Investigation of the Cavitation Index of Bottom Outlets Equipped with a Sluice Gate

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Abstract

Cavitation, erosion, vibration, and crushing are the main causes of damage in hydraulic structures. Cavitation is a phenomenon that can damage hydraulic structures at high velocities. Cavitation occurs when the pressure in the water flow drops below the vapor pressure of the water. Flow aeration in hydraulic structures is known to reduce cavitation damage. Bottom outlet aeration is a particular instance of this. The high-velocity flow in the bottom outlet is a mixed air-water flow. The airflow results from the sub-atmospheric pressure downstream of the gate. The air entrained by the high-velocity flow is supplied by the air vent. If the air required by the flow is not supplied, the pressure drop downstream of the gate will cause cavitation. This study investigates the cavitation index of bottom outlets equipped with a sluice gate using three different bottom outlet cross-sections. Results indicate that the cavitation index decreased with increasing Froude number. The bottom outlet cross-sectional geometry did not have a big effect on the cavitation index. It is also presented a formula for estimating the cavitation index, which relates the cavitation index to the Froude number, the gate opening rate, and the ratio of the hydraulic radius to the bottom outlet length.

Keywords: Air-water flow, bottom outlet, cavitation, hydraulic structures, sluice gate

1. Introduction

Bottom outlets serve a variety of functions in large dams, including providing an emergency spillway for the reservoir, regulating the water level in the reservoir, and preventing sediment accumulation at the base of the dam. They are hydraulic structures that contain a high-velocity air-water flow. A high-velocity, low-pressure flow occurs downstream of a gate that partially closes the cross-sectional area of the bottom outlet. Because of this high-velocity flow, pressures lower than atmospheric can occur in the bottom outlet. These pressures could theoretically be as low as the vapor pressure of water. When connected to the atmosphere with a vent downstream of the gate, air is drawn into the vent as shown in Figure 1. The reduction in pressure downstream of the gate relative to atmospheric pressure depends on the degree of the gate opening.

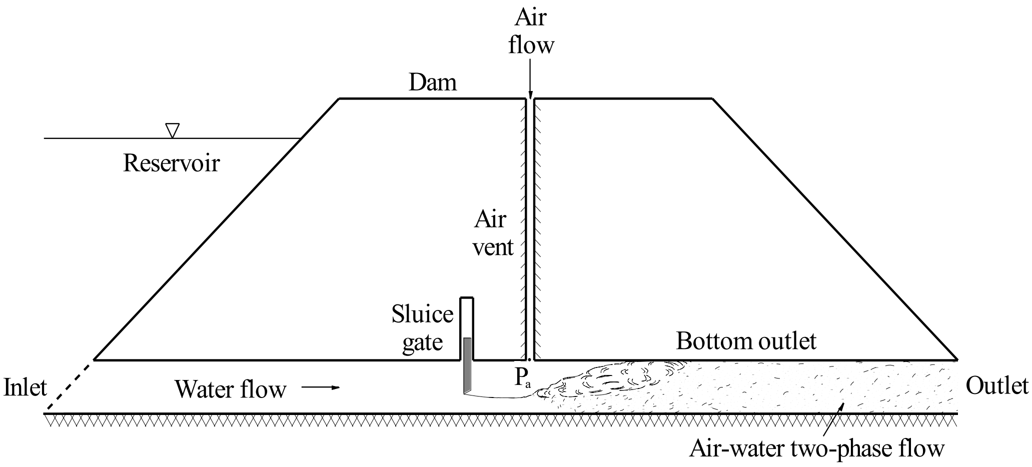


Figure 1. High-velocity, low-pressure flow in a bottom outlet

The main problem with bottom outlets is cavitation phenomena, particularly after the flow control gates, which occur at different gate opening rates due to the high flow velocity and pressure drop downstream of the gates. Cavitation occurs whenever the pressure in the flow of water drops to the value of the pressure of the saturated water vapor, P_v (at the prevailing temperature); cavities filled by vapor, and partly by gases excluded from the water as a result of the low pressure, are formed. When these bubbles are carried by the flow into regions of higher pressure, the vapor rapidly condenses and the bubbles implode, the cavities being suddenly filled by the surrounding water. Not only is this process noisy, with disruption in the flow pattern, but - more importantly - if the cavity implodes against a surface, the violent impact of the water particles acting in rapid succession at very high pressures (of the order of 1000 atm), if sustained over some time, causes significant damage to the (concrete or steel) surface, which can lead to a complete failure of the structure. Cavitation corrosion (pitting) and the often-associated vibration is therefore a phenomenon that needs to be considered in the design of hydraulic structures and prevented whenever possible (Novak et al, 2007).

The presence of cavitation in a high-velocity bottom outlet introduces a critical condition that can cause damage. Chanson (2000) recommended that cavitation damage can occur when the velocity exceeds 12 m/s in clear water. For a given flow characteristic, the cavitation index also indicates whether a structure is susceptible to cavitation. It is a dimensionless parameter defined by Equation (1). Falvey (1990) suggested that the critical value of the cavitation index is about 0.2. If the cavitation index is less than this critical value, surface damage should be expected.

