ROLE OF GATE TYPE IN THE AIR-DEMAND RATIO IN CLOSED CONDUITS

A. B. Aydin[a], A. Baylar[b*], F. Ozkan[a], M. C. Tuna[a], Mualla Ozturk[c]

[a] Department of Civil Engineering, Firat University, Elazig, Turkey; E-mails: baydin@firat.edu.tr, fozkan@firat.edu.tr, mctuna@firat.edu.tr
[b*] Department of Civil Engineering, Eskisehir Technical University, Eskisehir, Turkey; E-mail: abaylar@eskisehir.edu.tr
[c] Department of Civil Engineering, Munzur University, Tunceli, Turkey; E-mail: muallaozturk@munzur.edu.tr

Received: 08.12.2023 / Accepted: 15.12.2023 / Revised: 26.02.2024 / Available online: 31.05.2024

DOI: 10.2478/jaes-2024-0003

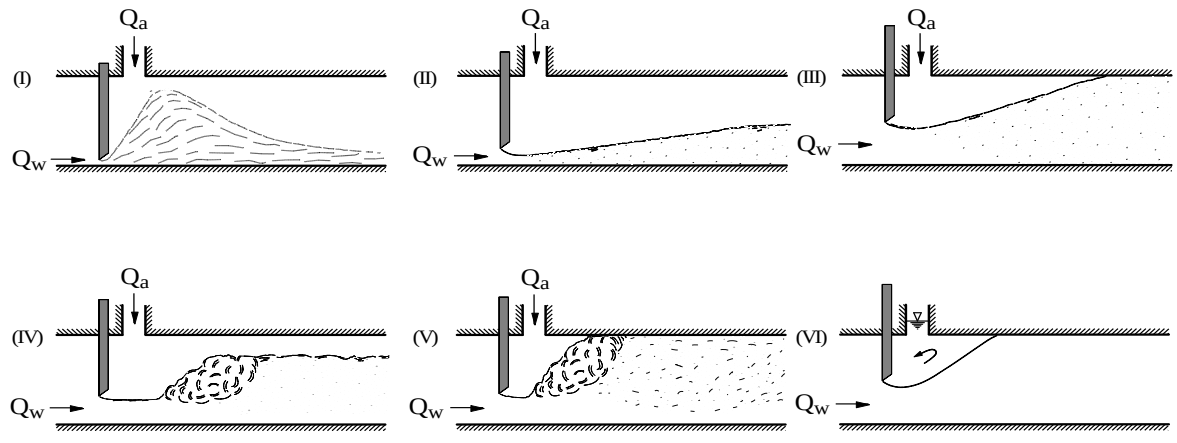
KEYWORDS: air-water flow, cavitation, gate, high-head flow, high-velocity flow.

ABSTRACT:

Sluice and radial gates are common devices used to control flow in closed conduits. In high-head gated conduits, the high-velocity flow exiting the gate drags and entrains a lot of air. If the air demand of the flow is not met, the pressure drop downstream of the gate will cause structural damage or cavitation. Typically, an air vent is installed immediately downstream of the gate to supply sufficient air to the flow. In this study, the effect of the conduit gate type on the air-demand ratio was investigated. The results showed that the gate type had a very significant effect on the air-demand ratio. Significantly higher air-demand ratios were observed in the conduit with a sluice gate compared to the conduit with a radial gate. The results obtained will be useful in future modeling and design processes.

1. INTRODUCTION

Gated conduits are hydraulic structures that involve high-velocity air-water flow (Figure 1). They are commonly used in large dams for reservoir drawdown, sediment flushing, river diversion, and environmental flow release. The main problem with these structures is cavitation phenomena, particularly after the flow control gates, which occurs at different gate opening rates due to high flow velocity and pressure drop downstream of the gates. Cavitation is a phenomenon that can damage gated conduits at high velocities.



(I) Spray flow
(II) Free-surface flow
(III) Foamy flow
(IV) Hydraulic jump followed by free-surface flow
(V) Hydraulic jump followed by high-head flow
(VI) High-head flow (submerged gate and air vent)
The first four types correspond to free-surface flow and the last two types correspond to high-head flow

Figure 1. Different flow regimes in a gated closed conduit (Sharma, 1976)

Cavitation occurs when the pressure in the water flow drops to the value of the pressure of the saturated water vapor, cavities filled by vapor, and partly by gases excluded from the water due to the low pressure, is 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)

In a gated conduit, an air vent is usually installed immediately downstream of the gate to provide sufficient air to the flow. Previous studies have shown that injecting air into the flow downstream of the gate can significantly reduce the risk of cavitation damage. The air-demand ratio and the aeration efficiency in gated closed conduits have been investigated by Aydin et al. (2021, 2022, 2023), Baylar and Batan (2010), Baylar et al. (2010, 2021, 2022), Campbell and Guyton (1953), Haindl and Sotornik (1957), Hohermuth (2017, 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), Rajaratnam (1962), Safavi et al. (2008), Sharma (1976), Speerli (1999), Speerli and Hager (2000), Tuna et al. (2014), Unsal et al. (2008, 2009, 2014), USACE (1964), Wisner (1965).

The first known work on the air-injection ratio in the gated conduit was carried out by Kalinske and Robertson (1943). Circular conduits were used, and it was shown that the air-injection ratio was a function of the Froude number upstream of the hydraulic jump. This work resulted in Equation 1.

$$\beta = 0.0066(\mathrm{Fr} - 1)^{1.4} \quad (1)$$

Campbell and Guyton (1953) used data from prototype observations to correlate the air-injection ratio and the Froude number at the contracted section downstream of the gate (Equation 2):

$$\beta = 0.04(\mathrm{Fr} - 1)^{0.85} \quad (2)$$

Haindl and Sotornik (1957) carried out laboratory experiments in a closed rectangular conduit. The flow cross-section was about three times larger than that used by Kalinske and Robertson (1943) and Equation (3) was obtained.

$$\beta = 0.012(\mathrm{Fr} - 1)^{1.4} \quad (3)$$

Rajaratnam (1962) made two-phase flow measurements in a hydraulic jump for different values of Froude number and derived Equation (4):

$$\beta = 0.018(\mathrm{Fr} - 1)^{1.245} \quad (4)$$

USACE (1964) developed Equation (5) using the prototype data from bottom outlet structures in several dams:

$$\beta = 0.03(\mathrm{Fr} - 1)^{1.06} \quad (5)$$

Wisner (1965) developed Equations (6) and (7) for free surface flow and foamy flow respectively.

