JHE Journal of Hydrosciences and Environment

Effect of Upstream Sedimentation on Hydraulic performance of Cylindrical Weirs Under Free and Submerged Conditions

M. Esmaeili Varaki[1,*], N. Pornematolahi[2]

1,. Assistant Professor, Department of Water Engineering, University of Gilan, Gilan, Iran. (Corresponding author).*
2. M.Sc. Student, Department. of Water Engineering, Faculty of Agriculture Science, University of Guilan, Gilan, Iran.

ARTICLEINFO

Article history:

Received: *26 August 2019*
Accepted: *2 December 2019*

Keywords:
Cylindrical weirs,
Discharge coefficient of weir,
Energy loss,
LST,
Pressure distribution,
Upstream sedimentation.

ABSTRACT

This study experimentally investigated the effect of surface roughness of cylindrical weirs and upstream sedimentation on discharge coefficient (C_{dw}), pressure distribution, and energy loss under free and submerged overflow conditions. The tests were carried out for a non-sedimentation upstream channel bed and sedimentation levels of 2/3 of the weir height (P). Three different weir diameters and four degrees of weir surface roughness were used with a broad range of flow discharge. The comparison of C_{dw} of weirs indicated that C_{dw} can be reduced by 8 percent with the increase in the surface roughness from almost 0 to 4.5 mm height. Moreover, C_{dw} was increased up to 4 percent with the increase in the upstream sedimentation level to 2/3P. In addition, C_{dw} was reduced by 3-7 percent with the increase in roughness to 4.5 mm at the upstream sedimentation level of 2/3P. C_{dw} was also increased up to 5 percent and the energy loss was decreased to 15 percent as the weir diameter was increased from 0.15 to 0.25 m. It was found that, in all the studied weirs, the energy loss was increased up to 14 percent with the increase in surface roughness, whereas it was reduced by approximately 22 percent with the increase in the upstream sedimentation level to 2/3P. The comparison of the results showed that the pressure variation along the weir at the sedimentation level of 2/3P followed a similar trend to that obtained under non-sedimentation level conditions. However, the magnitude of pressure was reduced with the increase in the upstream sedimentation level. In addition, the effect of roughness on the pressure distribution over the weirs was greater at the downstream face than at the upstream face.

1. Introduction

Weirs are one of the oldest man-made hydraulic structures utilized in various dimensions, forms, and applications such as measuring and controlling flow discharges and regulating water levels in different irrigation systems (Emami et al., 2018). Cylindrical weirs are a type of broad-crested weir widely used to control water levels in rivers, water conveyance, and sewage canals. Investigations of flow patterns over cylindrical weirs show that the curvature and shape of weirs greatly influence their hydraulic performance. Cylindrical and circular-crested weirs have several advantages over other weirs including the stability of the flow pattern, ease of passing the floating debris over the weir, simple design, high flow discharge, large-scale design capability, and lower construction and operation costs (Beygipour and Bina, 2005).

During the nineteenth century, weirs were studied for the first time by Bazin (1898) in France and further researches were done by Creager (1917) and Rehbok (1929).

* Corresponding author's email:
esmaeili.varaki@yahoo.com

Bos (1976) presented rating curves of circular-crested weirs and noted that the curvature of over flow stream line caused a difference between broad and circular crested weirs. Using the momentum equation, Ramamurthy et al. (1992) obtained the deviation of pressure from the hydrostatic pressure on the crest of a circular-crested weir. Ramamurthy and Vo (1993b) found that the variation of the upstream slope does not modify the discharge coefficient of circular-crested weirs.

Beygipour and Bina (2005) studied flow hydraulic on circular-crested and cylindrical weirs. They concluded that increasing a weir head would increase the discharge coefficient of the weir. Using a flow function around a cylindrical weir, Heidarpour and Chamani (2006) determined the velocity distribution over the weir crest and proposed a mathematical model for calculating the discharge coefficient in circular-crested weirs. Heidarpour et al. (2008) used the potential flow theory in the upstream half of a cylindrical weir to determine the velocity distribution over its crest. They also proposed a correction factor for the pressure distribution over the weir crest. Othman et al. (2010) studied the effect of surface roughness of cylindrical weirs and its diameter on the discharge coefficient. Results showed that decreasing the weir diameter increased the discharge coefficient of the weir.

However, increasing surface roughness considerably reduced the discharge coefficient of the weirs. Esmaeili et al. (2010) compared the pressure and velocity data obtained from their experiments on cylindrical weirs and those obtained from the simulation by FLUENT software. Their results indicated a good agreement between the experimental and numerical data. Parilcova (2012) studied the effect of surface roughness on a broad-crested weir. They stated that the crest roughness had greater effect on the weir discharge coefficient than the downstream slope roughness. Masoudian and Gharahgezlou (2012) considered the characteristics of flow over different cylindrical weirs in a small-scale laboratory flume. The comparison of the results showed that the discharge coefficient of the weirs was increased by the increase in the relative head of flow, the Reynolds number, and the Weber number. Shabanlou and Khorami (2013) studied the hydraulic characteristics of cylindrical weirs and found that the relative energy loss was decreased by the increase in the upstream head of the weir. The discharge coefficient of combined free over-under flow on a cylindrical weir-gate was investigated by Severi et al. (2015) and empirical equations were developed.