Many studies have been carried out on cavitation in hydraulic structures. Falvey HT (1983) presented several criteria to prevent cavitation damage to the flow surface based on the cavitation index. May (1987) reviewed the literature on cavitation in large hydraulic structures to summarize the current state of knowledge, provide guidance to designers, and identify areas requiring further research. Falvey (1990) developed equations to calculate the cavitation index. Lee & Hoopes (1996), Wahl et al. (2019) and Wahl & Falvey (2022) developed a model to predict the occurrence of cavitation damage using factors that influence the phenomenon: cavitation index, velocity, air concentration, material resistance, and time of exposure to flow. Dong and Su (2006) found that aerators can increase the pressure in the cavitation region, reducing the risk of cavitation damage to the spillway. Matos et al. (2022) analysed minimum extreme pressures in stepped spillways considering different ranges of specific discharges, chutes with a slope, and step widths. The results indicated that maximum unit discharges of about 15-20 m^2/s are considered advisable on 53° sloping large-stepped spillways without artificial aeration, for step heights ranging from 0.6 to 1.2 m. For much higher unit discharges, a considerable reach of the spillway may potentially be prone to the risk of cavitation damage.

In a bottom outlet, an air vent is usually installed immediately downstream of the gate to provide sufficient air to flow. Previous studies have shown that injecting air into the flow downstream of the gate can significantly reduce the risk of cavitation damage. Numerous studies have been reported on the air-demand ratio (Q_a/Q_w) in bottom outlets - e.g., Aydin et al. (2021, 2022, 2024a, 2024b), Baylar and Batan (2010), Baylar et al. (2010, 2021, 2022), Campbell and Guyton (1953), Escarameia (2007), Haindl and Sotornik (1957), Hohermuth (2019), Hohermuth et al. (2020), Kalinske and Robertson (1943), Mortensen (2009), Mortensen et al. (2011, 2012), Mortensen and Kubitschek (2016), Oveson (2008), Ozkan et al. (2006a, 2006b, 2010, 2014, 2015), Pengchengi et al. (2022), Sharma (1976), Speerli (1999), Speerli and Hager (2000), Stahl and Hager (1999), Tullis and Larchar (2011), Tuna et al. (2014), Unsal et al. (2008, 2009, 2014), and USACE (1964). These studies indicate that the air-demand ratio for bottom outlets is a function of hydraulic and geometric parameters and, for a given geometry, depends mainly on the flow types. Based on experimental data and theoretical studies, the authors have developed some equations to determine the air-demand ratio under different flow patterns.

There has been no detailed study of the effect of cross-sectional geometry on the cavitation index of sluice-gated bottom outlets. Based on this information, this study investigated the effect of cross-sectional geometry on the cavitation index of sluice-gated bottom outlets.

2. Experimental

The experiments were carried out using an experimental apparatus at the Hydraulic Laboratory of the Faculty of Engineering, Firat University, Elazig, Turkey. The experimental setup used to measure the air inlet velocity is shown in Fig. 2. The water in the reservoir was pumped to the pipe by a vacuum pump. The flow rate was adjusted by a flow control valve. A calibrated electromagnetic flowmeter was used to measure the flow rates.

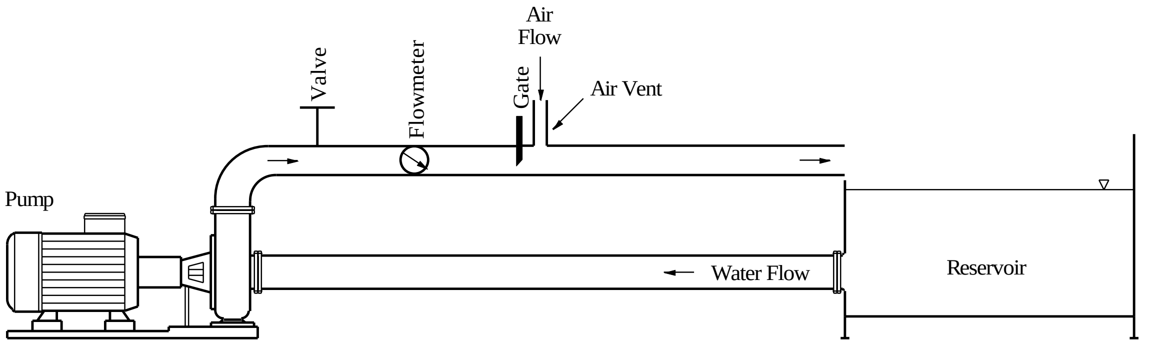


Figure 2. Schematic of experimental setup

Three different bottom outlet cross-sections were used to study the effect of cross-section geometry on the cavitation index. Rectangular bottom outlets with dimensions of width: 60 mm × height: 100 mm and width: 100 mm × height: 60 mm were selected to have the same cross-sectional area as a 3-inch diameter circular bottom outlet. 168 experiments were conducted for the 60 × 100 rectangular bottom outlet, 168 experiments were conducted for the 100 × 60 rectangular bottom outlet, and 168 experiments were conducted for the circular bottom outlet.