$$\beta = 0.024(\mathrm{Fr} - 1)^{1.4} \quad (6)$$

$$\beta = 0.033(\mathrm{Fr} - 1)^{1.4} \quad (7)$$

Sharma (1976) developed Equations (8) and (9) for free surface flow and foamy flow respectively.

$$\beta = 0.009\mathrm{Fr} \quad (8)$$

$$\beta = 0.2\mathrm{Fr} \quad (9)$$

where β = Air-injection ratio (Q_a/Q_w)
Fr = Froude number

A recent investigation by Mortensen et al. (2012) identified three cases of fully developed and truncated hydraulic jumps to describe how air demand is affected by the location of the jump relative to the downstream air vent. Mortensen and Kubitschek (2016) found that the travel speed of the hydraulic jump depends on both the size of the air vent and the gate closure rate, both of which affect the internal pressure in the conduit near the air vent connection. Hohermuth et al. (2020) showed that demand increases with increasing the Froude number at the vena contracta, increasing relative vent size, increasing relative tunnel length, and decreasing vent loss coefficient and tunnel slope. Aydin et al. (2021, 2023) investigated the effect of conduit cross-sectional geometry on the air-demand ratio in high-head conduits with a radial gate and a sluice gate. The results showed that the cross-sectional geometry of the conduit had an important effect on the air-demand ratio, especially at low gate opening rates, and the design equations for estimating the air-demand ratio were presented. Baylar et al. (2022) indicated that the cross-sectional geometry of the conduit plays an important role in oxygen transfer efficiency.

A comprehensive review of the literature did not identify any experimental studies on conduits that investigated the effect of gate type on the air-demand ratio. This study investigated the effect of gate type on the air-demand ratio in high-head conduits.

2. METHODS

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. As a result, significant pressure variations can increase the possibility of cavitation and vibration. Injecting air into the flow downstream of the gate is the most effective and efficient way of preventing cavitation attacks. When a connection to the atmosphere is made with an air vent located downstream of the gate, air is drawn into the air vent. The amount of air drawn in depends on the cross-sectional geometry of the conduit, gate opening rate, conduit length, flow rate, and gate type.

Sluice and radial gates are common devices used to control flow in closed conduits (Figure 2). Aydin et al. (2021, 2023) investigated the effects of cross-sectional geometry, gate opening rate, conduit length, and flow rate on the air-demand ratio in the high-head conduits with a radial gate and a sluice gate (Figure 3). The experimental setup was constructed at the Hydraulic Laboratory of Firat University, Elazig, Turkey, and the components used are shown in Figure 4. 504 experiments were carried out for the radial gates and 504 experiments were carried out for the sluice gates. Three different conduit sections were used. The first conduit was a 60 mm wide by 100 mm high rectangular conduit (60×100 rectangular), the second conduit was a 100 mm wide by 60 mm high rectangular conduit (100×60 rectangular), and the third conduit was a 3-inch diameter circular conduit. Gate opening rates, which refer to the ratio of water flow cross-sectional area to conduit cross-sectional area were chosen as 10%, 15%, 20%, 30%, 40%, and 60%. The conduit lengths were taken as 1 m, 2 m, 4 m, and 6 m. The Froude number was based on the effective depth in the conduit (Eq. 10).

$$Fr = V/\sqrt{g\, h_e} \tag{10}$$

where V = Water velocity at gate location
g = acceleration of gravity
h_e = effective depth (ratio of flow cross-sectional area to water surface width)

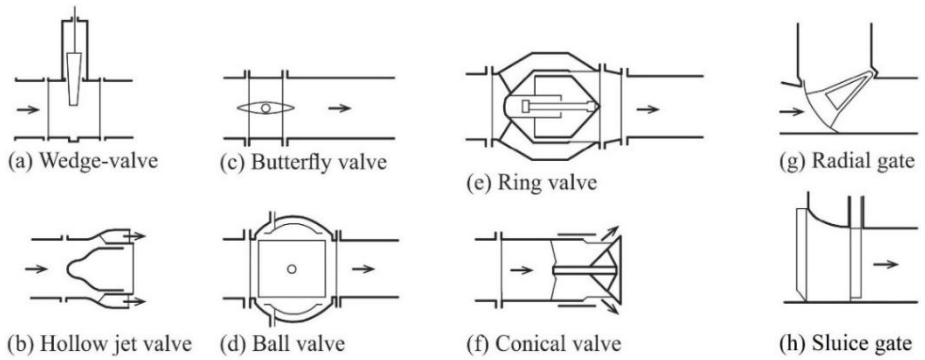


Figure 2. Types of valves (a)-(f) and gates (g), (h) used in conduits (Giesecke et al., 2014; Hohermuth, 2019)

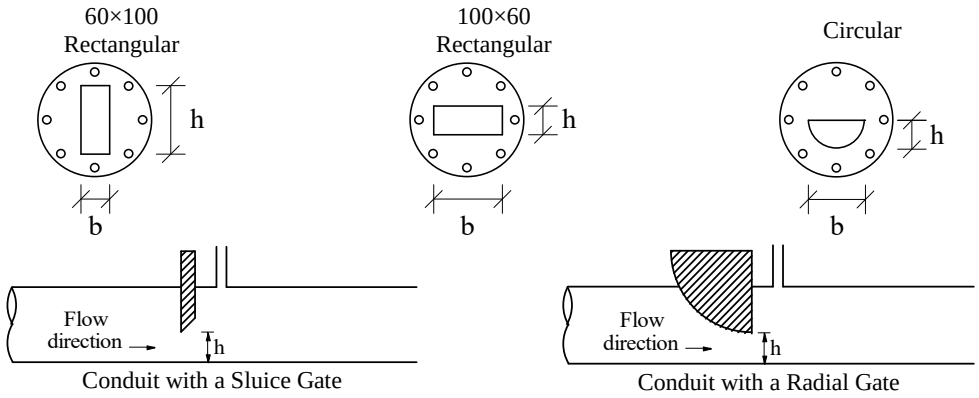


Figure 3. Conduit cross-section geometries and gate types

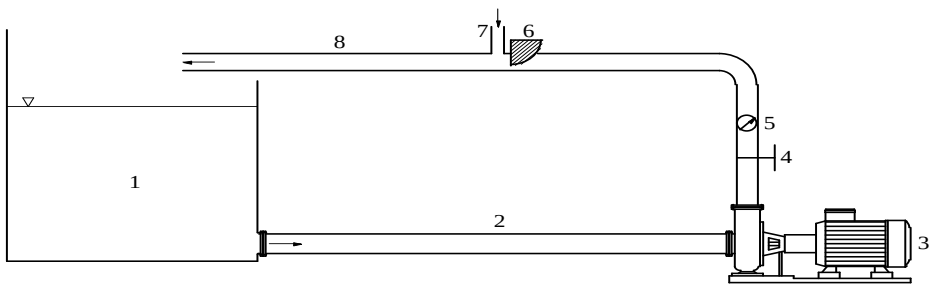


Figure 4. General view of experimental setup: 1. water tank, 2. water feed line, 3. water pump, 4. flow control valve, 5. flowmeter, 6. gate (radial or sluice gate), 7. air vent, 8. conduit

The aim of this study is to investigate the effect of gate type on the air-demand ratio in high-head conduits. For this purpose, the air-demand ratios of two different gate types, radial gate, and sluice gate, were compared with each other using the experimental results of Aydin et al. (2021, 2023). A total of 1008 experimental results were considered, 336 for the 60×100 rectangular cross-sectional conduit, 336 for the 100×60 rectangular cross-sectional conduit, and 336 for the circular conduit.