Sedimentation along irrigation canals, especially near the hydraulic structures such as intake/offtake, is a major problem in the operation of irrigation networks, which considerably influences the performance of water distribution structures. Dizji and Mahmoudkhani (2009) studied the effect of suspended sediment of flow on the discharge coefficient of triangular, rectangular, ogee, and overfall weirs. The comparison of the results revealed that the suspended sediment reduced the discharge coefficient of weirs, especially at low flow rates. Dastorani and Nasrabadi (2012) studied the effect of upstream sedimentation on the flow discharge coefficient of ogee spillway. They concluded that an increase in sedimentation reduced the discharge coefficient of the weir from 2.25 to 1.69. The same conclusion was reported by Asgarinezhad (2013) in a study on the effect of upstream sedimentation level and bed slope on the discharge coefficient of triangular weirs. Shafaattalab et al. (2016) studied the effect of the upstream sedimentation level on the hydraulic performance of trapezoidal labyrinth weirs and found that increasing the upstream bed level to 90 percent of the weir height reduced the discharge coefficient of weirs.

As already mentioned, sediment deposition upstream of weirs is a common problem, affecting the hydraulic performance of weirs. In this research, the effect of upstream sedimentation levels and surface roughness of the cylindrical weirs was investigated on discharge coefficient, pressure distribution, and relative energy loss experimentally under free and submerged conditions.

2. Materials and Methods

2.1 Dimensional analysis

The hydraulics of flow over cylindrical weirs could be considered in different aspects. Based on the objective of the research, discharge passing from cylindrical weirs can be written as:

$$Q_w = f_1(V, H_1, H_w, b_w, \mu, g, S_0, D, \rho, \delta, \sigma, \varepsilon, S) \quad (1)$$

in which H_1 is the water depth at the upstream of the weir, H_w is the total head of the upstream, b_w is the weir length, μ is the fluid dynamic viscosity, g is the gravity acceleration, S_0 is the channel slope, Q_w is the flow discharges, D is the diameter of the weir, ρ is the flow density, ε is the contraction coefficient of upstream walls of weir, δ is the surface roughness height, S, σ is the upstream sedimentation level and is the surface tension.

By using Buckingham's theory in dimensional analysis, Eq. 1 can be rephrased as the following functional equation.

$$\frac{Q_w}{g^{0.5}H_w^{1.5}b_w} = f_2\left(\frac{V^2}{gH_1}, \frac{\mu}{\rho V H_1}, \frac{\sigma}{\rho V^2 H_1}, \frac{H_1}{P}, \frac{H_w}{H_1}, \frac{H_1}{b_w}, \frac{\varepsilon}{H_1}, \frac{S}{P}, \delta, S_0\right) \quad (2)$$

Bos (1976) presented the following equation for the flow passing through a cylindrical weir:

$$Q_w = C_{dw} b_w \frac{2}{3}\sqrt{\frac{2}{3}g}H_w^{\frac{3}{2}} \quad (3)$$

in which C_{dw} is the discharge coefficient.

By substituting Eq. 3 into Eq. 2and its manipulation, the following equation is obtained:

$$C_{dw} = f_3\left(Fr, Re, W_e, \frac{S}{P}, \frac{H_w}{P}, \frac{H_w}{H_1}, \frac{b_w}{H_1}, \frac{\varepsilon}{H_1}, \delta, S_0\right) \quad (4)$$

in which *Re*, *We* and *Fr* are the Reynolds, Weber and Froude numbers, respectively. The upstream head of the flow on the crest of the weir was more than 3 cm and the flow regime was turbulent. Therefore, the effect of the viscous forces and surface tension are negligible. Also, δ is equal to unit since the channel width and weir length were the same. In all experiments, the channel bed slope was horizontal. Eq. 4 could be revised in from of Eq. 5 to analysis of experimental results.

$$C_{dw} = f\left(Fr, \frac{H_w}{H_1}, \frac{H_w}{P}, \frac{\varepsilon}{H_1}, \frac{S}{P}\right) \quad (5)$$

2.2. Laboratory equipment and experimental procedure

The experiments for the present study were carried out at the Hydraulic and Physical Hydraulic Modeling Laboratory of the University of Guilan, Rasht, Iran, using a rectangular recirculation flume that was 8.6 m long, 0.92 m wide, and 1 m deep (Fig. 1). The walls and bed of the flume were made of glass and iron, respectively.

A centrifugal pump (maximum flow rate=70 l/s) was used to supply water to the flume. The flow rate was measured by an ultrasonic flowmeter with an accuracy of ±0.1 l/s. A flow straightener was placed at the entrance of the flume to avoid inlet effects on the flow approaching the weirs. To regulate the depth of water in the flume, a butterfly gate was installed at the outlet section of flume.

According to the method proposed by Kirkgöz and Ardichoğlu (1997), flow development length can be estimated as equal to $y\times(76\text{-}0.0001\times Re/Fr)$. Here, Re is the Reynolds number computed as $4UR/\nu$ (with R as the hydraulic radius) and Fr is the Froude number equal to $U/(gy)^{0.5}$. For the experimental conditions that will be described later, the development length was obtained to be 4.4 m. Therefore, the weirs were located at about 5 m from the flume inlet.

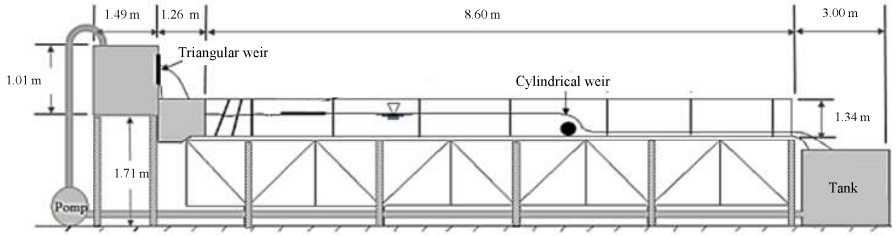


Fig.1. A sketch of the laboratory flume

The cylindrical weirs were made of PVC pipes (diameter: 0.15, 0.20, and 0.25 m). Uniform gravel particles (diameters: 1.5, 3, and 4.5 mm) were used to produce surface roughness of the weirs. The particles were glued on thin fabric by which they were glued on the surface of weirs (Fig. 2).