For all bottom outlet cross-sectional geometries, the gate opening rate, which refers to the ratio of the water flow cross-sectional area to the bottom outlet cross-sectional area, was selected as a percentage of 10, 15, 20, 30, 40, and 60. Bottom outlet lengths of 1, 2, 4, and 6 meters were used. A 200 mm high vent was placed downstream of the gate to entrain air into the bottom outlet. A Testo 435 anemometer was used to measure the air velocity in the vent. This measurement was made by placing the anemometer in the center of the vent. Air velocity measurements were taken for 60 seconds or longer. The accuracy of the anemometer was ±(0.2

m/s + 1.5% of mv). The verticality of the anemometer to the direction of flow in the vent was taken into account for accurate measurements.

In this study, the cavitation index was calculated by using Eq. 1.

$$\sigma = \frac{h_p + h_a - h_v}{V_w^{\,2}/2g} \tag{1}$$

where h_p is local water pressure in m of water, h_a is ambient pressure in m of water, h_v is saturated water vapor pressure in m of water, V_w is average clear-water flow velocity and g is gravitational acceleration.

Air pressure can be calculated by applying the Bernoulli equation to the air vent.

$$\frac{P_a}{\rho_a\, g} = -(1+\xi)\frac{V_a^{\,2}}{2g} \tag{2}$$

where P_a is relative air pressure, ρ_a is air density, g is gravitational acceleration, ξ is total loss coefficient of air vent and V_a is air velocity in air vent.

The total loss coefficient of the air vent is equal to the sum of the local fluid resistance coefficient (ξ_{loc}) and the frictional resistance coefficient of the air vent length (ξ_{fr}).

$$\xi = \xi_{loc} + \xi_{fr} \tag{3}$$

The local fluid resistance coefficient is due to a sudden change in the cross-sectional area of the airflow (sudden increase). The frictional resistance coefficient of the air vent length is calculated from the following equation.

$$\xi_{fr} = \lambda \frac{L_0}{D_0} \tag{4}$$

where λ is friction coefficient, which can be determined from the Moody diagram, L_0 is length of air vent and D_0 is diameter of air vent.

The cavitation index is a function of the following variables:

$$\sigma = f_1 (V_w, g, h_e, \varphi) \tag{5}$$

Using dimensional analysis, the most effective parameters for cavitation index in bottom outlets are derived as:

$$\sigma = f_2 (V_w/\sqrt{g\ h_e}, \varphi) \tag{6}$$

$$\sigma = f_3 (Fr, \varphi) \tag{7}$$

where σ is cavitation index, V_w is water velocity under gate, g is gravitational acceleration, h_e is effective depth (ratio of water flow cross-sectional area to water surface width), and φ is ratio of water cross-sectional flow area to bottom outlet cross-sectional area.

The Froude number was calculated from the effective depth rather than the depth at the vena contracta section. In literature, the Froude number has often been based on the vena contracta section. Since high-head gated bottom outlets involve high-velocity air-water mixture flow, in this study the Froude number was based on the effective depth in the bottom outlet to avoid the problem of determining flow depths and velocities at the vena contracta section.

3. Results and Analysis

The aim of this study was to determine the effect of bottom outlet cross-section geometry on the cavitation index. This objective was achieved by building a physical experimental setup, conducting experiments, obtaining data, analyzing the data, and presenting the results.

Figures 5-10 show plots of the cavitation index (σ) versus the Froude number (Fr) of the bottom outlet cross-sectional geometry, gate opening rate (φ), and bottom outlet length (L). It is seen that the cavitation index decreased for all bottom outlet cross-sectional geometries, gate opening rates, and bottom outlet lengths, as the Froude number increased. This indicates that there is an inverse relationship between the Froude number and the cavitation index.

As the Froude number increased, the cavitation index decreased rapidly for all bottom outlet cross-sectional geometries, gate opening rates, and bottom outlet lengths (Figures 5-10). It appears that Froude number 25 at 10% gate opening rates, Froude number 20 at 15% gate opening rates, Froude number 15 at 20% gate opening rates, Froude number 12 at 30% gate opening rates, Froude number 10 at 40% gate opening rates, and Froude number 8 at 60% gate opening rates showed negative values for the cavitation index. It was observed that there was no significant decrease in the cavitation index with a further increase in the Froude number after the points where the cavitation index went negative.

Following a detailed review of the experiments, it was observed that the cavitation index increased at low Froude numbers with the increase in the gate opening rate for all bottom outlet cross-sectional geometries and bottom outlet lengths. It was found that the cavitation index reached zero at lower Froude numbers as the gate opening rate increased. It was determined that there was no risk of cavitation for Froude numbers less than 20 at 10% gate opening rates, values of Froude numbers less than 15 at 15% gate opening rates, values of Froude numbers less than 13 at 20% gate opening rates, values of Froude numbers less than 11 at 30% gate opening rates, values of Froude numbers less than 10 at 40% gate opening rates and values of Froude numbers less than 9 at 60% gate opening rates. Furthermore, the change in cavitation index decreased as the gate opening rate increased for all bottom outlet cross-sectional geometries and bottom outlet lengths. The reason for this phenomenon appears to be that when the gate opening rate increased, the flow velocity below the gate decreased. This, in turn, led to a decrease in the pressure drop.

