

AN INVESTIGATION OF CAVITATION INDEX OF DAM BOTTOM OUTLETS WITH A SLUICE GATE

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ABSTRACT:

The main causes of damage in hydraulic structures are cavitation, vibration, and crushing. Cavitation, a phenomenon that occurs at high velocities, can damage hydraulic structures. It occurs when the pressure of the water flow drops below its vapor pressure. Flow aeration in hydraulic structures is known to reduce cavitation damage. Bottom outlet aeration is one example of this. The high-velocity flow in the bottom outlet is a mixture of air and water. This airflow results from the sub-atmospheric pressure downstream of the gate. The air vent supplies the air entrained by the high-velocity flow. Without a sufficient air supply, the pressure drop downstream of the gate will cause cavitation. This study investigates the cavitation index of bottom outlets with a sluice gate and three different outlet cross-sections. The results indicate that the cavitation index decreases with an increasing Froude number. The geometry of the bottom outlet cross-section did not significantly affect the cavitation index. An equation is also presented that relates the cavitation index to the Froude number, the gate opening rate, and the ratio of the hydraulic radius to the bottom outlet length.

1. INTRODUCTION

Bottom outlets are critical safety structures that are located at the lowest point of a dam. They serve several functions in large dams. They provide an emergency spillway for the reservoir, regulate its water level, and prevent sediment from accumulating at the base of the dam. The safe operation of the bottom outlet is crucial for many dams and reservoirs and affects the structural integrity of the entire facility.

Bottom outlets contain high-velocity air-water flow. Downstream of a partially closed gate, a high-velocity, low-pressure flow occurs. Due to 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 downstream vent, air is drawn in, as shown in Fig. 1. The reduction in pressure downstream of the gate relative to atmospheric pressure depends on the degree to which the gate is open.

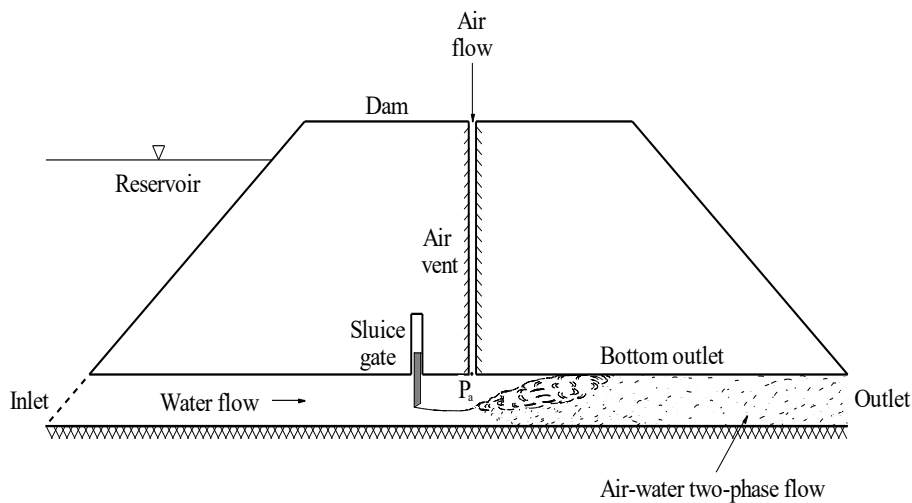


Figure 1. A high-head flow in a bottom outlet, followed by a hydraulic jump

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The main problem with bottom outlets is the occurrence of cavitation phenomena, particularly after the flow control gates. This is due to the high flow velocity and pressure drop downstream of the gates, which result in different gate opening rates. Cavitation occurs when the pressure of the flowing water drops to the pressure of saturated water vapor (P_v) at the prevailing temperature.