Fig. 2. Photos of the laboratory flume and the cylindrical weir

To measure static pressure over the weir, piezometers were installed in the centerline of the weir and mounted on a specially-designed board.

For each test, by regulating the flow discharge, the upstream head of the flow was measured at a location of 0.4 m of upstream of the weirs where the curvature of the flow was negligible using a digital point gage with an accuracy of ±0.01 mm. Furthermore, water surface profile over the weirs, as well as water levels at piezometers on board, was measured by taking photos with a digital camera (a Power Shot model SX500) and digitizing via the Grapher 9 software program. The experiments were conducted under free and submerged conditions. Table 1 shows the ranges of experimental parameters.

Table 1. Range of experimental parameters

Parameters	Symbol and unit	range
Weir diameter	D (m)	15-25
Flow discharge	Q_w (l/s)	16-66
Total upstream head	H_w (cm)	0.045- 0.115
Roughness height	ε (mm)	1.5-4.5
Sedimentation height	S	0-2P/3

3. Results and Discussion

3.1 Effects of weir surface roughness and upstream sedimentation levels on weir rating-curve and discharge coefficients

The comparison of the results showed that as the surface roughness of the weirs is increased from PVC to ε =4.5 mm, the upstream head increases by 8 and 5 percent near minimum and maximum flow discharges, respectively. In other words, by increasing the roughness, the velocity of the flow on the weir decreases and the upstream head of the water increases. In addition, increasing the weir diameter from 150 mm to 250 mm reduces the flow curvature and increases H_w by up to 3 percent (Fig. 4).

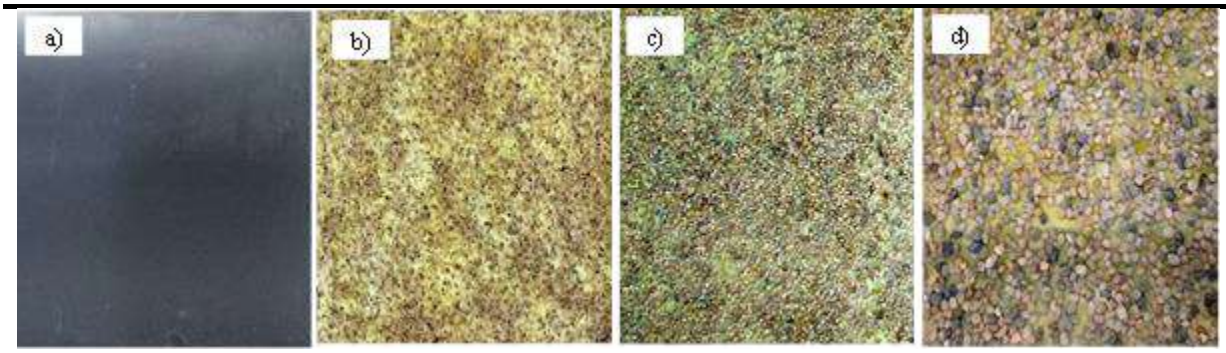


Fig. 3. Photos of the surface roughness of cylindrical weirs, a) smooth surface (PVC), b) ε= 1.5 mm,c) ε= 3mm, and d) ε= 4.5 mm

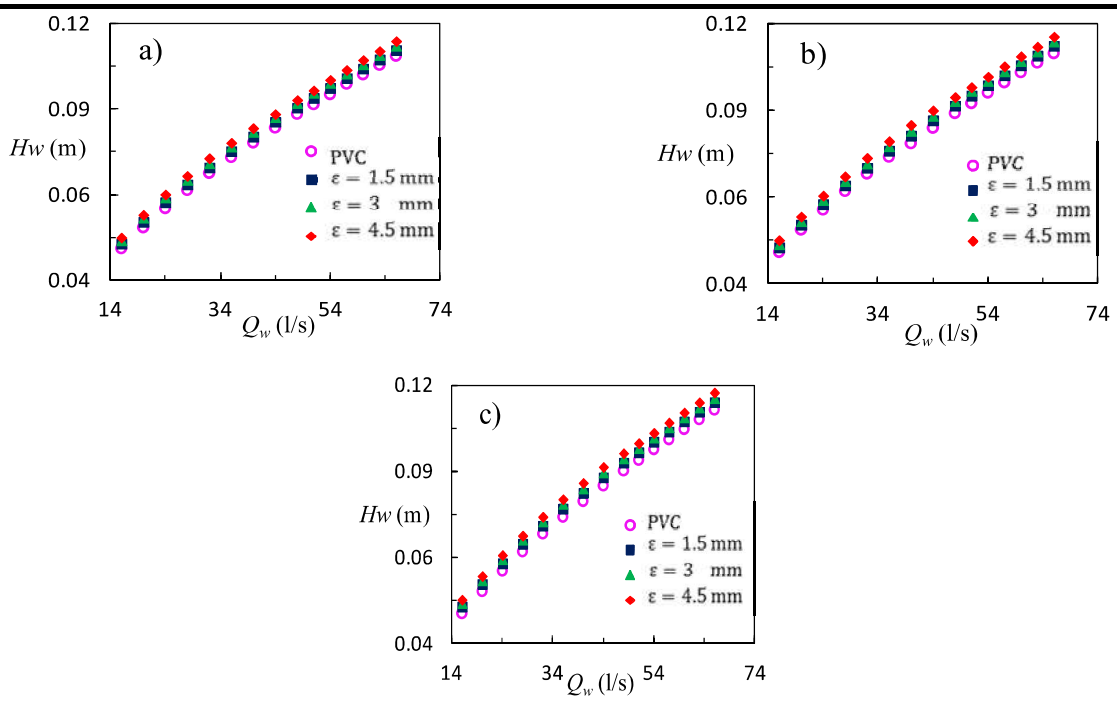


Fig. 4. Head-discharge curves for different surface roughnesses and diameters of the weirs, a) D=0.15 m, b) D=0.2 m, and c) D=0.25 m

As the upstream sedimentation level of the weir increases, the approach flow velocity is also increased, consequently increasing the contribution of the velocity head to the total velocity head. As a result, the depth of the flow at the upstream of the weir is reduced. By increasing the sedimentation level from 0 to 2/3P (for a PVC surface), the upstream head is reduced by 2 percent on average and the discharge coefficient increases by approximately 3 percent. At an upstream sedimentation level of 2/3P, increasing the roughness to 4.5 mm increases the upstream head by 5 percent and decreases the discharge coefficient by 7 percent (Fig. 5).

