

# Effect of Cross-section Geometry on Air-Demand Ratio in High-head Conduits With Sluice Gate

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## Research Article

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# Abstract

When the researches on the gated conduits were examined, it was determined that the air-demand ratio changed according to the hydraulic and geometric parameters. However, no study investigated the effect of the cross-section geometry of gated conduits on the air-demand ratio. In this study, the effect of conduit cross-section geometry on the air-demand ratio was examined. Results showed that conduit cross-section geometry was an important effect on the air-demand ratio especially at 10% and 15% gate opening rates. It was seen that the effect of the conduit geometry on the air-demand ratio decreased at 20%, and greater gate opening rates. In addition, a design formula related to the gate opening rate, Froude number, hydraulic radius, and conduit length was presented for estimating the air-demand ratio.

## Introduction

The most important parameter determining the water quality is the amount of oxygen dissolved in water. Oxygen gas dissolves in water through many methods, such as photosynthesis of plants, by diffusion occurring between water and the atmosphere, by churning waves hitting rocks. In contrast, the amount of dissolved oxygen in the water decreases because of many natural chemical and biological events. The reduction of dissolved oxygen concentration poses a great threat to living life. To reduce or eliminate this condition that threatens ecological life, oxygen in the atmosphere must be entrained into the water, that is, it must be aerated (Gulliver et al., 1998). Aeration, which is a water treatment application, is the process of raising small air bubbles in the water to ensure that air and water are in close contact; or is the process of exposing drops or water layers to the air.

The air-demand ratio and the aeration efficiency in closed conduits and outlet works have been studied experimentally by Kalinske and Robertson (1943), Sharma (1976), Stahl and Hager (1999), Speerli and Hager (2000), Ozkan et al. (2006, 2014, 2015), Escarameia (2007), Oveson (2008), Mortensen (2009), Tuna et al. (2014) and Unsal et al. (2008, 2009). In these studies, they determined that the air-demand ratio varies according to hydraulic and geometric parameters. However, when the literature was comprehensively examined, no studies investigating the effect of cross-section geometry on air-demand ratio were found among the experimental studies on gated conduits. In this article, the change of air-demand ratio using conduits with different cross-section geometry was examined.

### Air Entrainment Mechanism High-head Gated Conduits

Gated conduits are hydraulic structures that involve high-velocity air-water flow. In large dams, gated conduits are widely used for various purposes such as (i) discharging the dam reservoir in an emergency, (ii) regulating the water level in the reservoir, (iii) preventing sediment accumulation at the dam base.

When the cross-sectional area of a high-head conduit is partially closed by a gate, a high-velocity and low-pressure flow occurs downstream of the gate. Because of this high-velocity flow, pressure lower than atmospheric pressure can occur within the conduit. Theoretically, these pressures could be as low as the vapor pressure of water. When a connection is made to the atmosphere with an air vent located below the

gate, air suction takes place in the air vent as shown in Fig. 1. The amount of air suction inside varies according to the entraining and carrying capacity of the flow. The reduction in pressure behind the gate (from the atmospheric value) is a function of the gate opening.

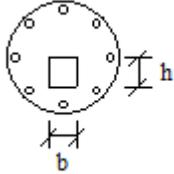
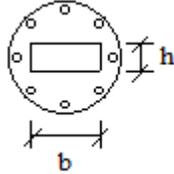
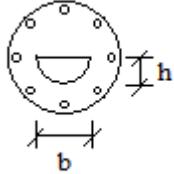
## Material And Method

**Experimental setup.** In this study by using high-head conduits with sluice gate, the effects of physical parameters such as different (i) cross-section geometries, (ii) gate opening rates, (iii) conduit lengths, and (iv) flow rates on the air-demand ratio with a single test setup were investigated and it was aimed to increase the air-demand ratio. All components used in the experimental setup are shown in Fig. 2. The water, which has a certain volume in the experiments, has been circulated continuously. The water in the tank is transmitted to the conduit by pressure. For this purpose, a water pump is used. The flow transmitted to the system was adjusted with the help of a flow control valve and electromagnetic flow meter. To eliminate head losses, the diameter of the pipeline that transmits the water to the conduits with the pump outlet diameter has been chosen in the same size (3-inch diameter).

Three different sections were used to investigate the effect of the cross-section geometry on the air-demand ratio (Fig. 3). Circular conduit was selected in the same diameter as the pipeline to eliminate head losses (i.e. 3-inch). Rectangular conduits were chosen in 100 mm x 60 mm dimensions to have the same cross-sectional area as circular conduits and used in two different positions.

Gate opening rates for all cross-sections were chosen as 10, 15, 20, 30, 40, and 60% (Fig. 4-6). The gate opening rate refers to the ratio of the cross-sectional area of the flow to the cross-sectional area of the conduit. The dimensions of the narrowing for each section are shown in Table 1.

Table 1  
Sluice gate dimensions

Gated opening rate ( $\varphi$ )	60x100	100x60	Circular				
							
	b (mm)	h (mm)	b (mm)	h (mm)	b (mm)	h (mm)	h (mm)
10%	54	9.4	94	5.4	58.8	12.7	
15%	54	14.1	94	8.1	65.6	16.8	
20%	54	18.8	94	10.8	70.4	20.6	
30%	54	28.2	94	16.2	76.7	27.5	
40%	54	37.6	94	21.6	79.9	34.1	
60%	54	56.4	94	32.4	79.9	46.8	

An air vent was opened downstream of the gate to bring the atmospheric air into water. The air vent consists of pipes 45 mm, 30 mm and 15 mm in diameter, and 200 mm in height. While measuring the air velocity entering the system with the help of an anemometer, an air vent with a diameter of 45 mm was used first. The amount of air drawn ( $Q_a$ ) in small flow rates ( $Q_w$ ) is small. Also, the anemometer cannot measure small air velocities. To eliminate this sensitivity of the anemometer, 30 mm and 15 mm diameter ventilation chimneys are used in flows that cannot be measured. 1 m, 2 m, 4 m, and 6 m long conduits were used to investigate the effect of conduit length on the air-demand ratio.