Cavities filled with vapor and gases are excluded from the water due to low pressure. When these bubbles are carried by the flow into regions of higher pressure, the vapor rapidly condenses, causing the bubbles to implode and the cavities to be suddenly filled by the surrounding water. This process is not only noisy and disruptive to the flow pattern, but also, more importantly, if a cavity implodes against a surface, the violent impact of water particles acting in rapid succession at very high pressures (of the order of 1000 atm) can cause significant damage to concrete or steel surfaces over time, leading to complete structural failure. Therefore, cavitation corrosion (pitting) and associated vibration are phenomena that must 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 creates critical conditions that can cause damage. According to Chanson (2000), cavitation damage can occur when the velocity exceeds 12 m/s in clear water. The cavitation index indicates whether a structure is susceptible to cavitation for a given flow characteristic. It is a dimensionless parameter defined by Equation 1. Falvey (1990) suggested that the critical value of the cavitation index is approximately 0.2. If the cavitation index is less than this critical value, surface damage should be expected.

Many studies have been conducted on cavitation in hydraulic structures. For example, Falvey (1983) presented criteria for preventing cavitation damage to flow surfaces based on the cavitation index. May (1987) reviewed the literature on cavitation in large hydraulic structures to summarize the current state of knowledge, provide designers with guidance, and pinpoint areas in need of further research.

Falvey (1990) developed equations to calculate the cavitation index. Lee and Hoopes (1996), Wahl et al. (2019), and Wahl and Falvey (2022) developed a model to predict cavitation damage occurrence using influential factors: the cavitation index, velocity, air concentration, material resistance, and time of exposure to flow.

Dong and Su (2006) found that aerators can increase pressure in the cavitation region, thereby reducing the risk of cavitation damage to the spillway. Matos et al. (2022) analyzed minimum extreme pressures in stepped spillways, considering different ranges of specific discharges, chute slopes, and step widths.

The results indicated that a maximum unit discharge of 15 to 20 m²/s is advisable for 53° sloping, large-stepped spillways without artificial aeration and with step heights ranging from 0.6 to 1.2 m. However, for much higher unit discharges, a considerable reach of the spillway may be prone to cavitation damage.

Previous studies have shown that injecting air into the flow downstream of the gate significantly reduces the risk of cavitation damage. An air vent is usually installed in the bottom outlet immediately downstream of the gate to provide sufficient airflow. Numerous researchers have studied air-water two-phase flow in bottom outlets, e.g., Aydin et al. (2021, 2022, 2024a,

2024b), Baylar and Batan (2010), Baylar et al. (2010, 2021, 2022), Bürgler et al. (2023), Demirel and Ozkan (2022), Escarameia (2007), Felder et al. (2019), Hohermuth (2019), Hohermuth et al. (2020, 2021), Kabiri-Samani et al. (2023), Li et al. (2022), Lian et al. (2021), Mortensen (2009), Mortensen et al. (2011, 2012), Mortensen and Kubitschek (2016), Oveson (2008), Ozkan et al. (2006a, 2006b, 2010, 2014, 2015), Pagliara et al. (2023, 2025a, 2025b), Pengcheng et al. (2022), Sassi et al. (2020), 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 Wei et al. (2021).

These studies indicate that the air-demand ratio (Q_a/Q_w) for bottom outlets is a function of hydraulic and geometric parameters. For a given geometry, it depends mainly on flow types. Based on experimental data and theoretical studies, the authors developed equations to determine the air-demand ratio under different flow patterns.

No detailed study has been conducted on the effect of cross-sectional geometry on the cavitation index of sluice-gated bottom outlets. This study investigated this effect based on this information.

2. EXPERIMENTAL

The experiments were carried out using an experimental apparatus at the Hydraulic Laboratory of the Faculty of Engineering at Firat University in Elazig, Turkey. Fig. 2 shows the experimental setup used to measure the air inlet velocity.

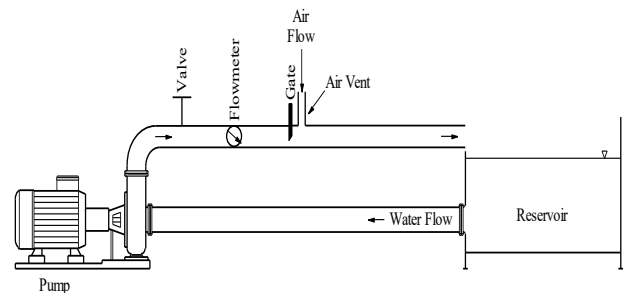


Figure 2. Schematic of experimental setup

A vacuum pump was used to pump the water in the reservoir to the pipe. A flow control valve was used to adjust the flow rate. A calibrated electromagnetic flowmeter was used to measure the flow rates.