The 100 × 60 rectangular cross-sectional bottom outlet generally exhibited a higher cavitation index for all gate opening rates and bottom outlet lengths. Conversely, the 60 × 100 rectangular cross-sectional bottom outlet generally demonstrated a lower cavitation index for all gate opening rates and bottom outlet lengths. However, the effect of bottom outlet cross-sectional geometry on the cavitation index was not found to be significant for all gate opening rates and bottom outlet lengths.

Similarly, the bottom outlet length did not have a big effect on the cavitation index for all bottom outlet cross-sectional geometries and gate opening rates. At high Froude numbers, the cavitation index reached higher values at 6 m bottom outlet length for all bottom outlet cross-sectional geometries and gate opening rates. At a 60% gate opening rate, the effect of bottom outlet length on the cavitation index was nearly negligible for all bottom outlet cross-sectional geometries.

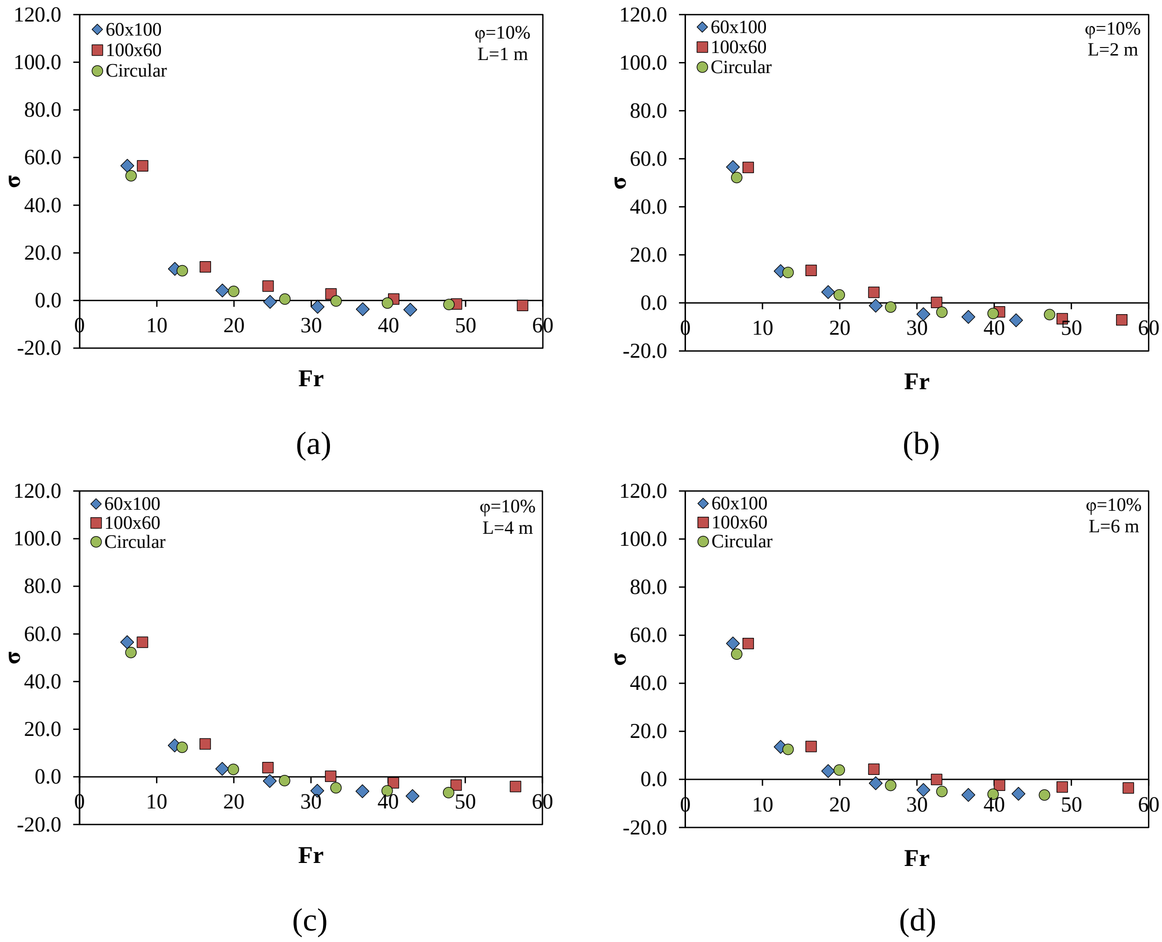
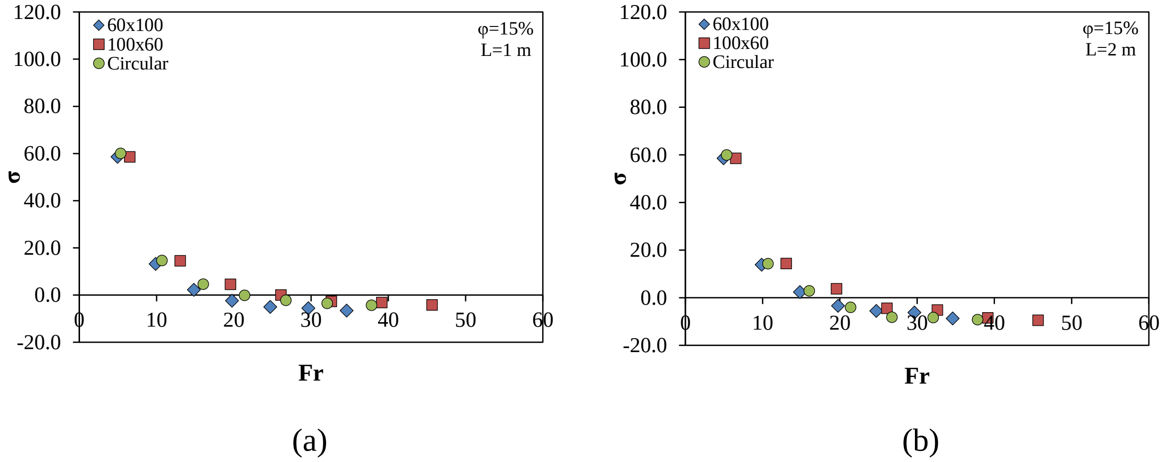
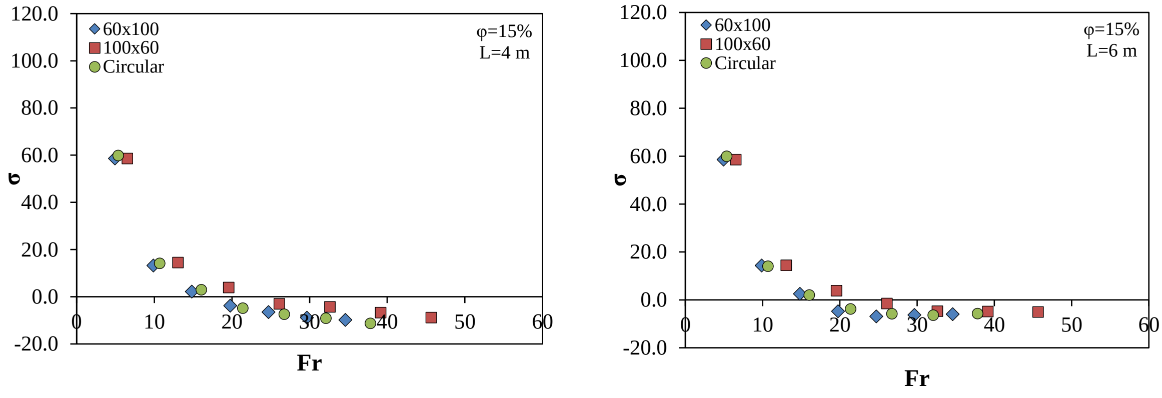


