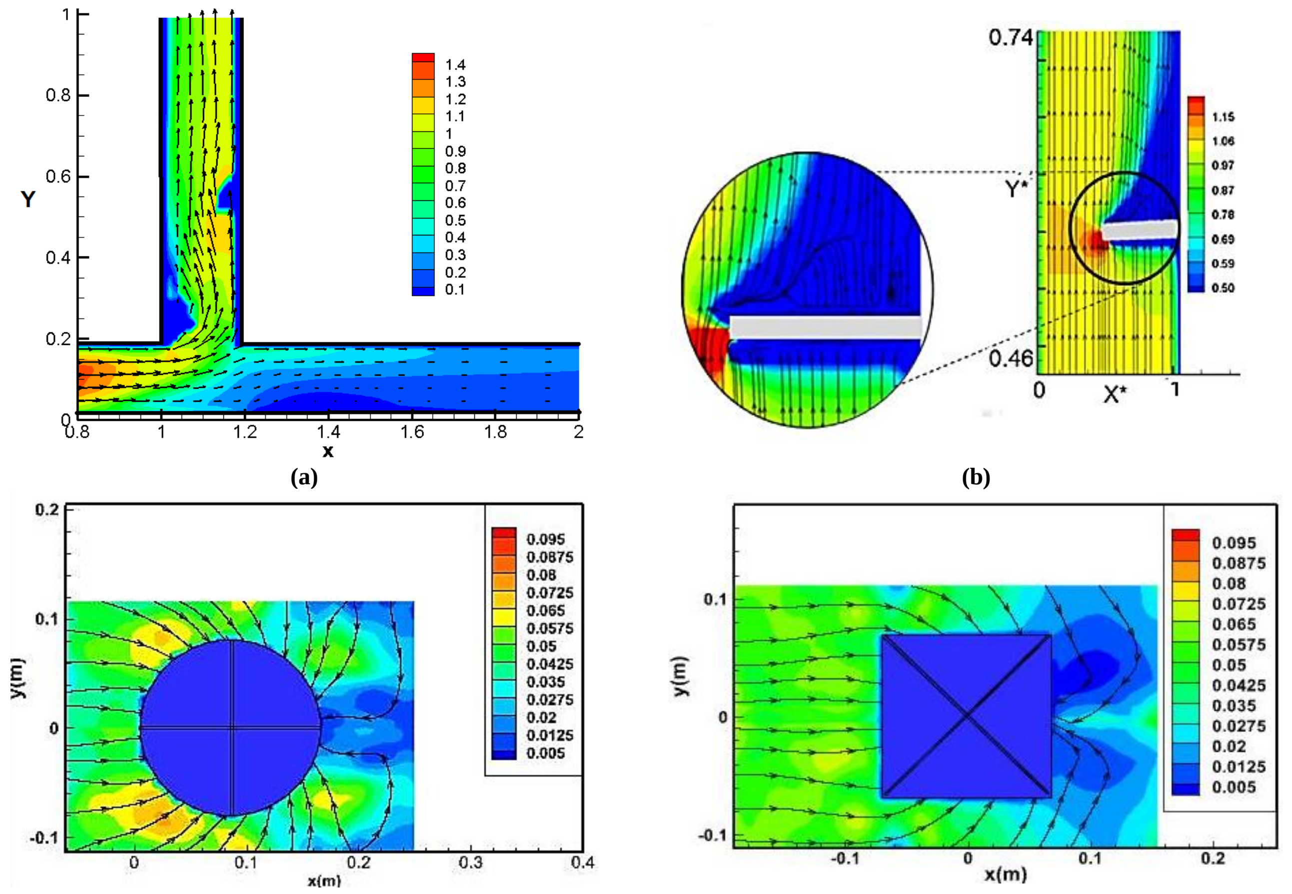
(C)

Fig. 4: [A1]**(a &b)** Side and plan view vortex formations without velocity cap **(c)** removing vortex using velocity cap.