Three different cross-sections for the bottom outlet were used to study the effect of 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.

The gate opening rate, defined as the ratio of the water flow cross-sectional area to the bottom outlet cross-sectional area, was set at 10%, 15%, 20%, 30%, 40%, or 60% for all bottom outlet cross-sectional geometries. Bottom outlet lengths of 1, 2, 4, and 6

meters were used. A 200-millimeter-high vent was placed downstream of the gate to entrain air into the bottom outlet.

An anemometer (Testo 435) was used to measure the air velocity in the vent. For this measurement, the anemometer was placed in the centre of the vent. Air velocity measurements were taken for at least 60 seconds.

The anemometer's accuracy was $\pm (0.2 \text{ m/s} + 1.5\% \text{ of MV})$. Accurate measurements were obtained by ensuring the anemometer was vertical to the flow direction in the vent.

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

$$\sigma = \frac{h_p + h_a - h_v}{V_w^2 / 2g} \quad (1)$$

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

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

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

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}).

$$\xi = \xi_{loc} + \xi_{fr} \quad (3)$$

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

$$\xi_{fr} = \lambda \frac{L_0}{D_0} \quad (4)$$

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 depends on the following variables:

$$\sigma = f_1 (V_w, g, h_e, R_h, L, \phi) \quad (5)$$

The most effective parameters for the cavitation index in bottom outlets are derived using dimensional analysis.

$$\sigma = f_2 (V_w / \sqrt{g h_e}, R_h / L, \phi) \quad (6)$$

$$\sigma = f_3 (Fr, R_h / L, \phi) \quad (7)$$

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), R_h is hydraulic radius, L is bottom outlet length, and ϕ is ratio of water cross-sectional flow area to bottom outlet cross-sectional area.

The Froude number was calculated based on the effective depth, rather than the depth at the vena contracta.

In the literature, the Froude number is often based on the vena contracta depth. Since high-head gated bottom outlets involve a high-velocity air-water mixture, this study used the effective depth of the bottom outlet to calculate the Froude number. This approach avoids the difficulty of determining the flow depths and velocities at the vena contract section.

3. RESULTS AND ANALYSIS

This study aimed to determine the effect of the bottom outlet cross-section geometry on the cavitation index. This objective was achieved through the construction of a physical experimental setup, the conduction of experiments, the collection of data, the analysis of the data, and the presentation of the results.

Figs. 3-8 show plots of the cavitation index (σ) versus the Froude number (Fr), the bottom outlet cross-sectional geometry, the gate opening rate (ϕ), and the bottom outlet length (L). As the Froude number increases, the cavitation index decreases for all bottom outlet cross-sectional geometries, gate opening rates, and bottom outlet lengths. This indicates 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 (Figs. 3-8). 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. Additionally, it was observed that there was no significant decrease in the cavitation index with a further increase in the Froude number after the points at which the cavitation index became negative.

After a thorough examination of the experiments, it was determined that the cavitation index increased at low Froude numbers with the increase in the gate opening rates for all bottom outlet cross-sectional geometries and bottom outlet lengths.

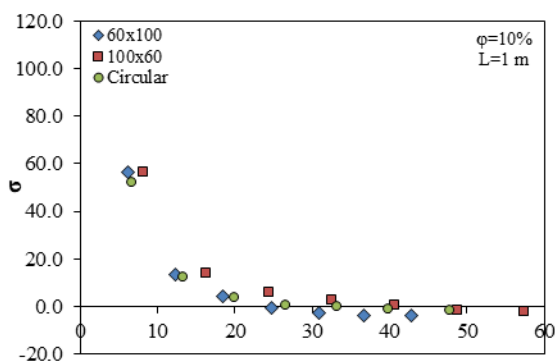
It was found that the cavitation index reached zero at lower Froude numbers as the gate opening rate increased. It was determined that there was no risk of cavitation for Froude numbers less than 20 at 10% gate opening rates, values of Froude numbers less than 15 at 15% gate opening rates, values of 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