3. RESULTS

The purpose of this research was to determine the effect of gate type on the air-demand ratio for physical experiments with three different conduit cross-sections. This objective was accomplished by setting up a physical experimental setup, conducting experiments, collecting data, analyzing the data, and presenting the results.

Figures 5-10 show plots of the air-demand ratio versus the Froude number for conduit cross-sectional geometry, gate type, gate opening rate, and conduit length. It was observed that for the 60×100 rectangular cross-sectional conduit with both a sluice gate and a radial gate at small gate opening rates, the air-demand ratio increased rapidly with the Froude number, and then the increasing trend decreased. At large gate opening rates, the air-demand ratio increased with the Froude number up to a certain value and then remained almost horizontal. For the conduit with a sluice gate, the air-demand ratio at small gate opening rates and maximum conduit length began to decrease after a certain peak value. At small gate opening rates, the conduit with a sluice gate had a significantly higher air-demand ratio than the conduit with a radial gate, and this difference decreased as the gate opening rate increased. In other words, as the gate opening rate increased, the effect of gate type on the air-demand ratio decreased. The air-demand ratio for the conduit with both a sluice gate and a radial gate was close to zero at the largest gate opening rate and conduit length. At low Froude numbers, while the conduit with a sluice gate had a higher air-demand ratio than the conduit with a radial gate at small gate opening rates, the air-demand ratios approached each other as the gate opening rate increased. The highest air-demand ratio for the 60×100 rectangular cross-sectional conduit with a sluice gate was 7.28 at 10% gate opening rate and 4 m conduit length. For the 60×100 rectangular cross-sectional conduit with a radial gate, the highest air-demand ratio was 4.04 at a 10% gate opening rate and 4 m conduit length.

It can be seen from Figures 5-10 that for the 100×60 rectangular cross-sectional conduit with both a sluice gate and a radial gate at small gate opening rates, the air-demand ratio increased rapidly with increasing the Froude number, and then the upward trend decreased. At large gate opening rates, the air-demand ratio increased with the Froude number up to a certain value and then remained at almost the same level. In the conduit with a sluice gate, the air-demand ratio at small gate opening rates and the largest conduit length began to decrease after a certain peak value. At small gate opening rates, the air-demand ratio of the conduit with a sluice gate was significantly higher than that of the conduit with a radial gate, and this difference decreased as the gate opening rate increased. In other words, the effect of gate type on the air-demand ratio decreased as the gate opening rate increased. At the largest gate opening rate and conduit length, the air-demand ratio was close to zero for both the conduit with a sluice gate and the conduit with a radial gate. At low Froude numbers, while the conduit with a sluice gate had a higher air-demand ratio than the conduit with a radial gate at small gate opening rates, the air-demand ratio approached close values as the gate opening rate increased. The highest air-demand ratio for the 100×60 rectangular cross-sectional conduit with a sluice gate was 6.89 at a 10% gate opening rate and 2 m conduit length. For the 100×60 rectangular cross-sectional conduit with a radial gate, the highest air-demand ratio was 4.18 at a 10% gate opening rate and 4 m conduit length.

Figures 5-10 show that for the circular cross-sectional conduit with both a sluice gate and a radial gate at small gate opening rates, the air-demand ratio increased rapidly with increasing the Froude number and then decreased in an upward direction. At large gate opening rates, the air-demand ratio increased with the Froude number up to a certain value and then remained at about the same level. For the conduit with a sluice gate, the air-demand ratio at small gate opening rates and the largest conduit length began to decrease after a certain peak value. At small gate opening rates, the air-demand ratio of the conduit with a sluice gate was much higher than that of the conduit with a radial gate, and this difference decreased as the gate opening rate increased. In other words, the effect of gate type on the air-demand ratio decreased as the gate opening rate increased. At the largest gate opening rate and conduit length, the air-demand ratio of the conduit with both a sluice gate and a radial gate approached zero. At low Froude numbers, the conduit with a sluice gate had a higher air-demand ratio than the conduit with a radial gate at small gate opening rates, but the air-demand ratios approached close values as the gate opening rate increased. The highest air-demand ratio for the circular cross-sectional conduit with a sluice gate was 6.53 at a 10% gate opening rate and 4 m conduit length. For the circular cross-sectional conduit with a radial gate, the highest air-demand ratio was 4.71 at a 10% gate opening rate and 2 m conduit length.

Figures 5-10 show that although the gate type had a significant effect on the air-demand ratio, it did not have much effect on the air-demand ratio in terms of conduit cross-sectional geometry. The conduit with a sluice gate had a higher air-demand ratio than the conduit with a radial gate. The air-demand ratio increased as the Froude number increased, and the air-demand ratio decreased as the gate opening rate increased. The highest air-demand ratio of 7.28 was obtained in the 60×100 rectangular cross-sectional conduit at a sluice gate with a 10% gate opening rate and 4 m conduit length.

4. CONCLUSIONS

Gated conduits carry high-velocity air-water mixtures. Predicting the air-demand ratio in a gated conduit is essential to ensure the proper design and operation of hydraulic structures. In this study, the effect of the gate type of a high-head conduit on the air-demand ratio was investigated. Based on the results of this study, the following conclusions were made.

- Gate type has a significant effect on the air-demand ratio. However, the gate type did not have a significant effect on the air-demand ratio with respect to conduit cross-sectional geometry.
- For all conduit cross-sectional geometries, gate opening rates, and conduit lengths, the conduit with a sluice gate had a higher air-demand ratio than the conduit with a radial gate.
- One of the most important parameters affecting the air-demand ratio was the Froude number. The air-demand ratio increased as the Froude number increased.