**Experimental procedure.** Then, the determined flow rates were adjusted with the help of an electromagnetic flowmeter, the velocity of the air absorbed from the air vent opened to the downstream of the gate was measured using an anemometer. The air velocity was measured to determine the air flow rate ( $Q_a$ ). Anemometer was used to determine the air velocity. For the measurements to be accurate, at least 60 seconds of measurements were made in the center of the air hole with an anemometer. The air flow rate was calculated by multiplying the air velocity and the cross-sectional area of the air hole. This process was applied for all experimental series shown in Table 2.

Table 2  
Experimental series

Conduit cross-section shape	Gated opening rate	Conduit length	Water flow rate
60x100	10%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	15%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	20%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	30%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	40%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	60%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
100x60	10%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	15%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	20%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	30%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	40%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	60%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
Circular	10%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	15%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	20%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	30%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	40%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>
	60%	L= 1m, 2m, 4m, 6m	Q <sub>1</sub> ,Q <sub>2</sub> ,Q <sub>3</sub> ,Q <sub>4</sub> ,Q <sub>5</sub> ,Q <sub>6</sub> ,Q <sub>7</sub>

The Froude number is computed by the effective depth rather than by the depth at the vena contract section by using Eq. (1).

$$Fr = V / \sqrt{g h_e}$$

1

where V is water velocity at gate location; g is acceleration of gravity; and h<sub>e</sub> is effective depth, is water cross-sectional flow area divided by water surface width.

In the literature Froude number has often been based on the vena contract section. Because high-head gated conduits involve high-velocity air-water mixture flow, to avoid the problem of determining flow depths and velocities at the vena contract section, in this study the Froude number was based on the effective depth in the conduit.

## Experimental Results

In Figs. 7-12, the variation of  $Q_a/Q_w$  with the Froude number was examined to investigate the effect of conduit cross-section geometry. It is seen that as the Froude number increases, the  $Q_a/Q_w$  ratio increases in all gate opening rates and conduit lengths. It can be understood that there is a correct ratio between the Froude number and the air-demand ratio. This is also seen in the equations developed for the estimation of the air-demand ratio (Kalinske and Robertson, 1943; Campbell and Guyton, 1953; USACE, 1964). When all experimental series were examined, it was seen that the air-demand ratio reached the maximum value at 10% gate opening rate (Fig. 7). The air-demand ratio decreased as the gate opening rate increased. Here, it is understood that there is an inverse proportion between the gate opening rate and the air-demand ratio. This is because the pressure difference between the gate upstream and downstream decreases as the gate opening rate increases. Because the pressure difference is low, the air-demand ratio decreases. In addition, Speerli (1999) determined that the air intake to the system was from both the air vent and the conduit downstream. At large gate opening rates, the section flows more fully and there is no air intake from the downstream. Therefore, the air-demand ratio decreases as the gate opening rate increases.

When the experimental results are examined, it is seen that conduit cross-section geometry has an effect on the air-demand ratio at 10% and 15% gate opening rates (Figs. 7-8). It has been determined that 60 mm x 100 mm rectangular section conduits are more advantageous in terms of air-demand ratio compared to other alternatives. The best air-demand ratio in all test series was observed in rectangular conduits with 60 mm x 100 mm cross-section where the conduit length was 4 m and the gate opening rate was 10% (Fig. 7).  $Q_a/Q_w$  has been determined as 7.27. The lowest air-demand ratio was observed in rectangular conduits with 100 mm x 60 mm sections.

When the results of the experiment were examined, it was determined that the maximum air intake into the system occurred in circular conduits in all gate opening rates. However, since there are more energy losses in rectangular conduits, less water flow is transmitted. Therefore,  $Q_a/Q_w$  is lower in circular conduits.

It is seen that the effect of conduit cross-section geometry reduced at 20% and greater gate opening rates (Figs. 8-12). Even if the Froude number increases as the gate opening rate increases, it is observed that the increasing trend of  $Q_a/Q_w$  ratio has ceased. It is also observed that  $Q_a/Q_w$  ratio does not increase significantly after the value of about 20-30 Froude numbers.

In the gate opening rates up to 30% the lowest air-demand ratios are observed in the conduits having a length of 1 m and in the larger gate opening rates the lowest air-demand ratios are observed in the conduits having a length of 6 m. In other conduit lengths, it is seen that the air-demand ratios are close to each other. The reason for this is thought to be the hydraulic jump. Research has shown that hydraulic jump has a significant effect on the air-demand ratio. As a result of these studies, it has been determined that hydraulic jump occurs in the region where the air release occurs (Mortensen et al., 2011, 2012). It has also been determined that the air intake starts with the hydraulic jump and the aeration length continues even if the jump ends. Based on this information, it is thought that hydraulic jump occurs along the conduit in lengths with a high air-demand ratio. In addition, as the conduit length increases after the end of the hydraulic jump, it is estimated that the air-demand ratio decreases due to energy losses.

When the equations developed in the literature are examined, it is seen that the air-demand ratio varies depending on the Froude number (Kalinske and Robertson, 1943; Haindl and Sotornik, 1957; USACE, 1964; Campbell and Guyton, 1953; Rajaratnam, 1962; Wisner, 1965; Sharma, 1976; Shamsaei and Soleymanzadeh, 2006; Tuna et al., 2014). However, when the results of the experiment were analyzed, it was determined that the air-demand ratio varied depending on the Froude number, gate opening rate, conduit length, and cross-section geometry. For this reason, it is understood that the equations developed for the prediction of the air-demand ratio in the literature do not yield very suitable results. Separate formulas (Eqs. 2-4) have been developed for each cross-section geometry considering all the parameters mentioned in this study.