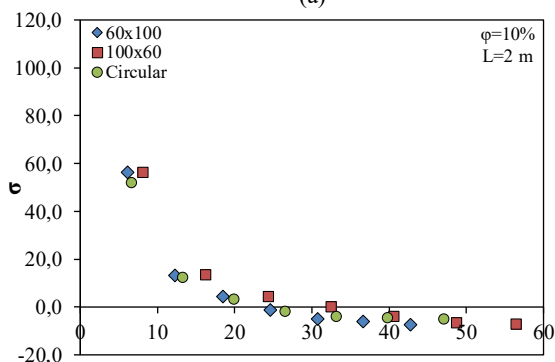
phenomenon appears to be that when the gate opening rate increased, the flow velocity below the gate decreased. This, in turn, led to a decrease in the pressure drop.

The 100×60 rectangular cross-sectional bottom outlets generally exhibited a higher cavitation index for all gate opening rates and bottom outlet lengths. Conversely, the 60×100 rectangular cross-sectional bottom outlets 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.

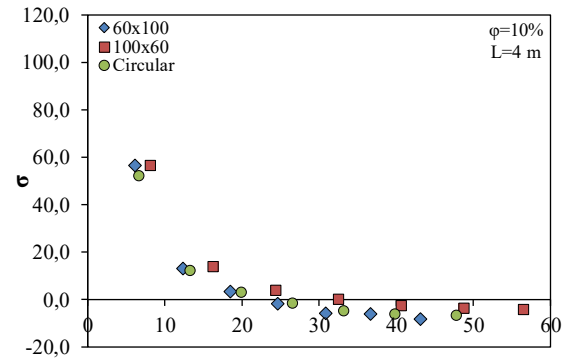
Similarly, the length of the bottom outlet did not significantly affect the cavitation index for all outlet cross-sectional geometries and gate opening rates. At high Froude numbers, the cavitation index was higher at a 6 m bottom outlet length for all outlet cross-sectional geometries and gate opening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



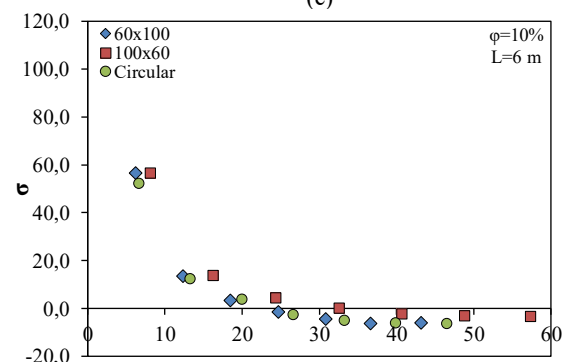
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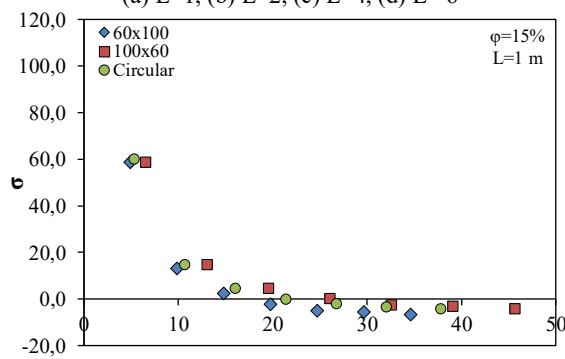


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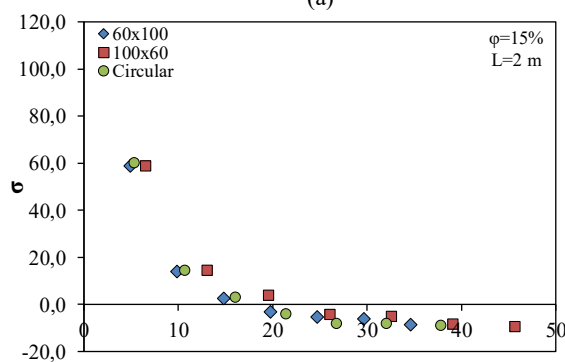