Figures 6 and 7 show the effect of roughness on the discharge coefficient of the weirs with different diameters for S=0 under free and submerged downstream flow conditions, respectively. The comparison of the results indicates that the discharge coefficient of the weirs increases as the discharge or relative upstream head (H_w/P) increases. Furthermore, by increasing the surface roughness to 4.5 mm, the discharge coefficient decreases by 8 and 7 percent in free and submerged downstream flow conditions, respectively. This trend was the same as the results presented by Othman et al. (2010) for the free flow conditions.

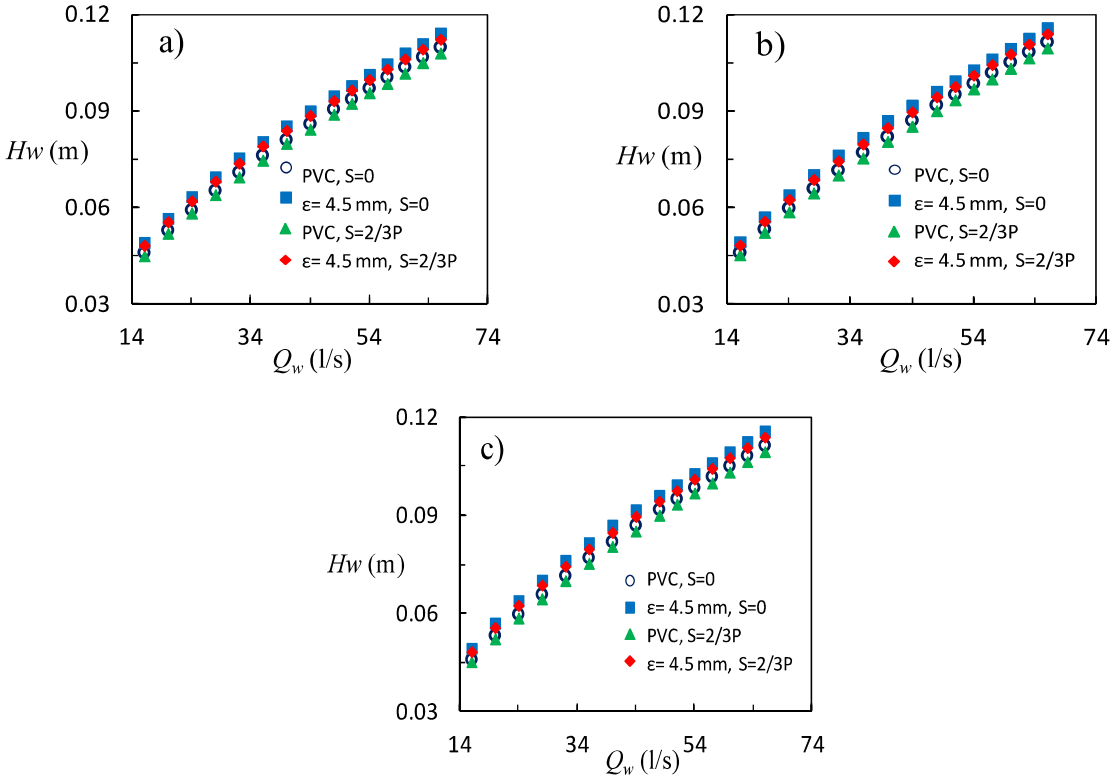


Fig. 5. The combined effect of surface roughness of weirs and upstream sedimentation on the rating curve for a) D=0.15 m, b) D=0.2 m, and c) D=0.25 m

The comparison of the results indicated that for all the three diameters of the cylindrical weirs and at a given surface roughness, the discharge coefficient of the weir under submerged flow conditions at the downstream was 5 to 8 percent lower than the corresponding value under the free flow conditions.

The comparison of the results indicated that increasing the diameter of cylindrical weirs decreased the parameter C_{dw}. It is believed that the resistance force acting on the cylindrical weirs have a direct relationship with the diameter of the weir. Therefore, increasing a weir diameter increases the upstream head, which in turn reduces the parameter C_{dw} at a given discharge. The same explanation applies to increasing the surface roughness of the weirs. The analysis of the results showed that increasing the weir diameter from 0.15 to 0.25 m reduced C_{dw} up to 5 percent on average.

The diagram in Fig. 9 shows the instantaneous effect of the upstream sedimentation level and surface roughness on C_{dw}. The comparison of the results indicates that by increasing the upstream sedimentation level to 2/3P, the parameter C_{dw} increases by about 4 percent. In addition, at an upstream sedimentation level of 2/3P, increasing the surface roughness to 4.5 mm reduced C_{dw} by roughly 4 to 7 percent.