Eq. (2) developed for rectangular conduit with a cross-section of 60 mm x 100 mm:

$$\frac{Q_a}{Q_w} = 0.070(\text{Fr} - 1)^{0.872} \phi^{-0.527} \left( \frac{h}{L} \right)^{-0.039}$$

$$R^2=0.91 \text{ (2)}$$

Eq. (3) developed for rectangular conduit with a cross-section of 100 mm x 60 mm:

$$\frac{Q_a}{Q_w} = 0.061(\text{Fr} - 1)^{0.893} \phi^{-0.239} \left( \frac{h}{L} \right)^{-0.081}$$

$$R^2=0.83 \text{ (3)}$$

Eq. (4) developed for circular section conduit:

$$\frac{Q_a}{Q_w} = 0.046(\text{Fr} - 1)^{0.739} \phi^{-0.549} \left( \frac{h}{L} \right)^{-0.161}$$

$$R^2=0.87 \text{ (4)}$$

In addition, Eq. (5) which can be used for all cross-section geometries has been developed by considering the data of 504 experiments.

$$\frac{Q_a}{Q_w} = 0.085(\text{Fr} - 1)^{0.743} \phi^{-0.531} \left( \frac{R}{L} \right)^{-0.037}$$

$R^2=0.83$  (5)

where Fr is Froude number;  $\phi$  is gate opening rate; h is gate opening (m); L is conduit length (m); and R is hydraulic radius (m).

The measured air-demand ratios were compared with those predicted with Eq. (5). Good agreement between the measured values and the values computed from the empirical correlation was obtained.

## Conclusions

In this study, the effect of cross-section geometries of high-head conduits on the air-demand ratio in a recirculation experimental setup was investigated. The results obtained are listed as items.

- The experimental results showed that high-head conduits can be used efficiently in the aeration of water.
- The best air-demand ratio in all test series took place in rectangular conduits with 60 mm x 100 mm cross-section where the conduit length was 4 m and the gate opening rate was 10%. The air-demand ratio has been determined as 7.27.
- As the Froude number increased in all cross-sections and gate opening rates, the air-demand ratio increased.
- In all cross-sections, the air-demand ratio decreased as the gate opening rate increased.
- As the length of the conduit increases in all cross-sections and gate opening rates, the air-demand ratio increases up to a certain value and then decreases. The best air-demand ratio is achieved in the conduit lengths of 2 m and 4 m.
- In all cross-sections, it has been observed that the lowest air-demand ratio is at L = 1 m conduit length at the gate opening rates up to 30%, and the lowest air-demand ratio is at L = 6 m conduit length at the larger gate opening rates.
- The most air ( $Q_a$ ) was drawn in circular conduits in all gate opening rates. However, since the amount of water ( $Q_w$ ) transmitted in conduit with circular sections is high, the air-demand ratio ( $Q_a/Q_w$ ) has decreased.
- Equations developed in this study will provide a great convenience in estimating the air-demand ratio to designers.
- Designers can use the results of this work as a basis for future research.

# Abbreviations

Fr	Froude number based on effective depth in conduit
g	acceleration of gravity
h	gate opening
L	conduit length
R	hydraulic radius
$Q_a$	air flow rate measured through air vent
$Q_w$	water flow rate in conduit
$Q_a/Q_w$	air-demand ratio
V	water flow velocity at gate location
$h_e$	effective depth
$\phi$	ratio of water cross-sectional flow area to conduit cross-sectional area