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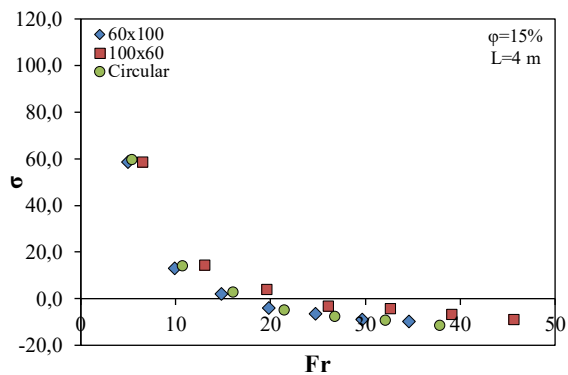
Figure 3. σ versus Fr for various values of L [m] at $\phi=10\%$
(a) $L=1$, (b) $L=2$, (c) $L=4$, (d) $L=6$



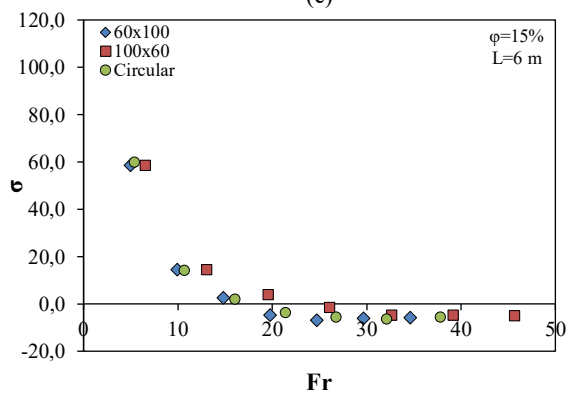
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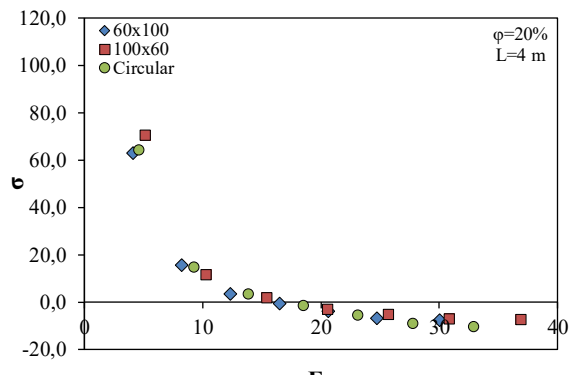


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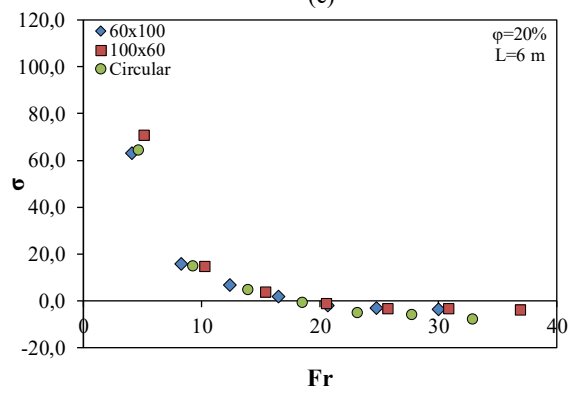


(d)

Figure 4. σ versus Fr for various values of L [m] at $\phi=15\%$
(a) $L=1$, (b) $L=2$, (c) $L=4$, (d) $L=6$

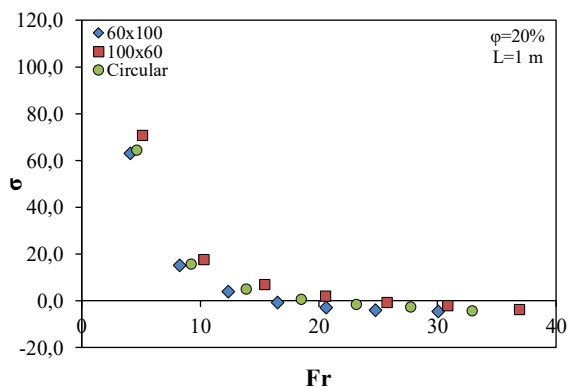


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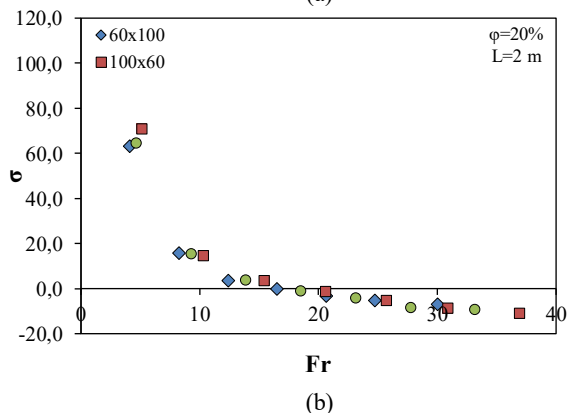