3.2. Effect of surface roughness and upstream sedimentation on pressure distribution over the cylindrical weir

The pressure exerted on hydraulic structures is an important factor as it can cause cavitation, vibration, and structure instability. The curves in Figs. 10 and 11 show the distribution of pressure over cylindrical weirs under different flow rates and upstream sedimentation levels. The comparison of the results showed that at all flow discharges, the pressure head reduces as the flow moves over the weir due to the curvature of the streamlines. The reduction continues up to an angle of approximately 230-260 degrees, depending on the weir diameter. The lowest and the highest pressure heads occur at the highest and lowest flow rates, respectively. The velocity profile is two dimensional in the vicinity of the upstream face of the weir, implying that the velocity is represented by both horizontal and vertical components. At the upstream face of the weirs, the horizontal component assumes a greater magnitude than the vertical component. As flow approaches an angle of 180 degrees over the weirs, the horizontal velocity reaches its maximum magnitude. However, at the downstream face of the weirs, as the flow reaches an angle of 230-260 degrees, it is the vertical component that increases, consequently causing a dramatic reduction in the pressure head. In this scenario, a higher discharge corresponds to a lower pressure head.

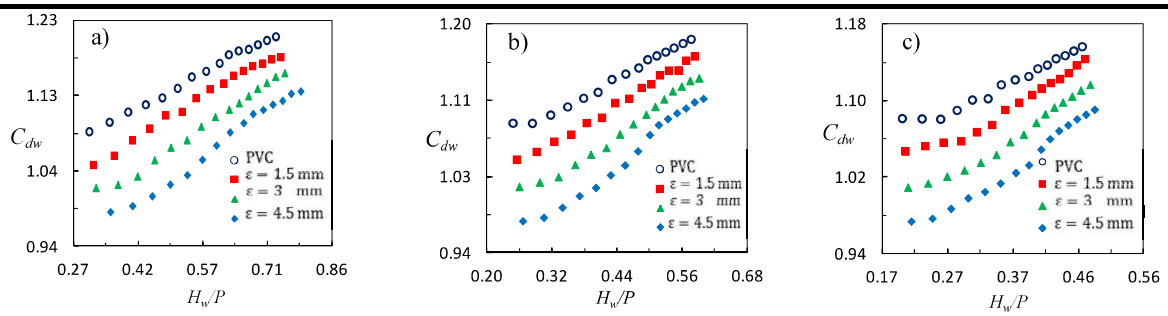


Fig. 6. The effect of surface roughness of weirs on C_{dw} for free downstream flow conditions, a) D=0.15 m, b) D=0.2 m, and c) D=0.25 m

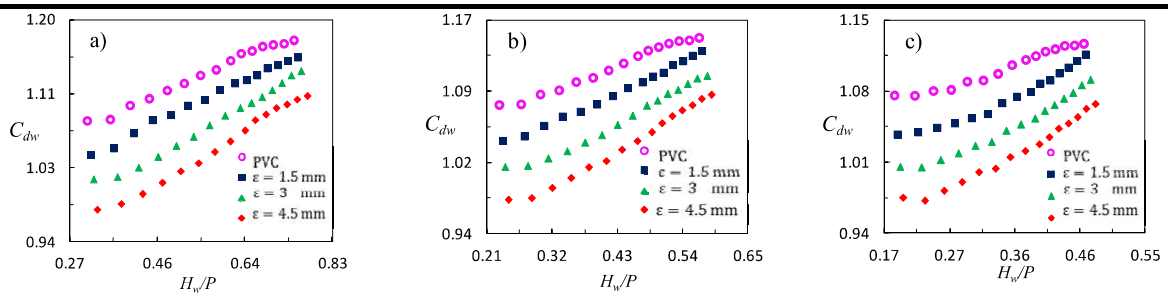


Fig. 7. The effect of surface roughness of weirs on C_{dw} for submerged downstream flow conditions, a) D=0.15 m, b) D=0.2 m, and c) D=0.25 m

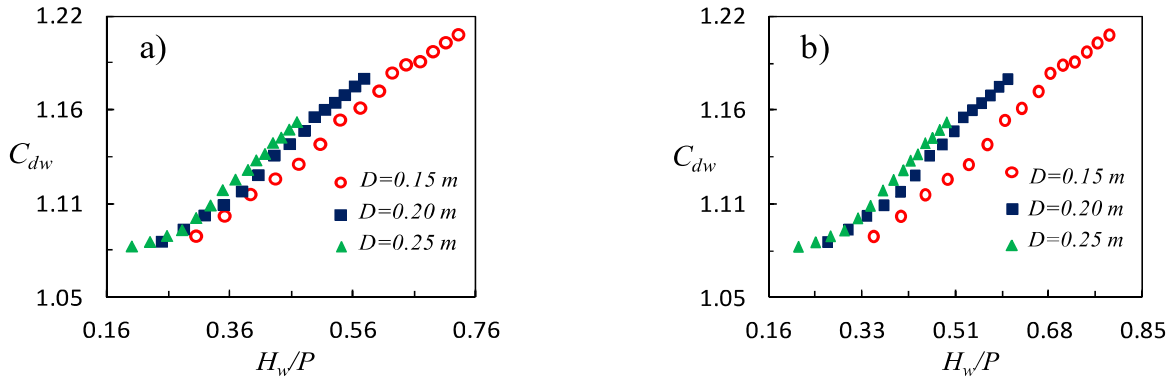


Fig. 8. The effect of weirs diameter on C_{dw} for free downstream conditions, a) PVC surface and b) ε =4.5 mm