# Declarations

# Acknowledgments

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## Figures

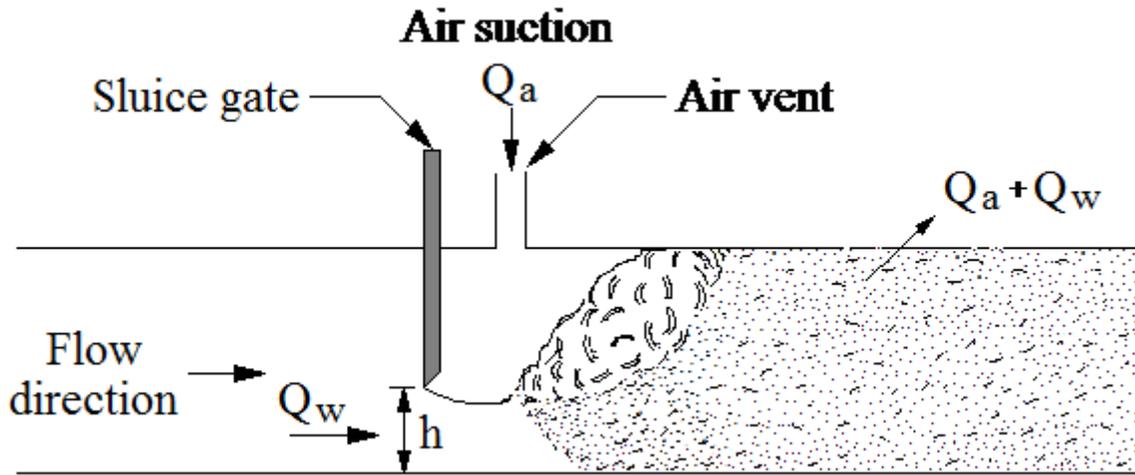


Figure 1

Air entrainment in high-head gated conduit

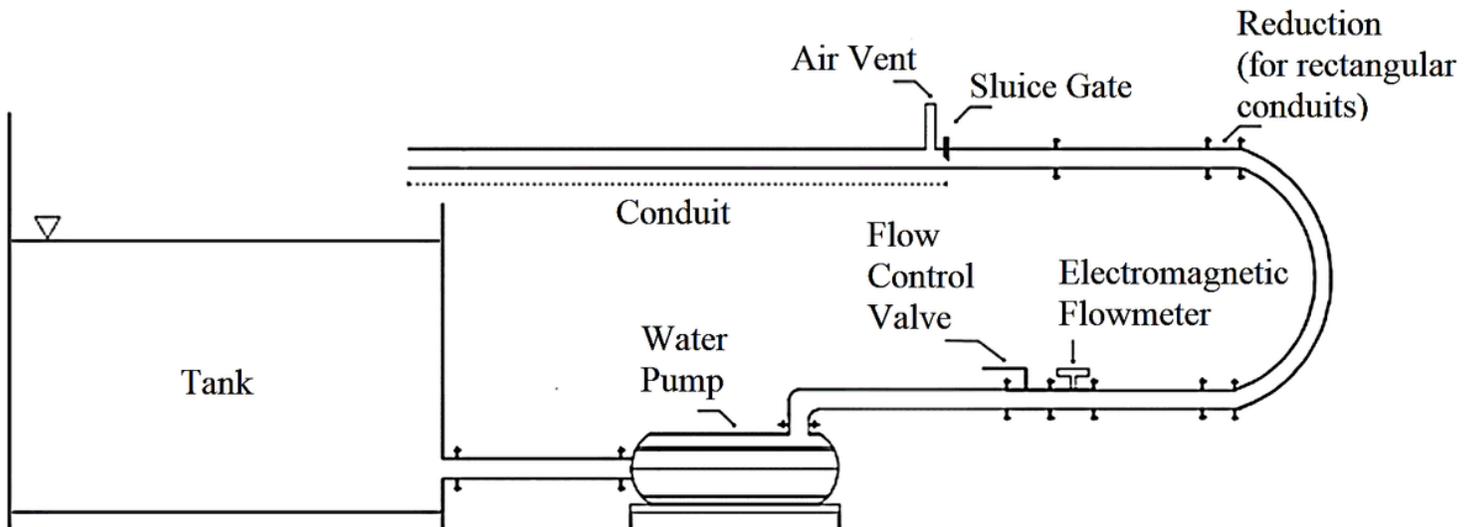
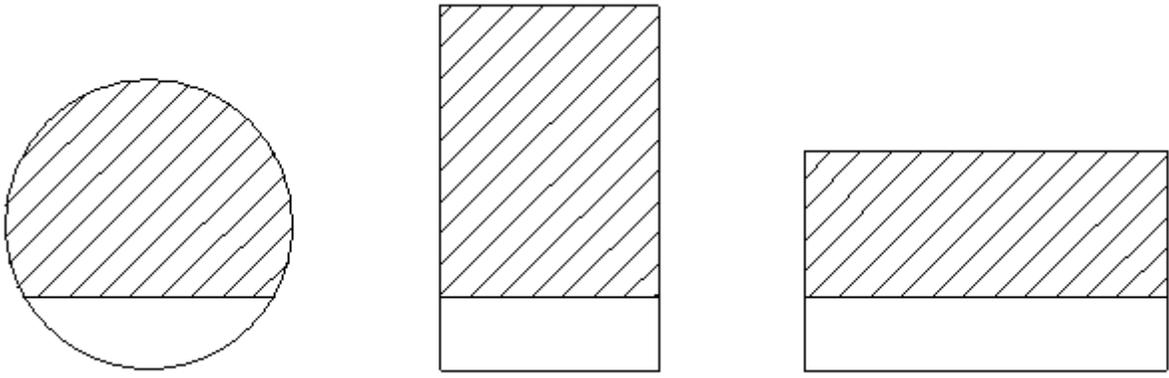