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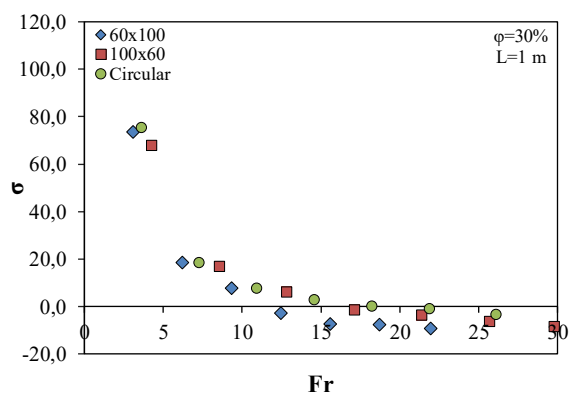
Figure 5. σ versus Fr for various values of L [m] at $\phi=20\%$
(a) $L=1$, (b) $L=2$, (c) $L=4$, (d) $L=6$



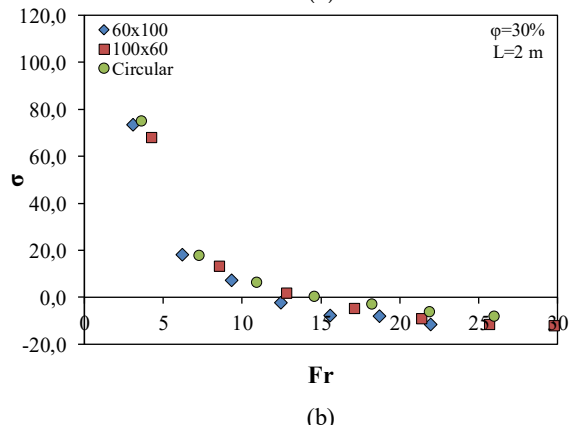
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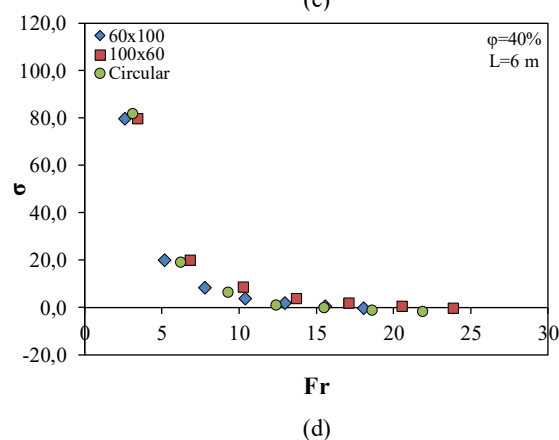