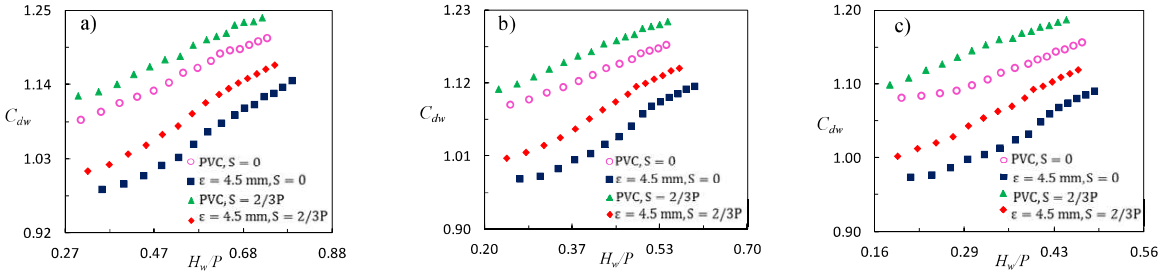


Fig. 9. The effect of surface roughness and upstream sedimentation level on C_{dw} under free downstream flow conditions, a) D=0.15 m, b) D=0.2 m, and c) D=0.25 m

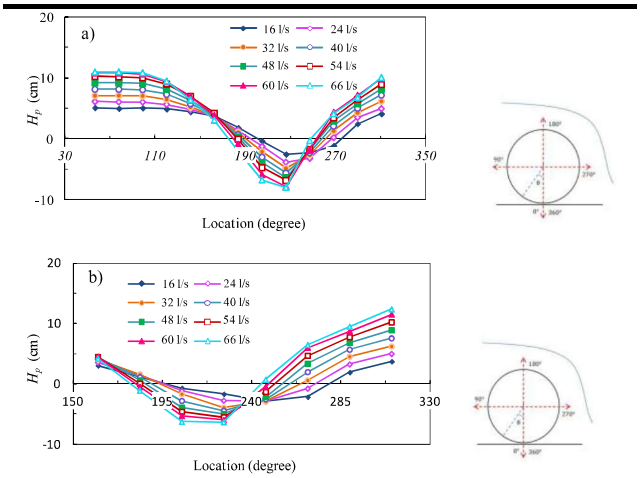


Fig. 10. Pressure variations on the cylindrical weir of D=0.15 m, a) S=0 and b) S=2P/3

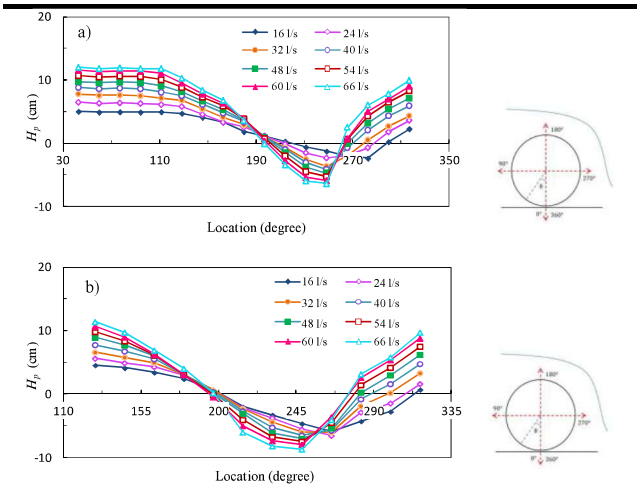


Fig. 11. Pressure variations on the cylindrical weir of D=0.20 m, a) S=0 and b) S=2P/3

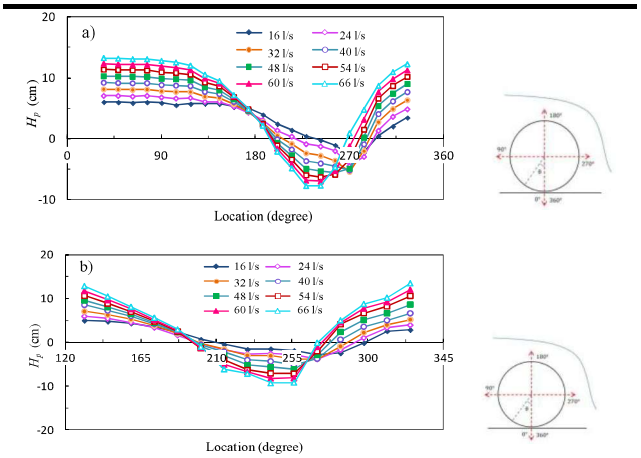


Fig. 12. Pressure variations on the cylindrical weir of D=0.25 m, a) S=0 and b) S=2P/3

The comparison of pressure variations along the weir at different upstream sedimentation levels (Fig. 13) showed that a higher upstream sedimentation level leads to a lower pressure head. As already mentioned, by increasing the upstream sedimentation level, the approaching flow velocity over the weirs increases. Therefore, over convex surfaces where the centrifugal acceleration is negative at a static pressure distribution, increasing the flow velocity causes further reduction in the pressure head.

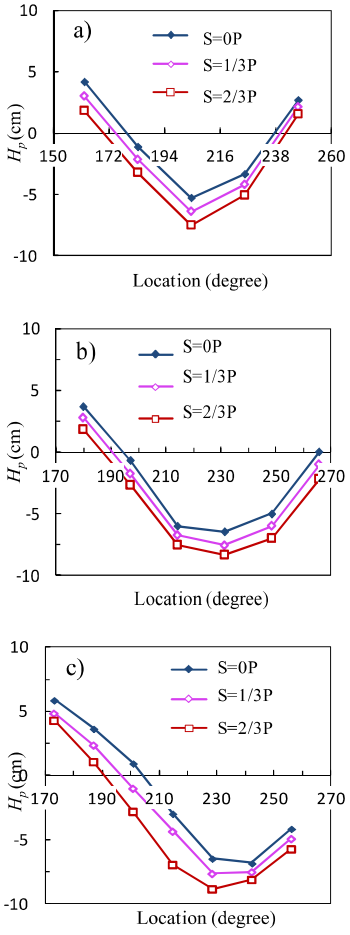


Fig.13. Pressure variations in the downstream face of the cylindrical weir for Q= 66 l/s, a) D=0.15 m, b) D=0.2 m, and c) D=0.25 m

Fig. 14 shows the effect of roughness on the pressure profile along the surface of the cylindrical weir with a diameter of D=0.25 m for different flow discharges (44 and 66 l/s) at S=0 and S=2/3P. The comparison of the results showed that increasing the roughness height increases the pressure head, particularly in regions experiencing negative pressure. In addition, at a downstream angle of 270 degrees and unlike the previous intervals, increasing the roughness decreases the pressure head because the tailwater depth is reduced due to the increase in energy loss.