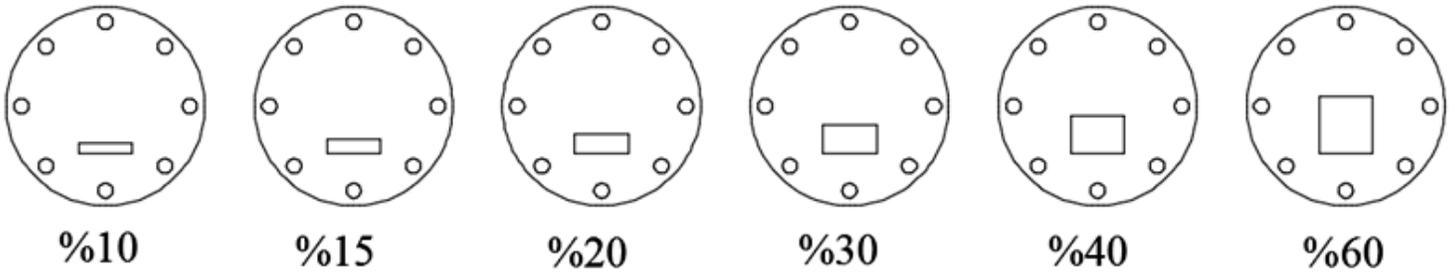
Figure 2

Physical model overview



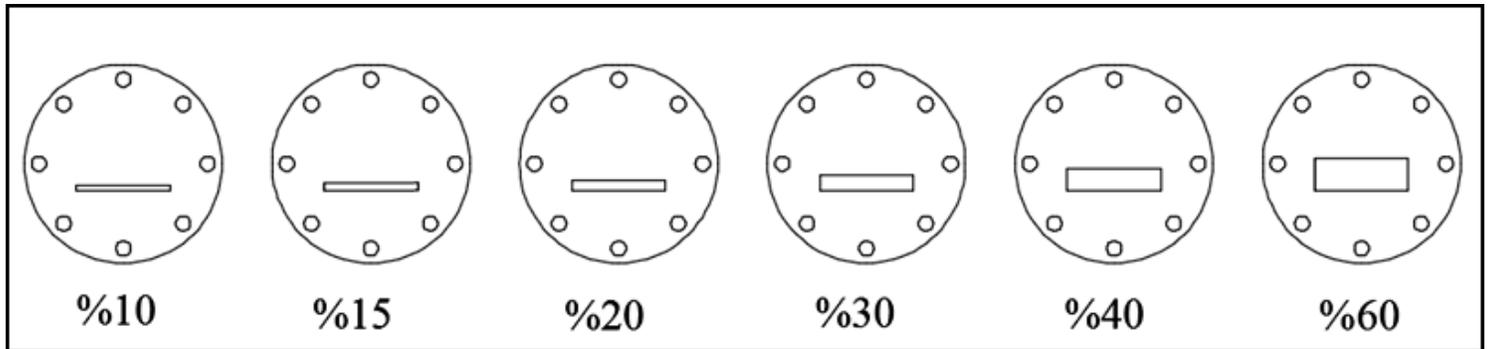
**Figure 3**

Conduit cross-sections



**Figure 4**

Gate opening rates of 60x100 (width/height) rectangular conduits



**Figure 5**

Gate opening rates of 100x60 (width/height) rectangular conduits

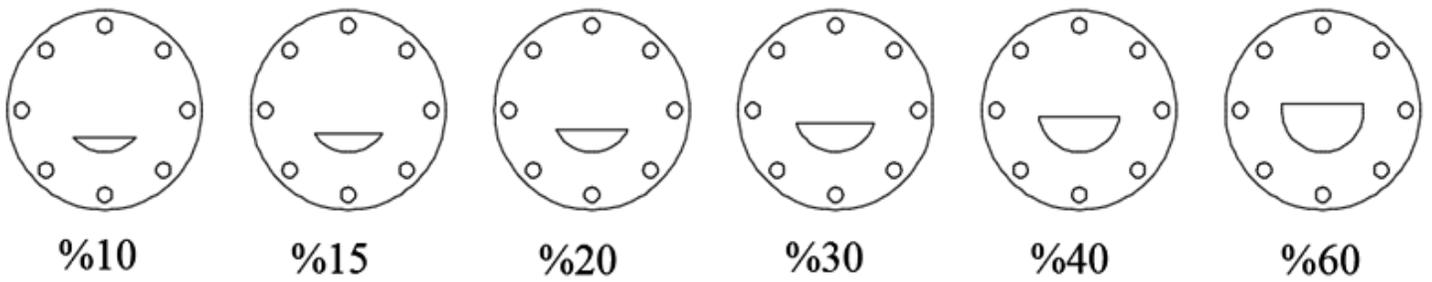


Figure 6

Gate opening rates of circular conduits

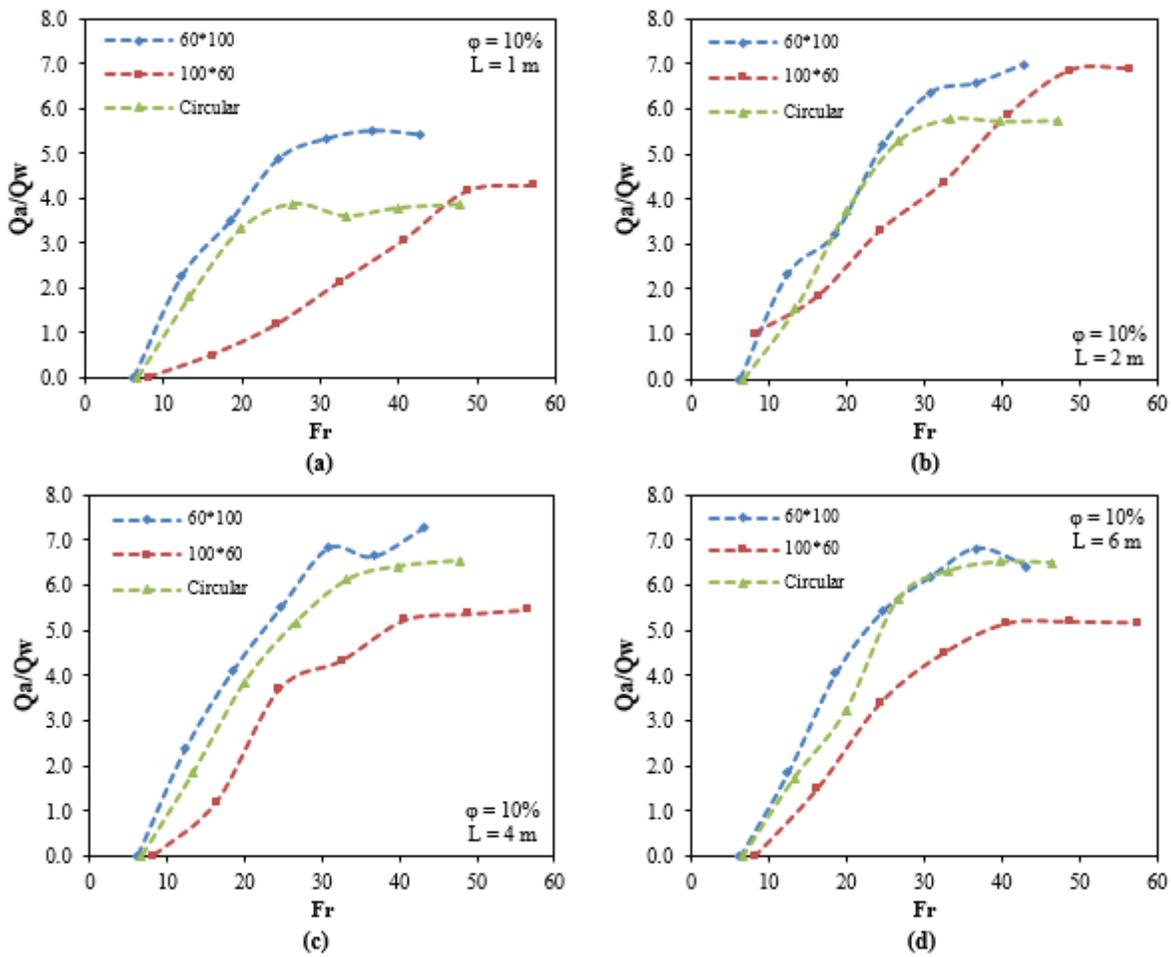
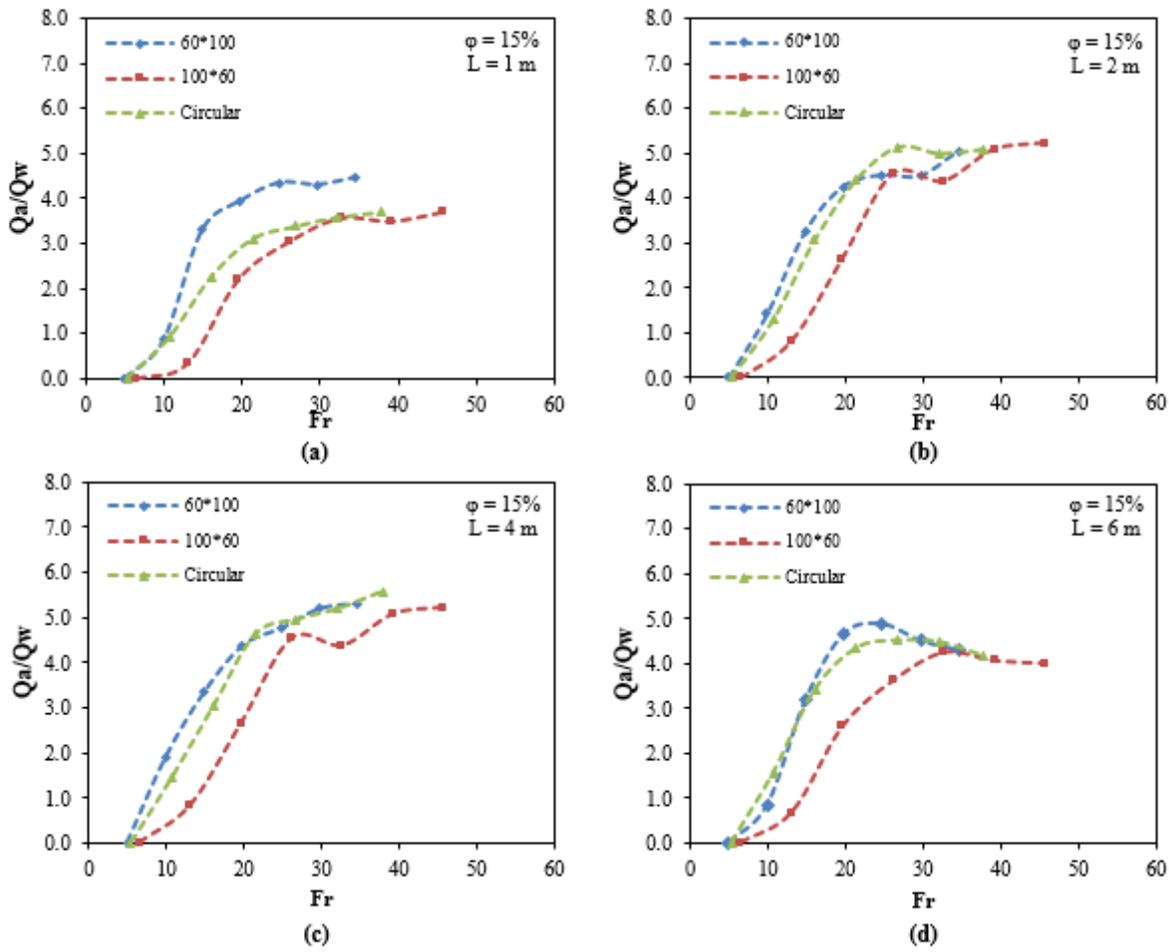