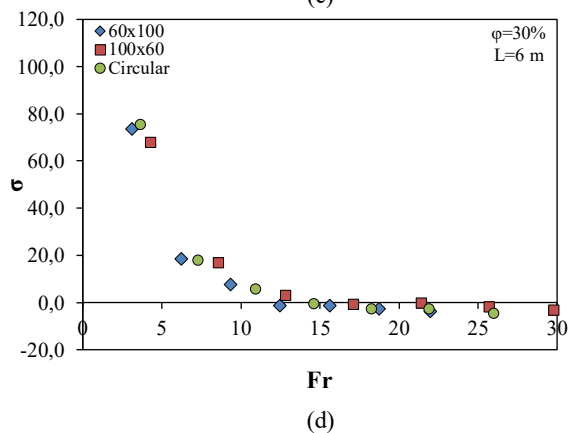
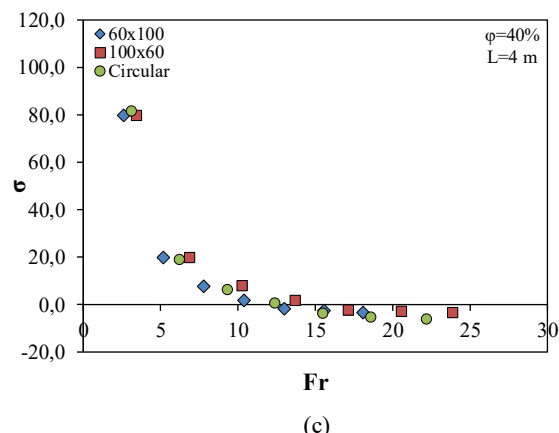
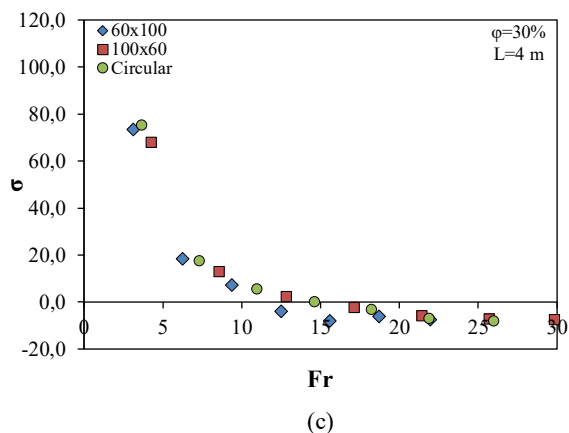
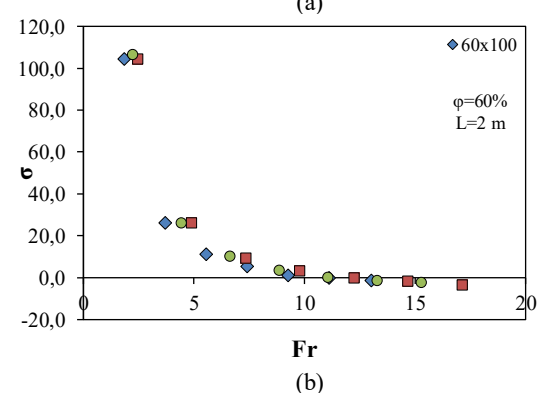
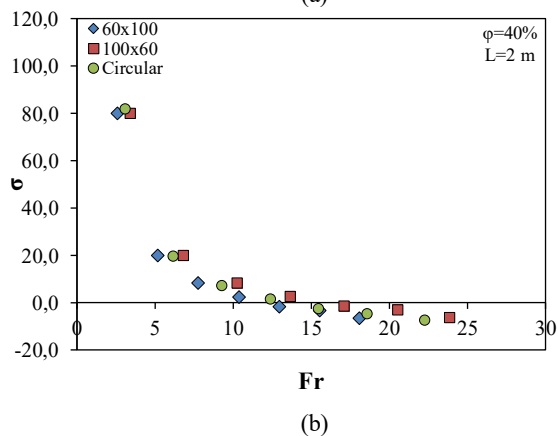
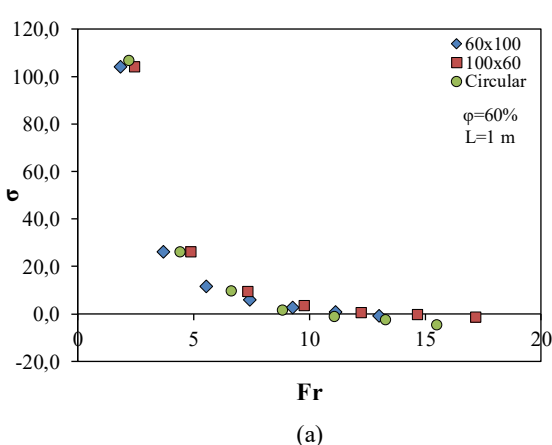
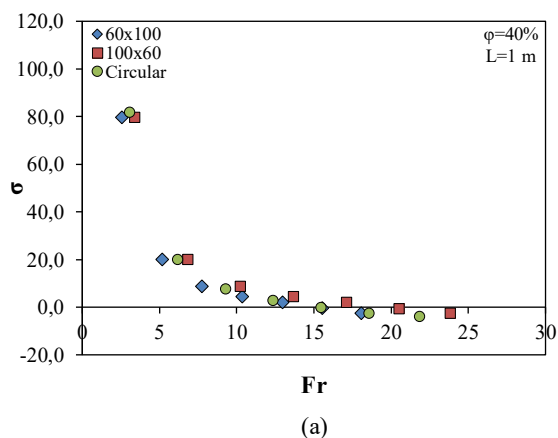