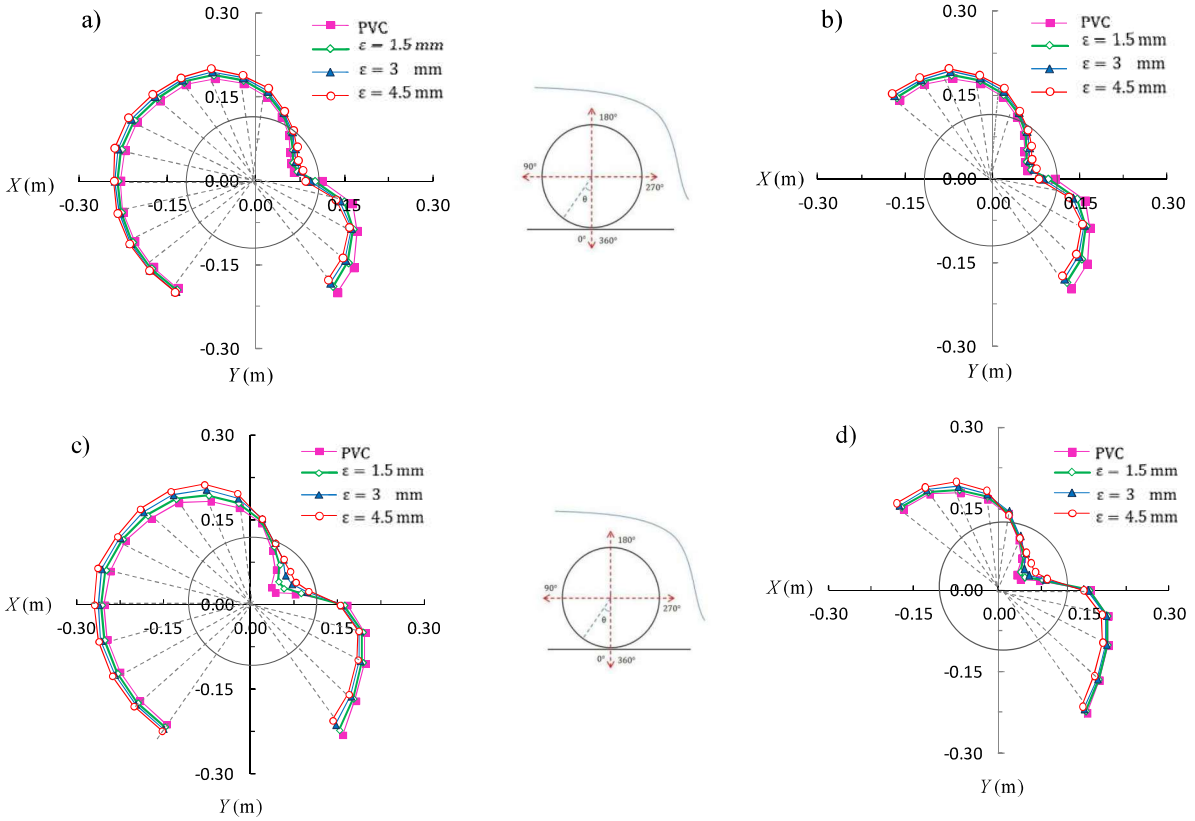


Fig. 14. Pressure variations on the cylindrical weir of D=0.25 m, a) Q= 44 l/s and S=0, b) Q= 44 l/s and S=2P/3, c) Q=66 l/s and S=0, and d) Q=66 l/s and S=2P/3

3.3. Effect of surface roughness and upstream sedimentation on energy loss of flow over the cylindrical weir

Fig. 15 shows the effect of weir diameter on energy loss at different weir surface roughnesses. The comparison of the results indicated that increasing the weir diameter from 0.15 to 0.25 m reduces energy loss by approximately 15 percent. It is believed that by increasing weir diameter, the form friction on the weirs is reduced, which in turn reduces the energy loss of the streamlines passing over the crest. Furthermore, for all weir surface geometries and roughness heights, increasing the flow discharge reduces energy loss due to the increase in flow velocity over the weir, which in turn reduces the pressure head at the downstream face of the weir.

Increasing the surface roughness of the weirs from PVC to a roughness height of 4.5 mm increases the friction loss of the flow and the pressure head over the downstream face of the weir. The comparison of the results showed that energy loss increases by about 14% (Fig. 16).

The comparison of the results at a given surface roughness showed that increasing the upstream sedimentation level to 2/3P reduces the energy loss by 22 percent on average. By increasing the upstream sedimentation level, the flow velocity over the weirs increases, thereby increasing the rate of reduction of pressure head at the downstream face of the weirs. As a result, the form friction and its corresponding energy loss over the cylindrical weirs are reduced.

3.4. Development of regression equation for discharge coefficient of the cylindrical weirs

The performance of a cylindrical weir is influenced by different geometric parameters including channel width, the diameter of the weir structure, roughness height, and different hydraulic parameters such as upstream sedimentation and downstream flow submergence conditions. Therefore, developing equations to predict the discharge coefficient of cylindrical weirs can be useful for designers.