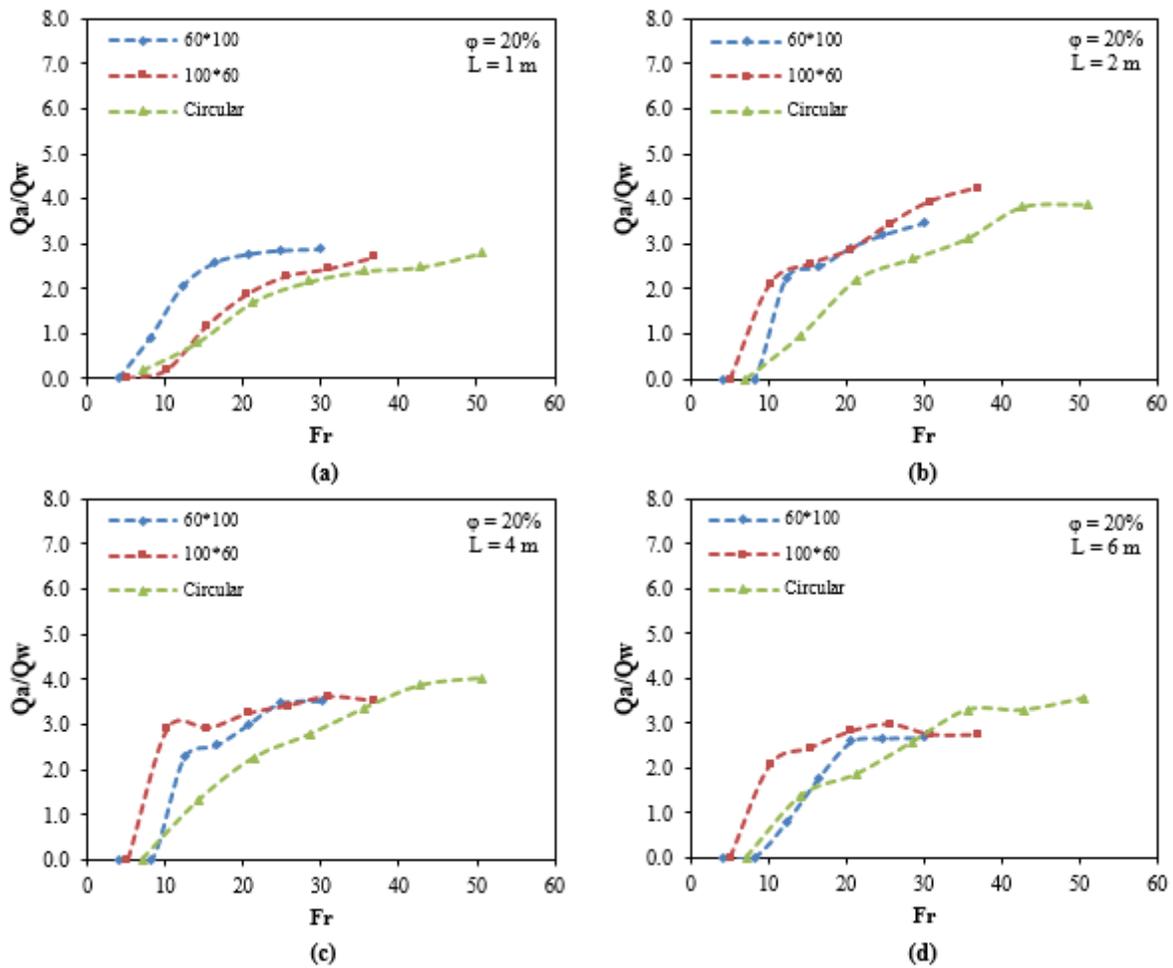
Figure 7

The variation of  $Q_a/Q_w$  with the Froude number and conduit length for  $\phi=10\%$