Flow pattern around intake structure drawn out numerically. Figure 5 illustrates a flow pattern comparison around the intake structure. The flow pattern around the lateral channel intake was studied by Rahmani Firozjaei et al. (2019) [3]. Their results showed that separation zones are formed in the main channel and lateral channel (Figure 5a). Also, Rahmani Firozjaei et al. (2020) studied lateral pipe intake (Figure 5b) [10]. Their result indicated that separation zones are created after the intersection with the lateral open channel, near the internal. Various factors influence the formation of separation zones, such as the angle of intake structures and intake position. Observations of the bottom intakes indicate that the recirculation area locations in the main channel are entirely different from a lateral open channel intake, similar to the lateral pipe intake. This study briefly investigates the flow pattern around the bottom intake for two circle and square velocity caps (Figure 5c &d). Observation shows a separation zone is formed at the back side of the bottom intake. In the front of the velocity cap, the flow velocity is higher in the square shape than the circular shape, while it is more in the circle type on both sides. Also, observation shows that the separation zone at the back side is more prominent in the square than in the circular shape. Flow patterns and factors will be studied in detail in future studies.

3.1. *Effect of various parameters on* C_d

In this study, based on Equation (3), the discharge coefficient is computed for each data set for known values of w, h, N, A, and Q for two shapes, square and circle. The effects of dimensionless parameters Y_m/B, w/B, h/B, A/B^2, Fr, N, and shape have been determined on Cd .It is worth mentioning that the effect of parameter A on the Cd has been considered in the circle shape. Most velocity caps commonly are square and circular. A comparison of the discharge coefficient through the circle and square type of velocity cap is shown in Figure 6. The measured discharge in the seawater intake indicates that the circle shape intake has higher efficiency than the square one. Observations show that this flow rate difference will decrease while the fluid velocity in the main channel increases. So, compared to the square shape, the circle shape can increase the efficiency by about 2% to 4%, the former in a high fluid velocity and the latter in a low one. This difference in efficiency is because of the flow pattern around the shape. Observations show that the flow pattern around the circle velocity cap is smoother than square one. It should be noted that the flow pattern around the velocity cap will be discussed in more detail in future research.



(a) **(b)**

(c) **(d)**

Fig. 5: Streamline with velocity magnitude contour (m/s). **(a)** lateral channel intake. **(b)** lateral pipe intake. **(c, d)** bottom intake with circle and square type of velocity cap, respectively

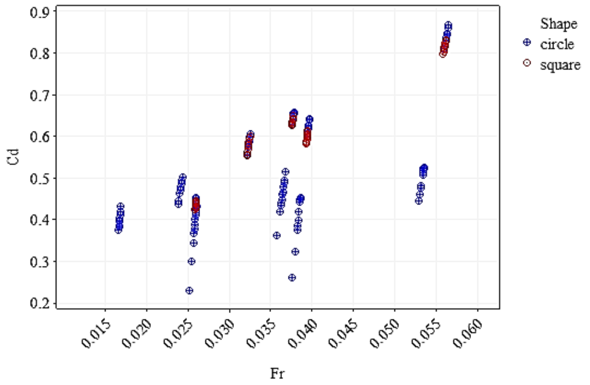
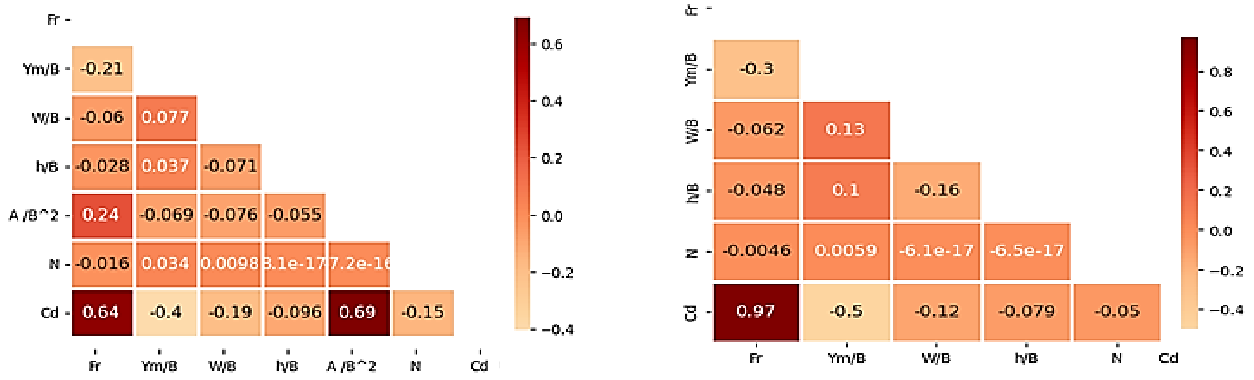