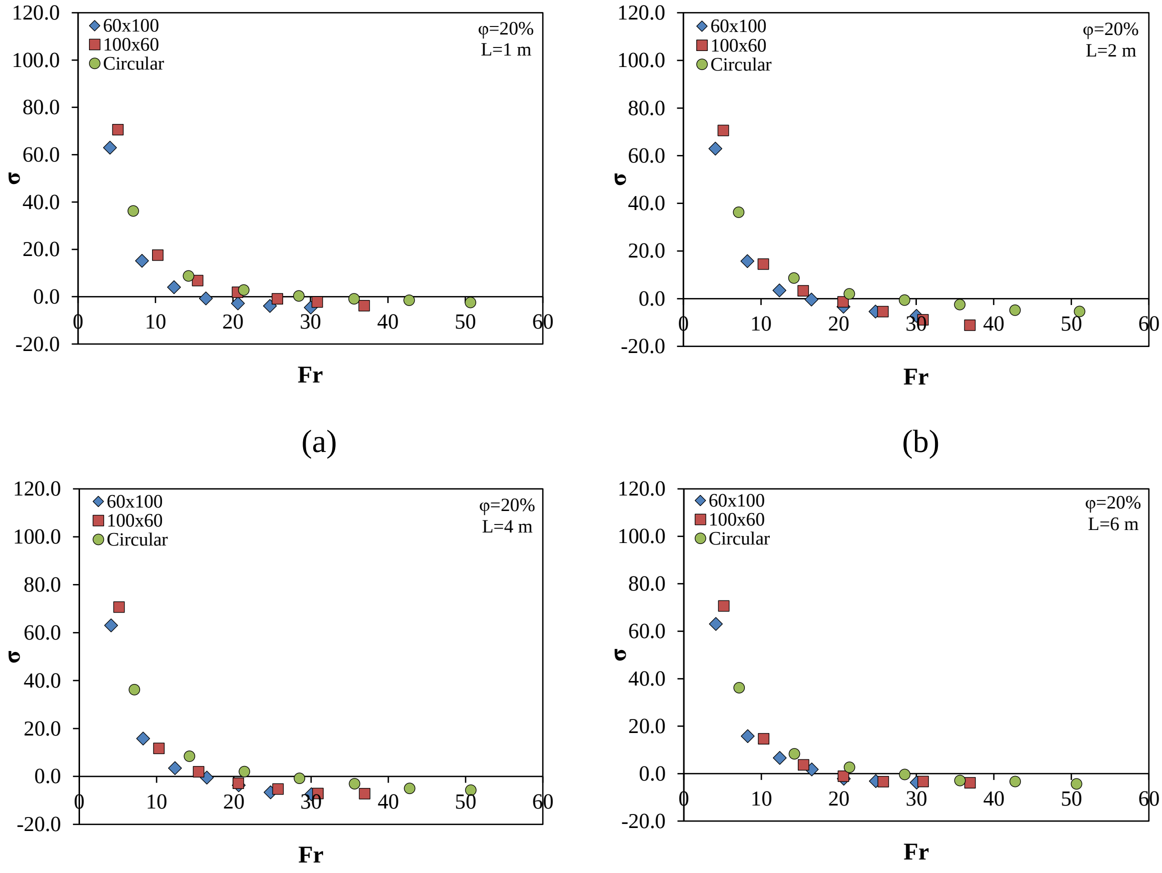
Figure 5. Variation of σ plotted against the Froude number for different bottom outlet lengths at φ=10% (a) L=1 m, (b) L=2 m, (c) L=4 m, (d) L= 6 m