Figure 6. σ versus Fr for various values of L [m] at $\phi=30\%$
(a) $L=1$, (b) $L=2$, (c) $L=4$, (d) $L=6$

Figure 7. σ versus Fr for various values of L [m] at $\phi=40\%$
(a) $L=1$, (b) $L=2$, (c) $L=4$, (d) $L=6$



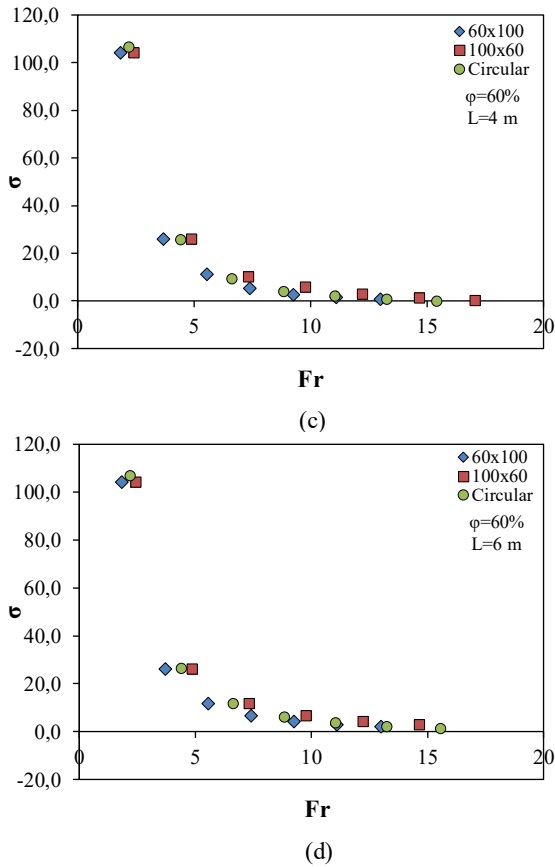


Figure 8. σ versus Fr for various values of L [m] at $\phi=60\%$
(a) $L=1$, (b) $L=2$, (c) $L=4$, (d) $L=6$

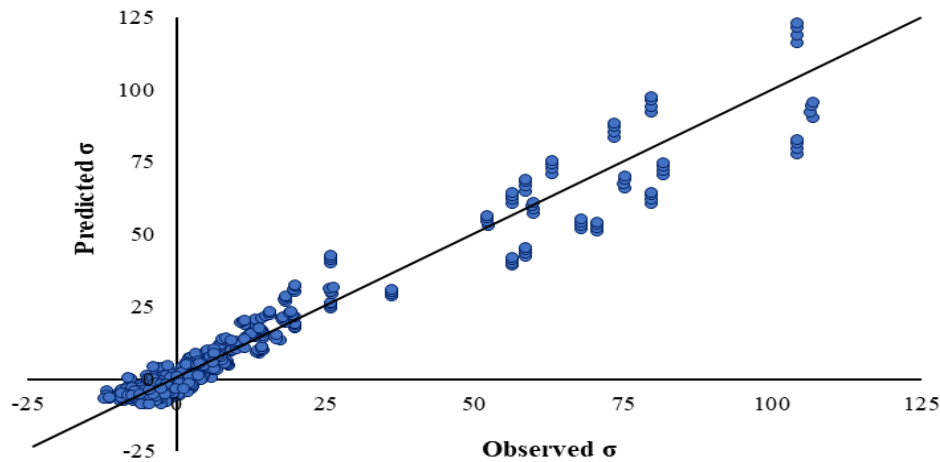


Figure 9. Observed σ values compared with predicted σ values

4. 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.

Acknowledgments

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