Fig. 6: Variation of Cd with Fr for two square and circle shapes

The relationship between the variables is indicated by correlation coefficients, which represent a probability (p-value). High p-values express weak correlations because they are very likely no relationship. Correlation is always a number between -1 and 1. When it is greater than zero, it indicates a positive association. It shows a fragile relation if the correlation values are near 0. So, when correlation values move away from 0 toward -1 or 1, the strength of the linear relationship grows. Correlation values between parameters are shown in Figure 7. Analyzing the thorough data reveals that the most influential parameters on Cd are Fr and A/B^2. By contrast, based on datasets used in this study, C_d is almost unaffected by *h/B*. However, it is expected that the Cd increases by increasing the h/B. These results are also observed for the side orifice, side weir, and side sluice gate [8, 20, and 21]. Other parameters, such as the primary channel's intake area and flow conditions, are important in discharge. Numerous blades are used in the velocity caps to control the overall flow pattern moving through intakes. As a result, injury and mortality of fish during downstream passage through seawater intake are significantly reduced. Based on correlation values, the water intake efficiency is almost less affected by the number of blades in the square type. By contrast, it has more effect on the flow rate in the circle type. Figure 8 shows the effect of N on the Cd in different Fr. It shows that cd increases gradually by decreasing the number of blades. Generally, the performance of the blades depends a lot on the shape of the velocity cap. Moreover, according to the authors, the thickness of the blades can affect the percentage of their performance on the discharge efficacy. If the blade's thickness increases considerably, it blocks and returns flow. As a result, it will have a negative impact on Cd. The effect of blade thickness can be investigated in future studies. Hussain et al. (2010) stated that the discharge coefficient is unaffected by crest height (the location of the side orifice from the bed) [8]. Statistical indices reported in this study show that this parameter has less effect on discharge coefficient than other parameters (such as Fr). However, as an overall trend, as shown in Figure 8, the discharge through the intake has decreased by increasing W. Water intake seems to feed from the area with a lower velocity due to velocity distributions across the channel height. The most significant disadvantage of diverting water near the bed is higher sediment densities near the bed. A more significant sediment discharge is entered to intake levels near the bed. On the other hand, vortexes are a considerable threat to intake near the surface, especially seawater intake, which is exposed to tides. Figure 9, W/B= 0.24 is suggested to have high efficacies in seawater intake.



(a)   (b)

Fig. 7: Correlation values of different parameters. **(a)** Circle shape. **(b)** Square shape.