(c) (d)

Figure 6. Variation of σ plotted against the Froude number for different bottom outlet lengths at φ=15% (a) L=1 m, (b) L=2 m, (c) L=4 m, (d) L= 6 m



(a) (b)

(c) (d)

Figure 7. Variation of σ plotted against the Froude number for different bottom outlet lengths at φ=20% (a) L=1 m, (b) L=2 m, (c) L=4 m, (d) L= 6 m

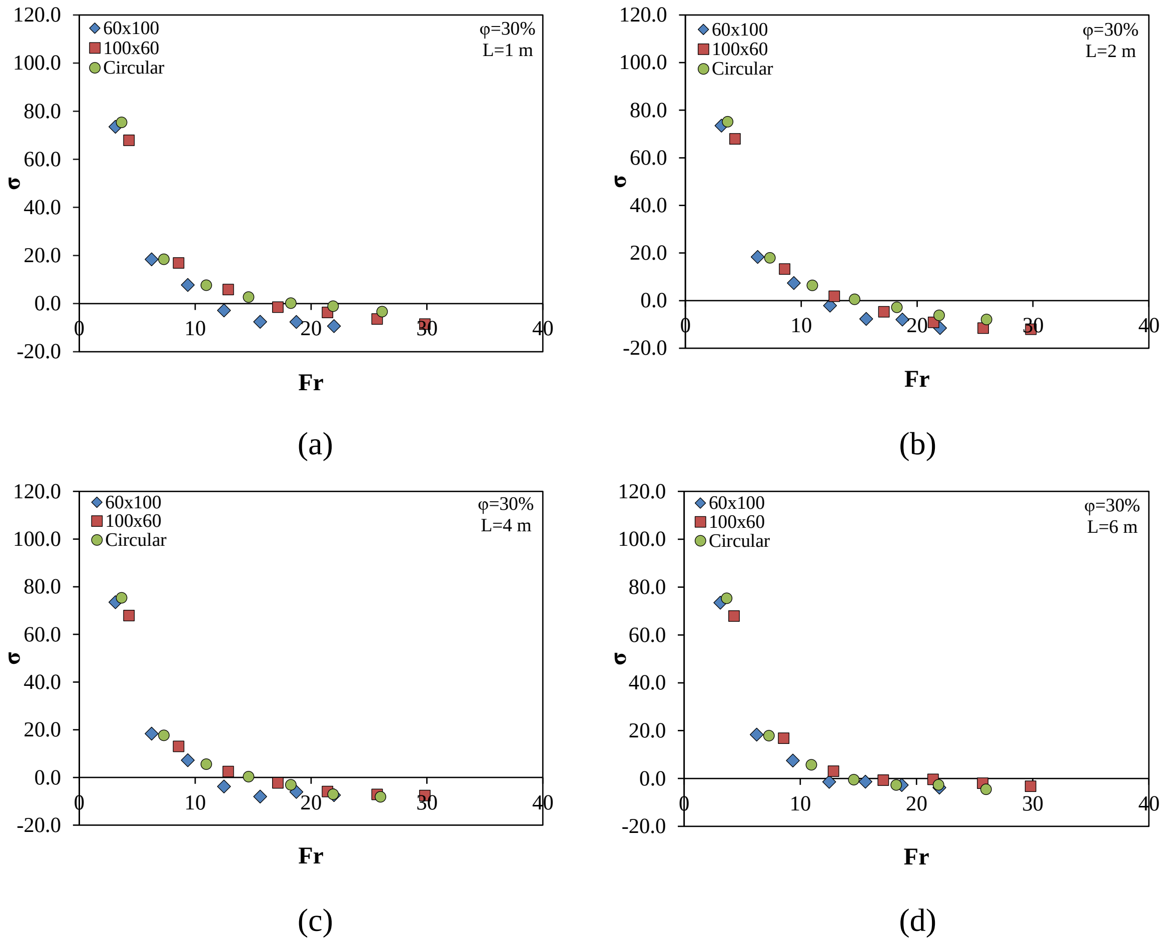
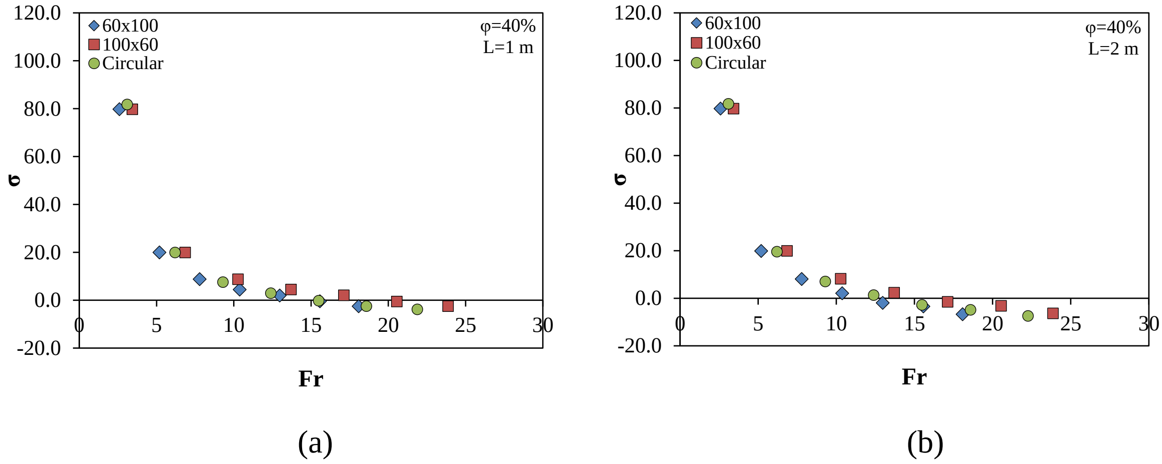
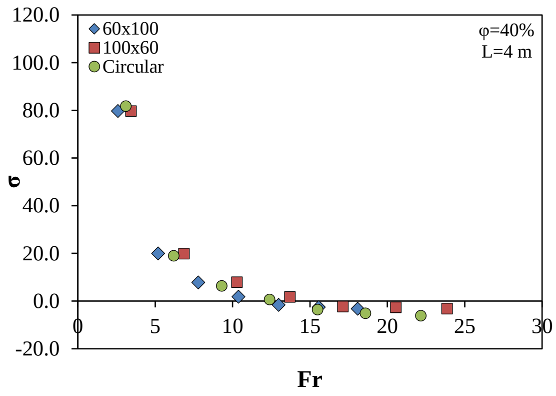
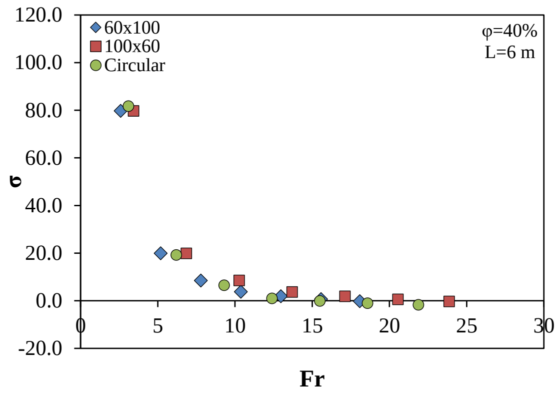