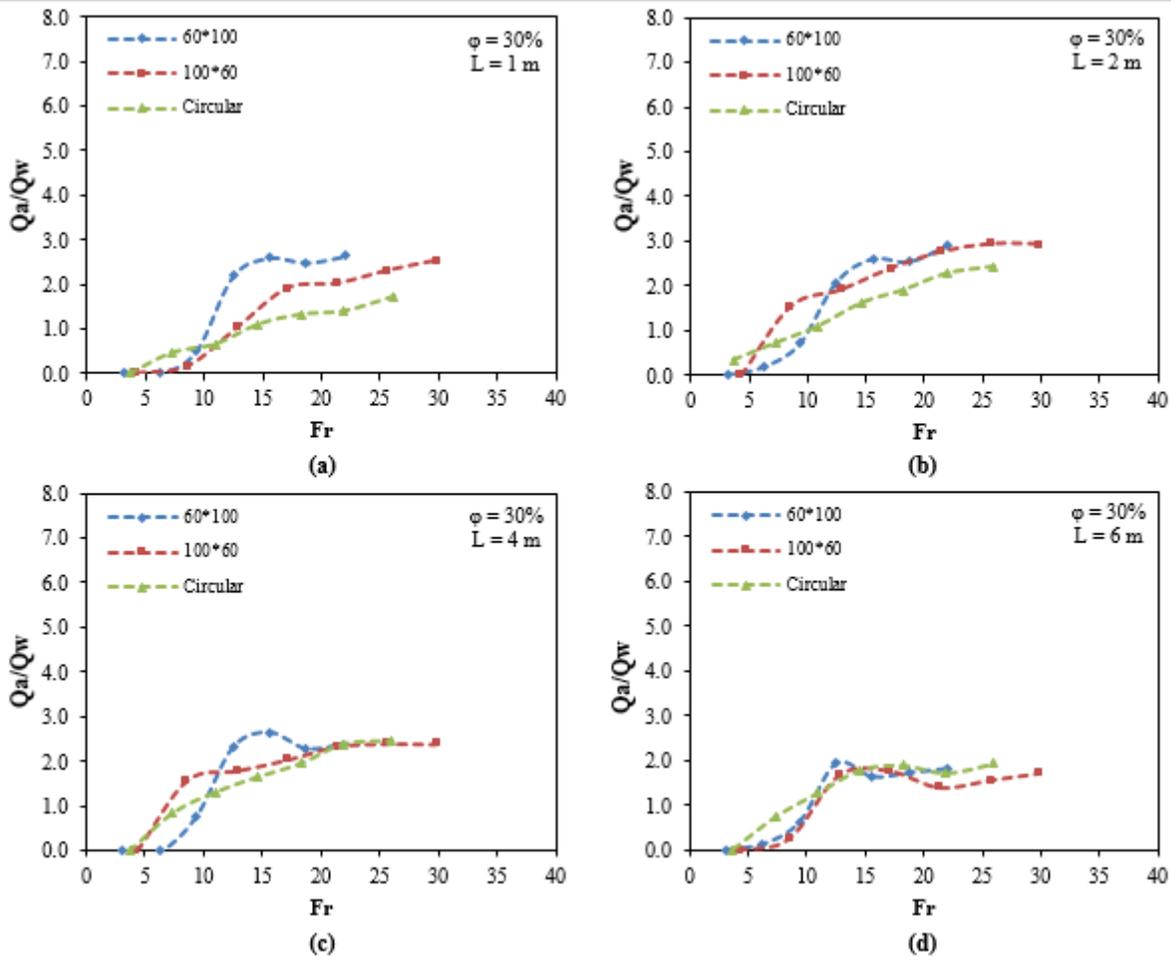
**Figure 8**

The variation of  $Q_a/Q_w$  with the Froude number and conduit length for  $\phi=15\%$