- The air-demand ratio decreased as the gate opening rate increased in the conduit with both a sluice gate and a radial gate.
- Among all conduit cross-sectional geometries, the highest air-demand ratio was 7.28 in the 60×100 rectangular cross-sectional conduit with a sluice gate at 10% gate opening rate and 4 m conduit length.
- The detailed data from this study provides a good basis for the development of numerical models.
- Several models at different scales should be tested to determine if scale effects are present. In addition, these results should be compared to the prototype data.
- Tests should be conducted to investigate the effect of changes in the conduit slope.
- In future studies, the conduit should be made of transparent material to allow visualization of the flow.
- In the case of free-surface flow, further research is needed to better understand the effect of gate type on the air-demand ratio.
- Future studies should determine the maximum air velocities that will cause undesirable vibrations.

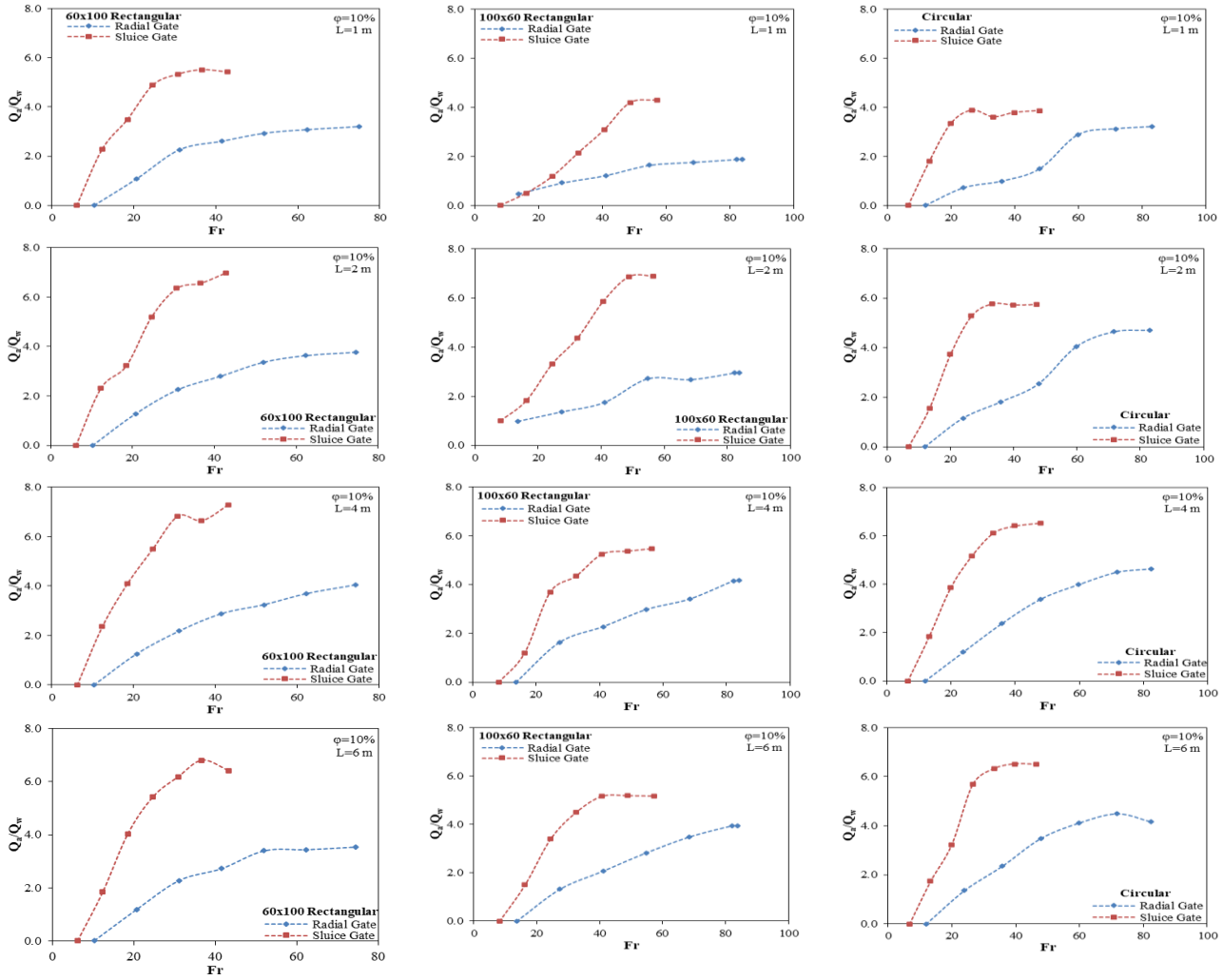
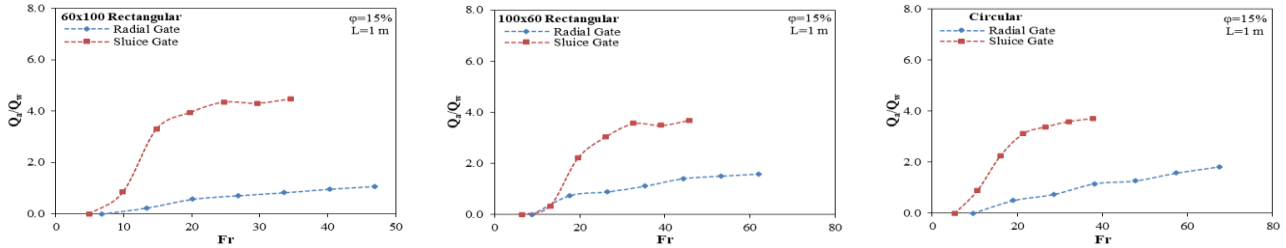


Figure 5. Variation of Q_a/Q_w with Froude number in three different conduit cross-sections for φ=10% and L=1, 2, 4, 6 m