Figure 8. Variation of σ plotted against the Froude number for different bottom outlet lengths at φ=30% (a) L=1 m, (b) L=2 m, (c) L=4 m, (d) L= 6 m



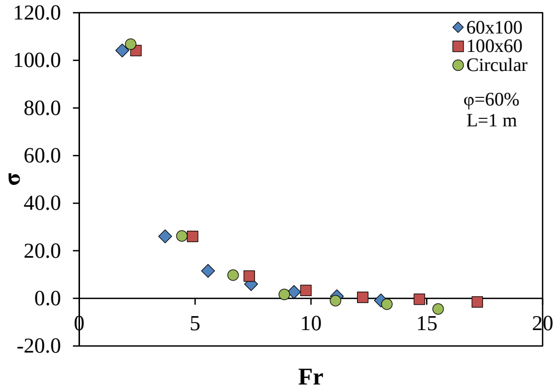


(c)

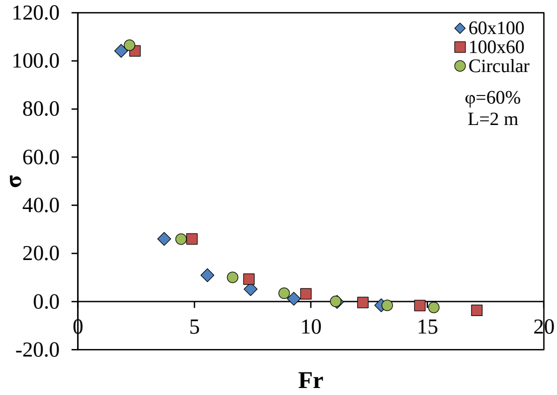


(d)