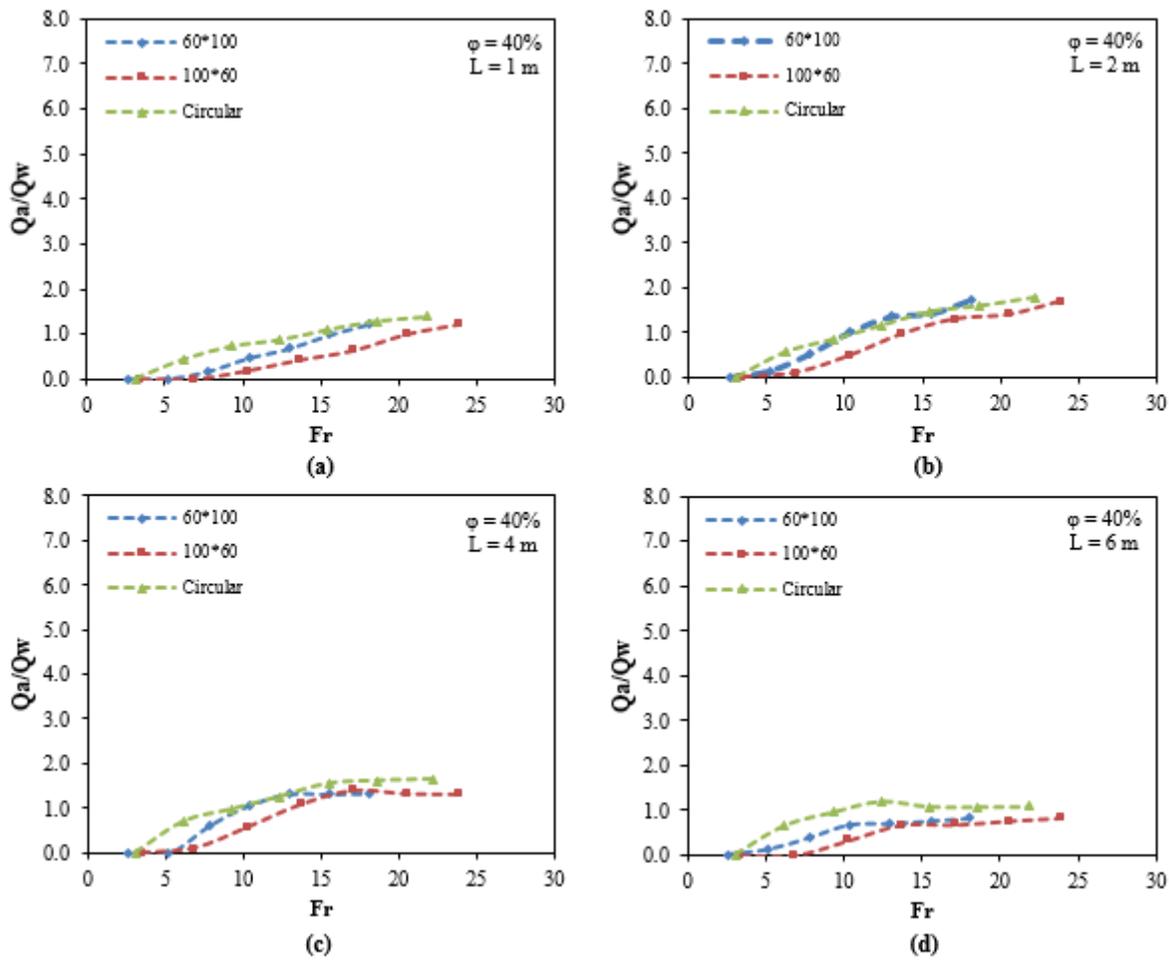
**Figure 9**

The variation of  $Q_a/Q_w$  with the Froude number and conduit length for  $\phi=20\%$



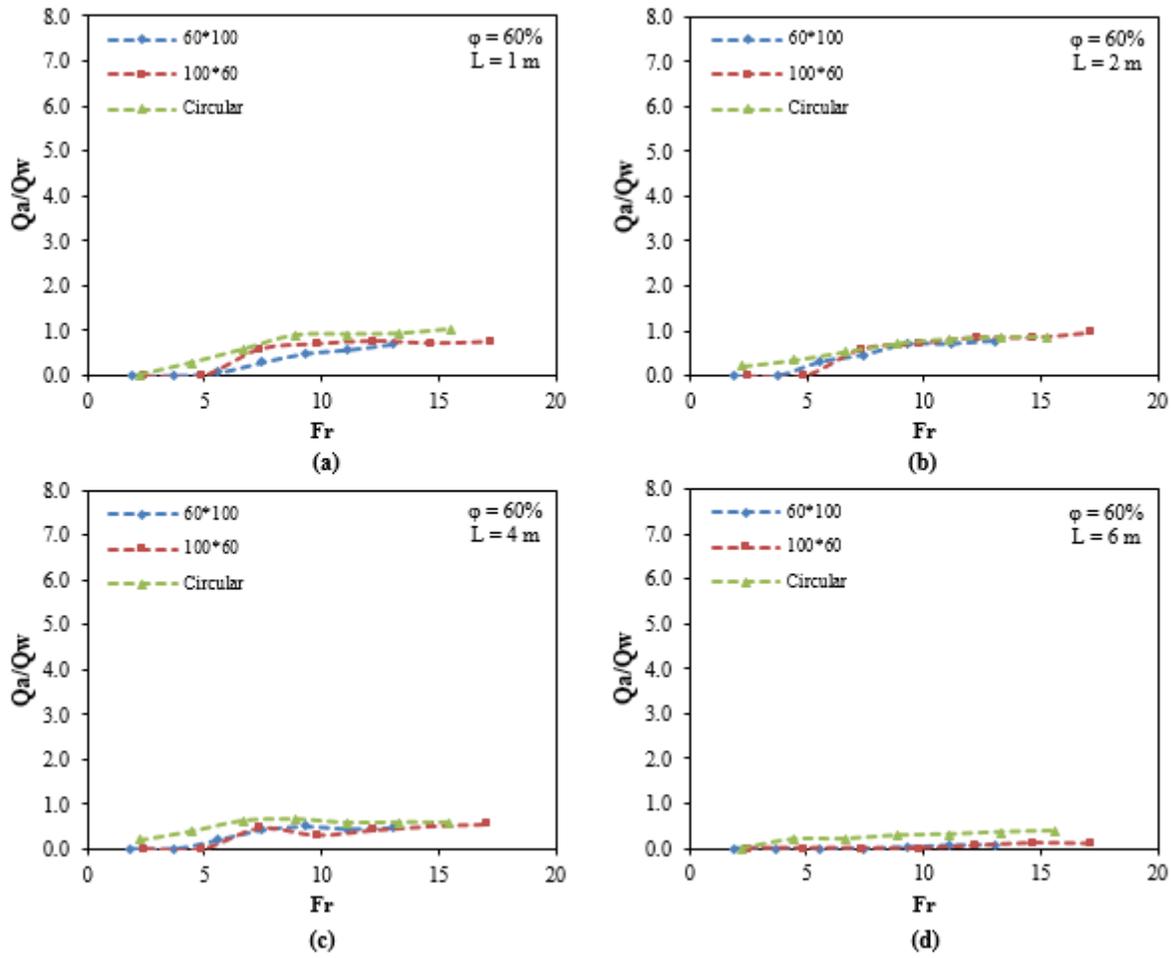
**Figure 10**

The variation of  $Q_a/Q_w$  with the Froude number and conduit length for  $\phi=30\%$



**Figure 11**

The variation of  $Q_a/Q_w$  with the Froude number and conduit length for  $\phi=40\%$



**Figure 12**

The variation of  $Q_a/Q_w$  with the Froude number and conduit length for  $\phi=60\%$