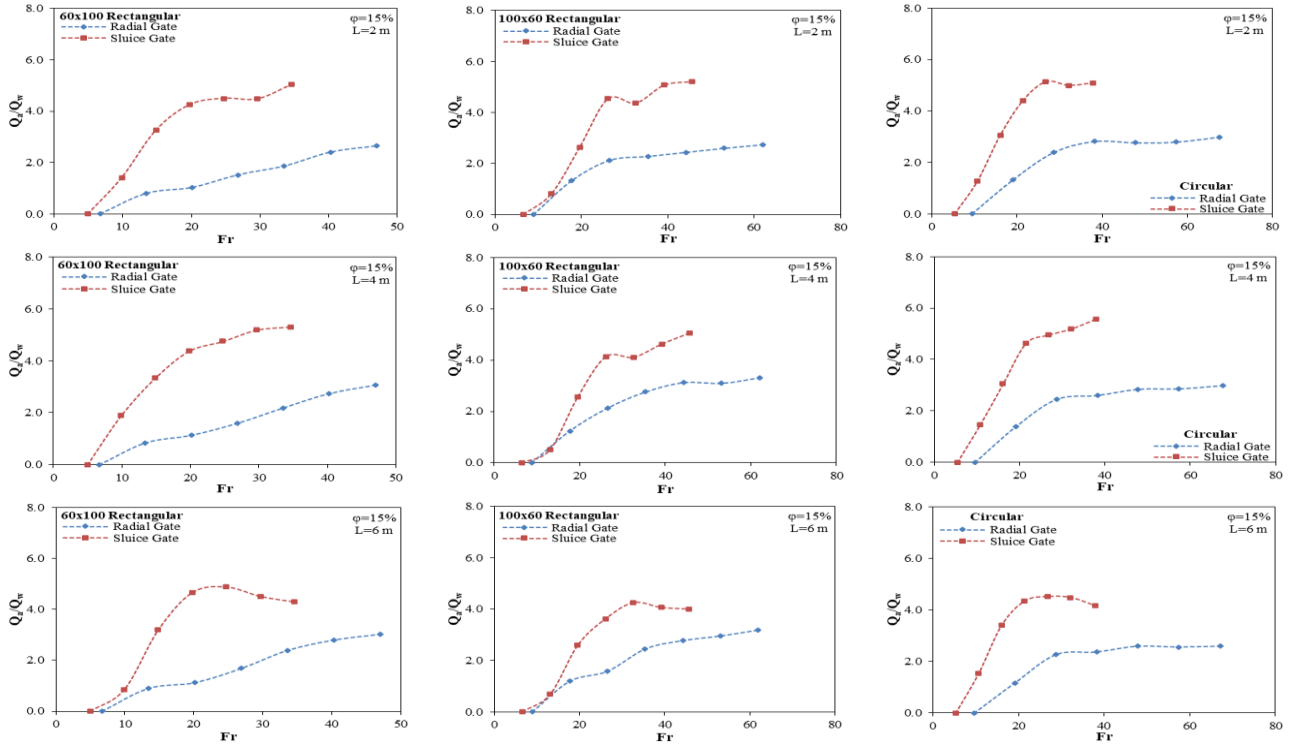


Figure 6. Variation of Q_a/Q_w with Froude number in three different conduit cross-sections for φ=15% and L=1, 2, 4, 6 m

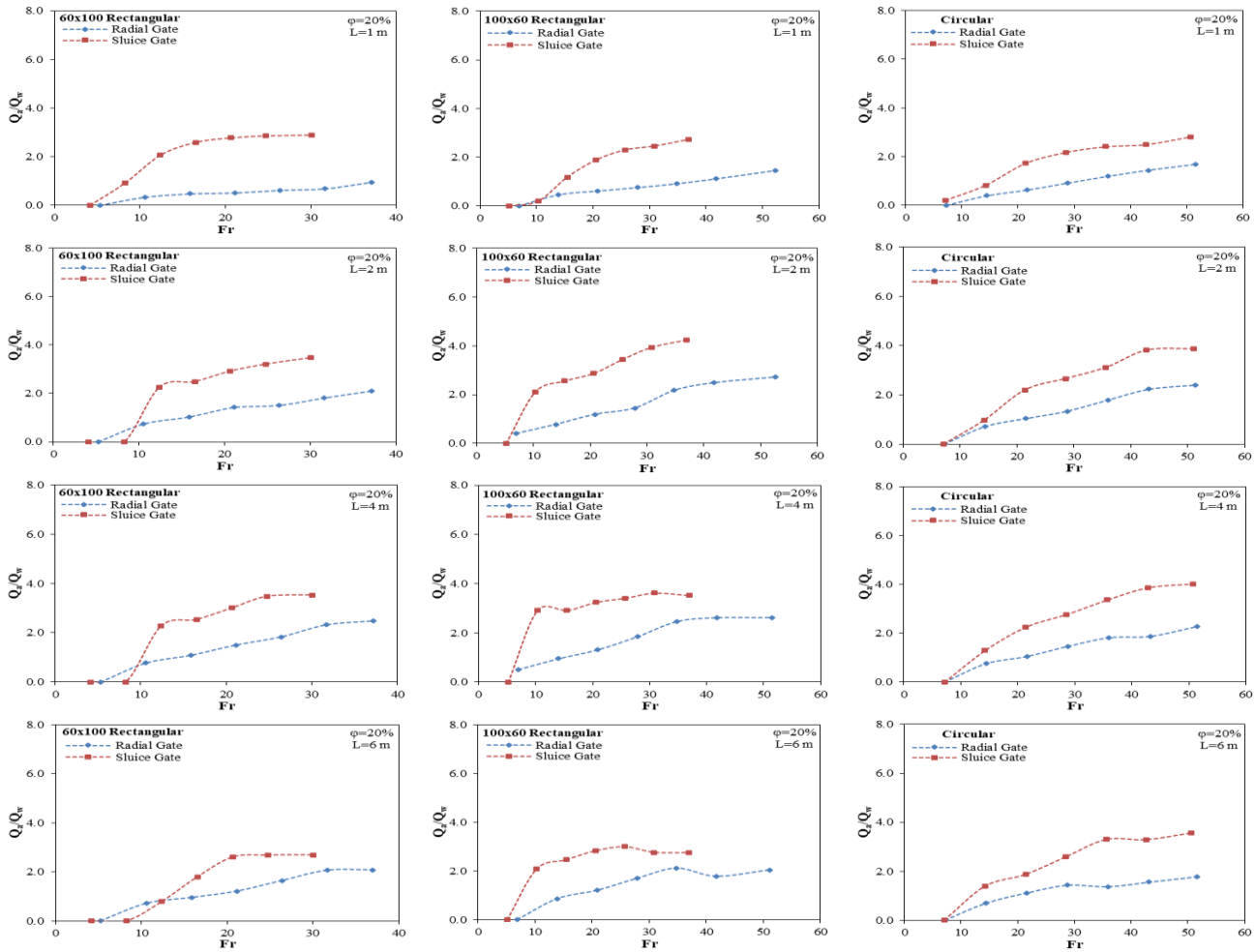


Figure 7. Variation of Q_a/Q_w with Froude number in three different conduit cross-sections for φ=20% and L=1, 2, 4, 6 m