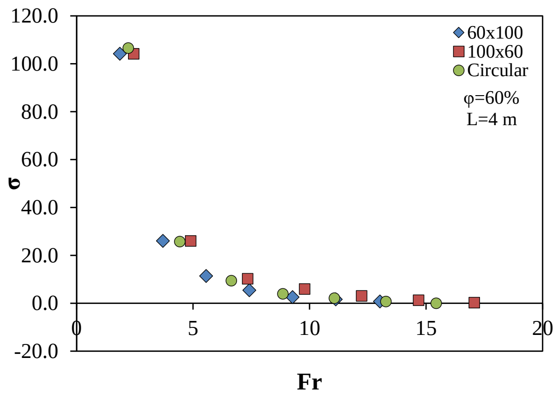
Figure 9. Variation of σ plotted against the Froude number for different bottom outlet lengths at φ=40% (a) L=1 m, (b) L=2 m, (c) L=4 m, (d) L= 6 m



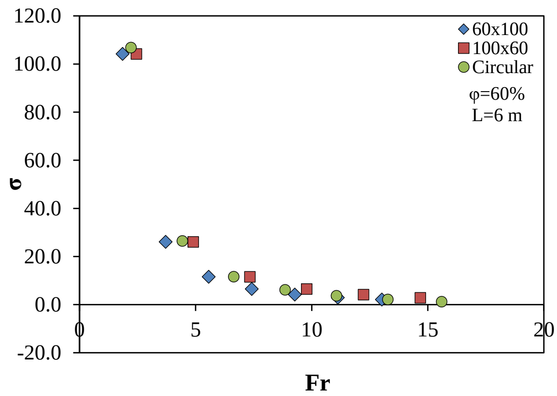
(a)



(b)



(c)



(d)

Figure 10. Variation of σ plotted against the Froude number for different bottom outlet lengths at φ=60% (a) L=1 m, (b) L=2 m, (c) L=4 m, (d) L= 6 m

4. Prediction Model

Regression analysis was performed using the nonlinear regression module. An empirical correlation was developed to predict the cavitation index that can be used for all bottom outlet cross-sections with a sluice gate. The resulting correlation is shown in Eq. (8). For the 504 data points used, the correlation coefficient (R^2) is 0.95. Good agreement was found between the observed and calculated cavitation index.

$$\sigma = 192.590\,\mathrm{Fr}^{-1.306}\varphi^{-0.536}\left(\frac{\mathrm{R_h}}{\mathrm{L}}\right)^{-0.029} - 11.873 \tag{8}$$

where σ is cavitation index, Fr is the Froude number, φ is gate opening rate, R_h is hydraulic radius, and L is bottom outlet length.

5. Conclusions

The present study investigates the effect of bottom outlet cross-sectional geometry, gate opening rate, bottom outlet length, and Froude number on cavitation index. The results obtained are listed below.

- The cavitation index decreased with increasing Froude number for all bottom outlet cross-sectional geometries, gate opening rates, and bottom outlet lengths. This indicates the presence of an inverse relationship between the Froude number and the cavitation index.
- Negative values for the cavitation index were observed at Froude number 25 at 10% gate opening rates, Froude number 20 at 15% gate opening rates, Froude number 15 at 20% gate opening rates, Froude number 12 at 30% gate opening rates, Froude number 10 at 40% gate opening rates, and Froude number 8 at 60% gate opening rates.
- As the gate opening rate increased, the cavitation index had larger values at low Froude numbers for all bottom outlet cross-sectional geometries and bottom outlet lengths. The cavitation index reached zero at lower Froude numbers as the gate opening rate increased.
- There was no risk of cavitation for Froude numbers less than 20 at 10% gate opening rates, values of Froude numbers less than 15 at 15% gate opening rates, values of Froude numbers less than 13 at 20% gate opening rates, values of Froude numbers less than 11 at 30% gate opening rates, values of Froude numbers less than 10 at 40% gate opening rates and values of Froude numbers less than 9 at 60% gate opening rates.
- The bottom outlet cross-sectional geometry did not have a big effect on the cavitation index for all gate opening rates and bottom outlet lengths.

- The effect of bottom outlet length on the cavitation index was not found to be significant for all bottom outlet cross-sectional geometries and gate opening rates.
- The equation developed in this study will be of considerable utility in estimating the cavitation index. Researchers will be able to use this equation to determine the cavitation index at the design stage without the need for experimental studies. This will provide researchers with a significant advantage in terms of time and economy.

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Data Availability Statement

All data used is appended (available in the Supplementary Data section) or is included in the submitted article.

Notation

D_0	diameter of air vent.
Fr	Froude number based on effective depth in bottom outlet
g	gravitational acceleration
h_a	ambient pressure in m of water
h_e	effective depth
h_p	local water pressure in m of water
h_v	saturated water vapor pressure in m of water
L	length of bottom outlet
L_0	length of air vent
P_a	relative air pressure
P_v	saturated water vapor pressure
R_h	hydraulic radius
Q_a	air flow rate measured through air vent
Q_a/Q_w	air-demand ratio
Q_w	water flow rate in bottom outlet
V_a	mean air-flow velocity in air vent
V_w	mean water-flow velocity under gate
λ	friction coefficient

ξ total loss coefficient of air vent

ξ_{fr} frictional resistance coefficient of air vent length

ξ_{loc} local fluid resistance coefficient

ρ_a air density

σ cavitation index

φ ratio of water cross-sectional flow area to bottom outlet cross-sectional area

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