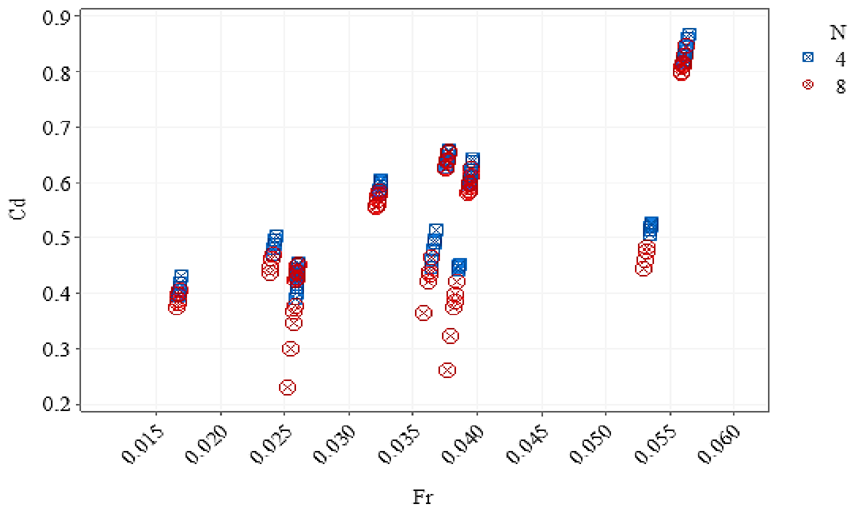
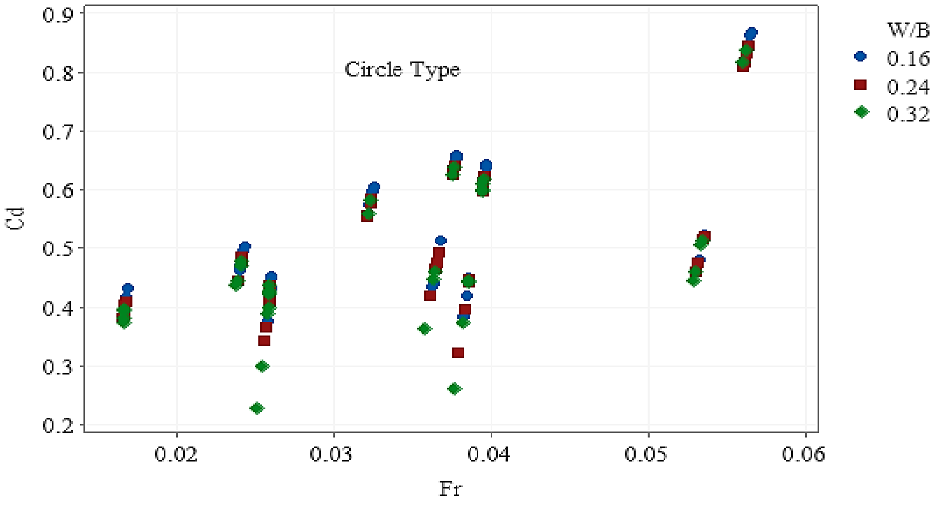
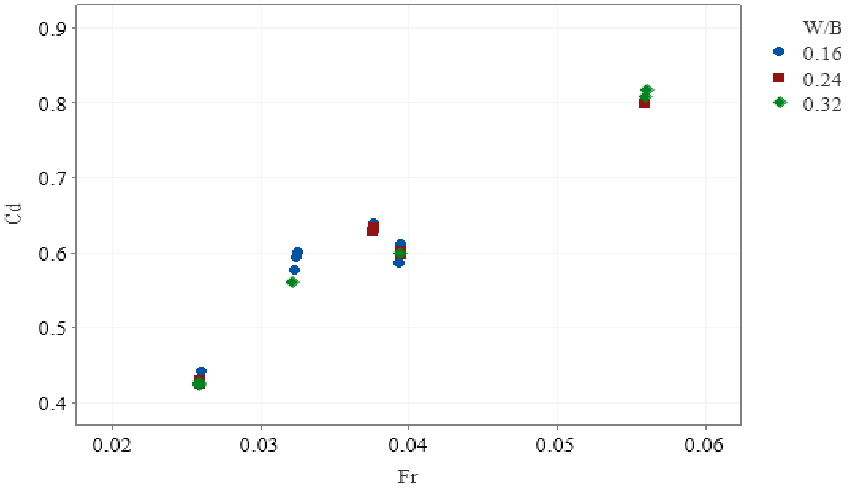


Fig. 8: Variation of Cd with Froude number for different values of N



(a)



(b)

Fig. 9: Variation of Cd with Fr for different values of W/B. **(a)** Circle type. **(b)** Square type

4. Conclusions

The bottom intake structure, widely used for supplying water from rivers and oceans, has been considered because of its advantages. Using the bottom intake has some advantages. It reduces the possibility of the entrance of wastes deposited near the river bank or seashore because of the position of the inlet compared to other types, such as lateral channel intake. On the other hand, vortex formations and how they progress are challenging items for bottom intake. Velocity caps have the most significant role in preventing the formation of a vortex from the surface. Observation shows that the absence of the velocity cap causes the vortex problems. A velocity cap with numerous blades is applicable significantly because it turns vertical flow into horizontal flow. The results show that compared to the square shape, the circle shape can increase the efficiency by about 2% to 4%, the former at a high-velocity rate and the latter at a low-velocity rate. This increase in efficiency is related to the flow pattern around the shapes. Numerical observations of the bottom intakes indicate that the recirculation area locations in the main channel are entirely different from a lateral open channel intake, similar to the lateral pipe intake. The separation zone, formed at the back side of the bottom intake, is larger in the square shape than in the circular shape. In the front of the velocity cap, the flow velocity is higher in the square shape than the circular shape, while it is more in the circle type on both sides. In addition, the discharge coefficient mainly depends on the Froude number in the main channel and the intake area.

In contrast, the number of blades and the height of the velocity cap are less effective on the discharge coefficient. Also, observations show that the discharge coefficient will decrease while the distance of opening of intake from the channel bed increases because intake feeds from the area with a lower velocity due to velocity distributions across the channel height. The impact of various parameters on the recirculation area and flow pattern around the intake structures is discussed in further studies in detail.

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