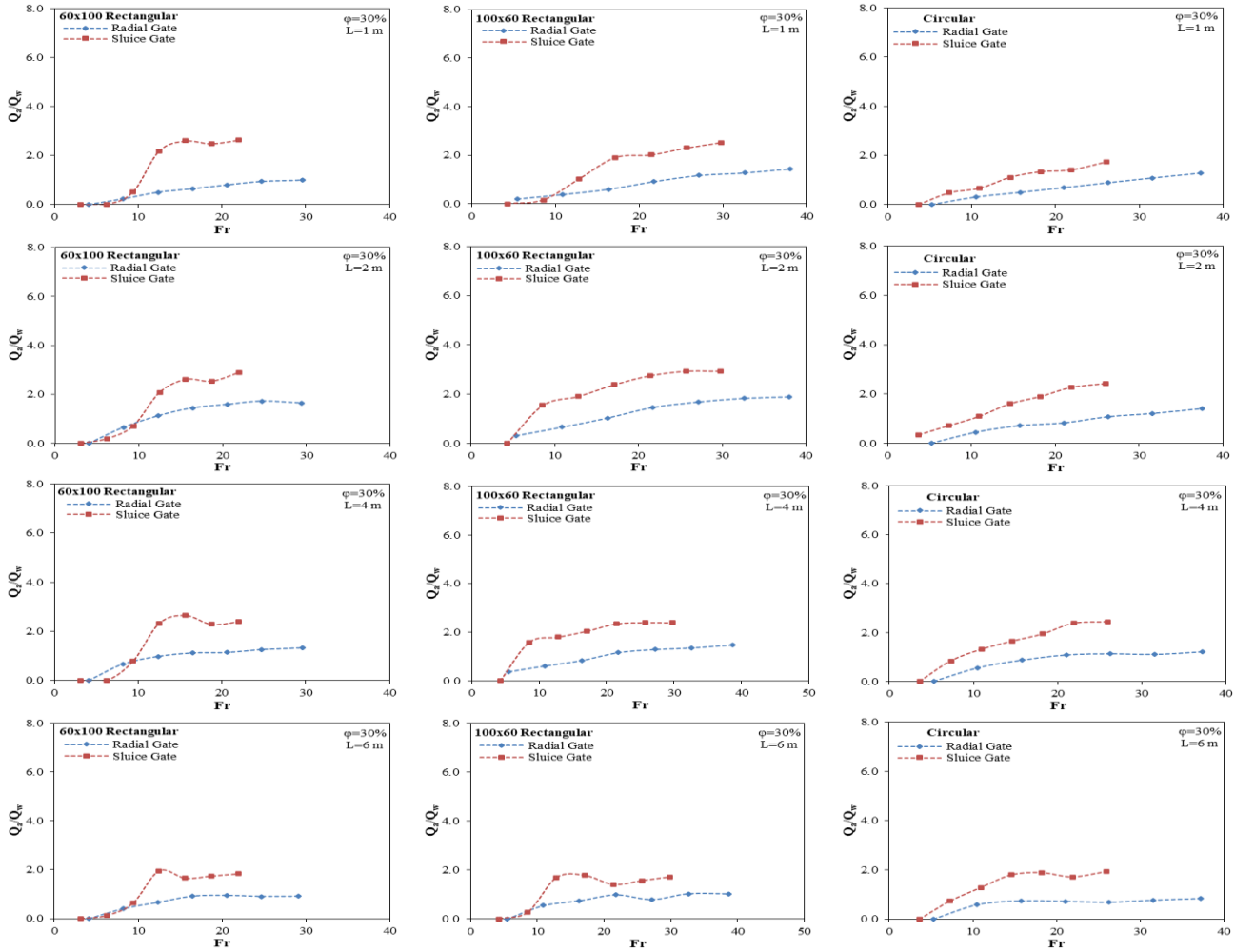
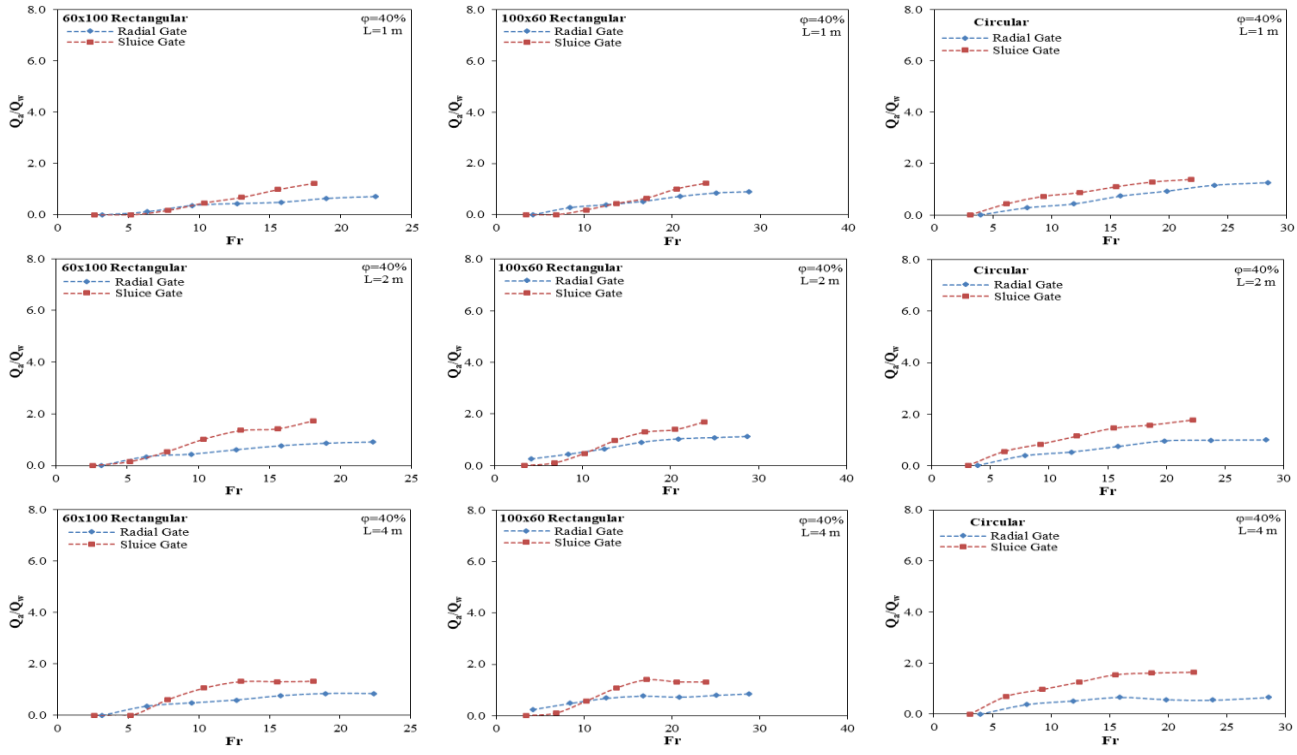


Figure 8. Variation of Q_a/Q_w with Froude number in three different conduit cross-sections for φ=30% and L=1, 2, 4, 6 m



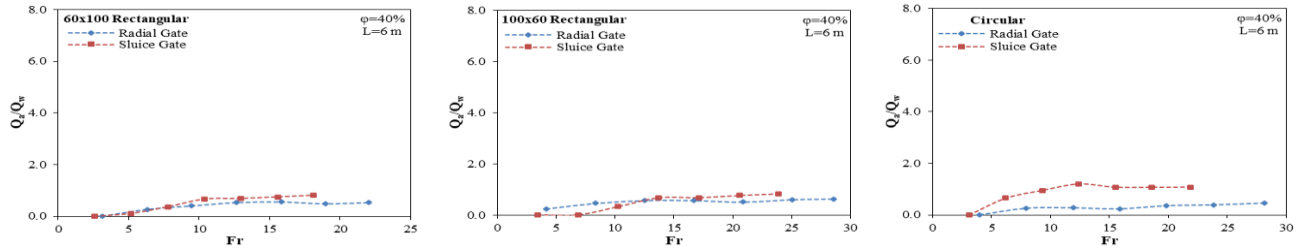


Figure 9. Variation of Q_a/Q_w with Froude number in three different conduit cross-sections for φ=40% and L=1, 2, 4, 6 m

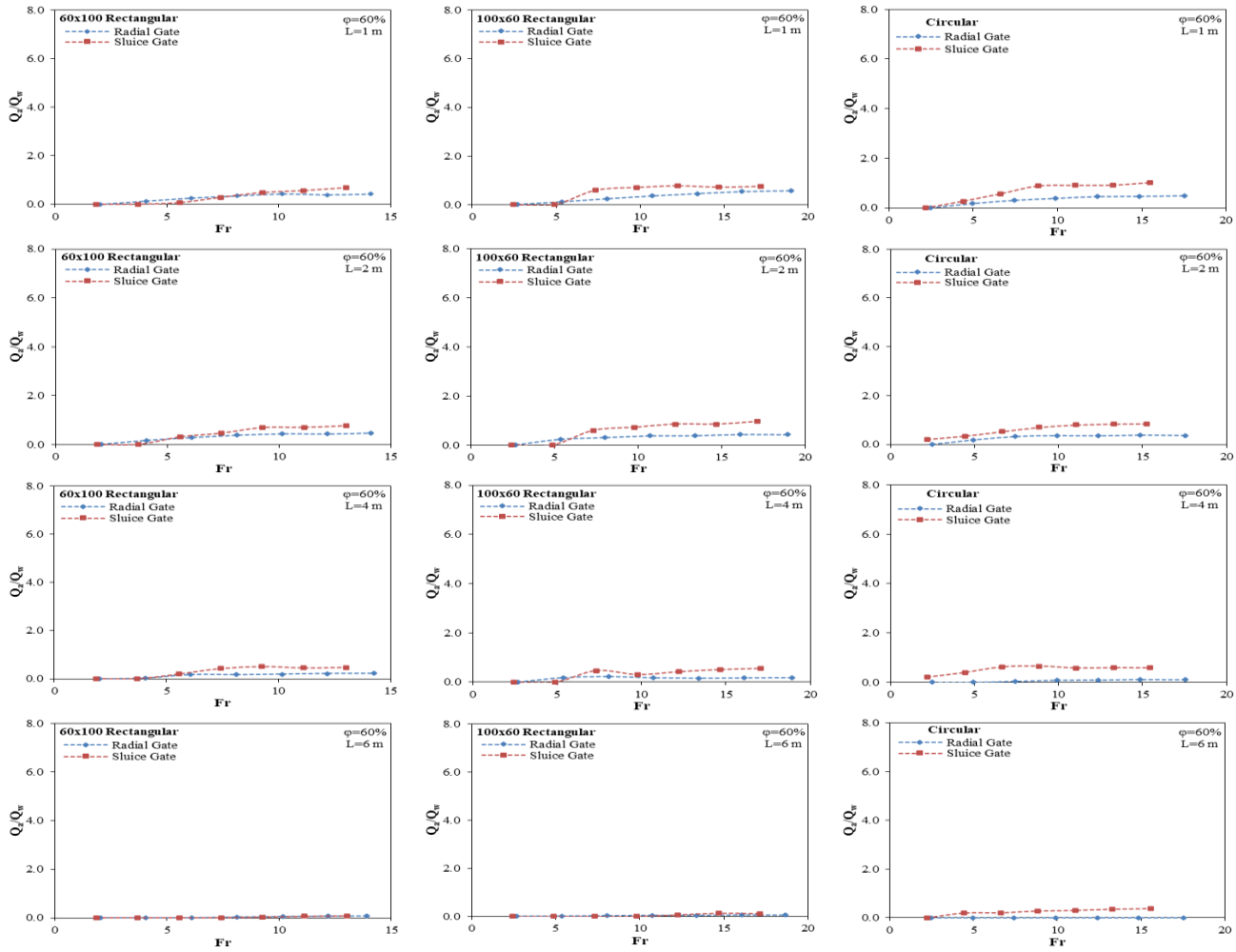


Figure 10. Variation of Q_a/Q_w with Froude number in three different conduit cross-sections for φ=60% and L=1, 2, 4, 6 m

Symbols

Fr	Froude number based on effective depth in conduit
g	gravitational acceleration
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
V	water flow velocity at gate location
h_e	effective depth
β	air-demand ratio (Q_a/Q_w)
φ	ratio of water flow cross-sectional area to conduit cross-sectional area

Acknowledgments

The authors thank the Scientific and Technological Research Council of Turkey (TÜBİTAK) for the financial support of the research project (Ref. No. 215M046).

References

Aydin, A.B., Baylar, A., Ozkan, F., Tuna, M.C. and Ozturk, M., 2021. Influence of cross-section geometry on air demand ratio in high-head conduits with a radial gate. Water Supply, 21(8), pp. 4086-4097.

Aydin, A.B., Baylar, A., Ozkan, F., Tuna, M.C. and Ozturk, M., 2023. Investigation of the geometry effect on air-demand ratio in conduits with a sluice gate. Proceedings of the Institution of Civil Engineers-Water Management, doi: 10.1680/jwama.22.00048.

Aydin, A.B., Tuna, M.C. and Baylar, A., 2022. Application of gated conduits for fertigation in irrigation systems. Water Practice and Technology, 17(7), pp. 1515-1522.

Baylar, A. and Batan, M., 2010. Usage of artificial intelligence methods in free flowing gated closed conduits for estimation of oxygen transfer efficiency. Advances in Engineering Software, 41(5), pp. 729-736.

Baylar, A., Ozkan, F. and Tuna, M.C., 2021. The effect of cross-section variation of high head gated conduits on aeration performance. Project No: 215M046, The Scientific and Technological Research Council of Turkey.

Baylar, A., Ozkan, F., Yildirim, C.B., Aydin, A.B., Tuna, M.C. and Ozturk, M., 2022. The role of cross-sectional geometry of high-head gated conduit in oxygen transfer efficiency. Water and Environment Journal, 36(3), pp. 372-379.

Baylar, A., Unsal, M. and Ozkan, F., 2010. Hydraulic structures in water aeration processes. Water, Air, and Soil Pollution, 210(1), pp. 87-100.

Campbell, F.B. and Guyton, B., 1953. Air-demand in gated outlet works. Proceedings of the 5th International Association of Hydraulic Research Congress, Minnesota, USA, 1-4 September, pp. 529-533.

Giesecke, J., Heimerl, S. and Mosonyi, E., 2014. Wasserkraftanlagen - Planung, Bau und Betrieb. 6th Edition, Springer Vieweg.

Haindl, K. and Sotornik, V., 1957. Quantity of air drawn into a conduit by the hydraulic jump and its measurement by gamma-radiation. Proceedings of the 7th International Association of Hydraulic Research Congress, Lisbon, Portugal, 7-9 January, pp. D31.1- D31.7.

Hohermuth, B., 2017. Air demand of high-head bottom outlets. Proceedings of the 37th IAHR World Congress, Kuala Lumpur, Malaysia, 13-18 August, pp. 2956-2965.

Hohermuth, B., 2019. Aeration and two-phase flow characteristics of low-level outlets. PhD thesis, ETH Zurich, Switzerland.

Hohermuth, B., Schmocker, L. and Boes, R.M., 2020. Air demand of low-level outlets for large dams. Journal of Hydraulic Engineering, ASCE, 146(8), pp. 04020055.

Kalinske, A.A. and Robertson, J.M., 1943. Closed conduit flow. Transactions of the American Society of Civil Engineers, ASCE, 108(1), pp. 1435-1447.

Mortensen, J.D., 2009. Factors affecting air entrainment of hydraulic jumps within closed conduits. MSc Thesis, Utah State University, Logan, Utah.

Mortensen, J.D., Barfuss, S.L. and Johnson, M.C., 2011. Scale effects of air entrained by hydraulic jumps within closed conduits. Journal of Hydraulic Research, 49(1), pp. 90-95.

Mortensen, J.D., Barfuss, S.L. and Tullis, B.P., 2012. Effects of hydraulic jump location on air entrainment in closed conduits. Journal of Hydraulic Research, 50(3), pp. 298-303.

Mortensen, J.D. and Kubitschek, J.P., 2016. Effects of hydraulic jump motion on air entrainment in closed conduits. 6th International Symposium on Hydraulic Structures, Portland, Oregon, USA, 27-30 June, pp. 511-518.

Novak, P., Moffat, A.I.B., Nalluri, C. and Narayanan, R., 2007. Hydraulic Structures. 4th Edition, CRC Press, London, https://doi.org/10.1201/9781315274898

Oveson, D.P., 2008. Air demand in free flowing gated conduits. MSc Thesis, Utah State University, Logan, Utah.

Ozkan, F., Baylar, A. and Ozturk, M., 2006a. Air entrainment and oxygen transfer in high-head gated conduits. Proceedings of the Institution of Civil Engineers-Water Management, 159(2), pp. 139-143.

Ozkan, F., Baylar, A. and Ozturk, M., 2010. Closure of "Air entraining and oxygen transfer in high-head gated conduits". Proceedings of the Institution of Civil Engineers-Water Management, 163(2), pp. 103-104.

Ozkan, F., Baylar, A. and Tugal, M., 2006b. The performance of two phase flow systems in pond aeration. International Journal of Science and Technology, 1(1), pp. 65-74.

Ozkan, F., Demirel, I.H., Tuna, M.C. and Baylar, A., 2015. The effect of length of free-surface gated circular conduit on air-demand ratio and aeration efficiency. Water Science and Technology: Water Supply, 15(6), pp. 1187-1192.

Ozkan, F., Tuna, M.C., Baylar, A. and Ozturk, M., 2014. Optimum air-demand ratio for maximum aeration efficiency in high-head gated circular conduits. Water Science and Technology, 70(5), pp. 871-877.

Rajaratnam, N., 1962. An experimental study of air entrainment characteristics of the hydraulic jump. Journal of the Institution of Engineers, 42(7), pp. 247-273.

Safavi, K., Zarrati, A.R. and Attari, J., 2008. Experimental study of air demand in high head gated tunnels. Proceedings of the Institution of Civil Engineers-Water Management, 161(2), pp. 105-111.

Sharma, H.R., 1976. Air-entrainment in high head gated conduits. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, ASCE, 102(11), pp. 1629-1646.

Speerli, J., (1999), Air entrainment of free-surface tunnel flow, Proceedings of the 28th IAHR World Congress, Graz, Austria, 22-27 August.

Speerli, J. and Hager, W.H., 2000. Air-water flow in bottom outlets. Canadian Journal of Civil Engineering, 27(3), pp. 454-462.

Tuna, M.C., Ozkan, F. and Baylar, A., 2014. Experimental investigations of aeration efficiency in high head gated circular conduits. Water Science and Technology, 69(6), pp. 1275-1281.

U.S. Army Corps of Engineers, 1964. Air-Demand-Regulated Outlet Works, In: Hydraulic Design Criteria. USACE, Chart 050-1.

Unsal, M., Baylar, A., Tugal, M. and Ozkan, F., 2008. Increased aeration efficiency of high-head conduit flow systems. Journal of Hydraulic Research, 46(5), pp. 711-714.

Unsal, M., Baylar, A., Tugal, M. and Ozkan, F., 2009. Aeration efficiency of free-surface conduit flow systems. Environmental Technology, 30(14), pp. 1539-1546.

Unsal, M., Baylar, A., Kayadelen, C. and Ozkan, F., 2014. The modeling of oxygen transfer efficiency in gated conduits by using genetic expression programming. Journal of Engineering Research, 2(2), pp. 15-28.

Wisner, P., 1965. On the role of the Froude criterion for the study of air entrainment in high velocity flows. Proceedings of the 11th IAHR Congress, Leningrad, USSR, 6-11 September, Paper 1.15.