To derive the regression models, a statistical analysis was conducted based on Eq. 5. The coefficient of determination (R^2), the model efficiency (EF), and the root mean square error (RMSE) were used to evaluate the performance of the models.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left|C_{d(Est)} - C_{d(Exp)}\right|^2}{n}} \qquad (6)$$

$$EF = \frac{\sum_{i=1}^{n}(C_{d(Est)} - \overline{C_{d(Exp)}})^2 - \sum_{i=1}^{n}(C_{d(Est)} - C_{d(Exp)})^2}{\sum_{i=1}^{n}(C_{d(Est)} - \overline{C_{d(Exp)}})^2} \quad (7)$$

where $C_{d(Est)}$ and $C_{d(Exp)}$ are the estimated and experimental discharge coefficients of the cylindrical weirs, respectively.

To extract regression equations, 70% of the experimental data was used for training and 30% for validation. Based on incomplete self-similarity, Eq. 9 had the best performance to estimate the desired output as shown in Fig. 18.

$$C_{d(Est)} = 0.9881 + 0.1677\left(\frac{H_w}{H_1}\right) + 0.1981\left(\frac{H_w}{P}\right) - 3.8393\left(\frac{\varepsilon}{H_1}\right) + 0.0173\left(\frac{S}{P}\right) \quad (8)$$

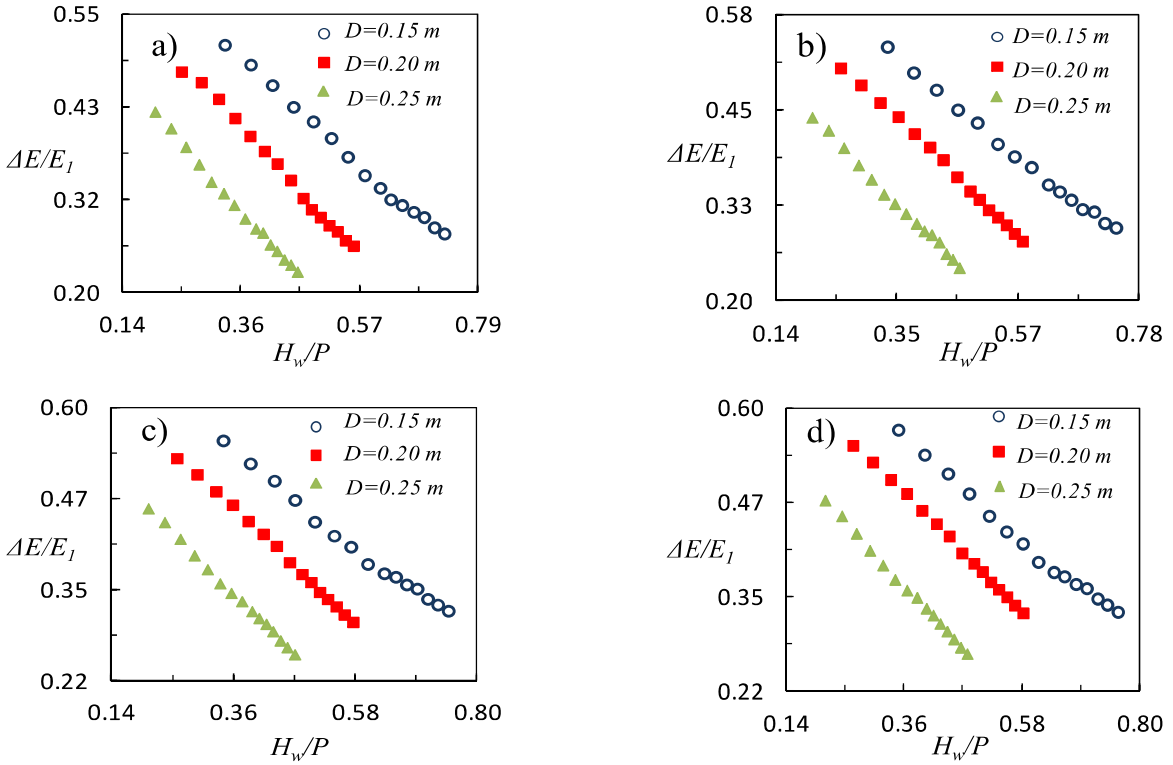
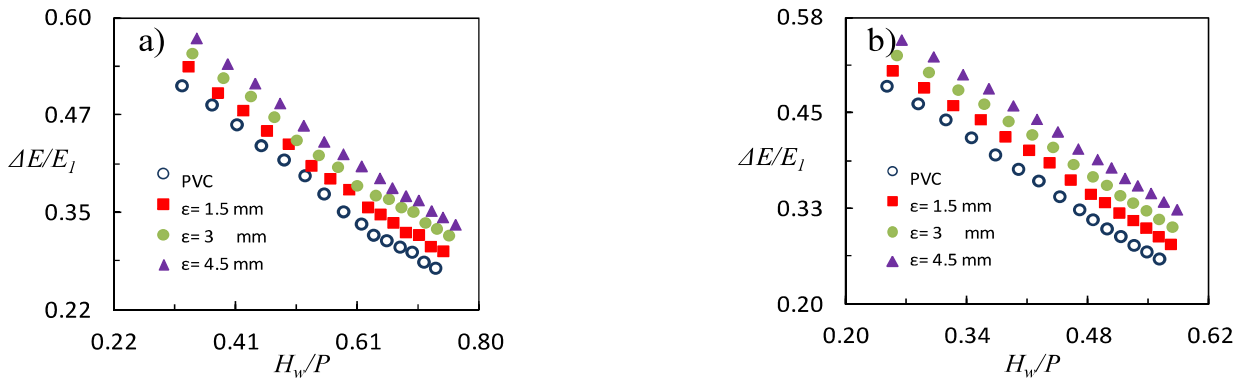


Fig. 15. The effect of weir diameter on relative energy loss a) PVC surface, b) ε =1.5 mm, c) ε =3 mm, and d) ε =4.5 mm



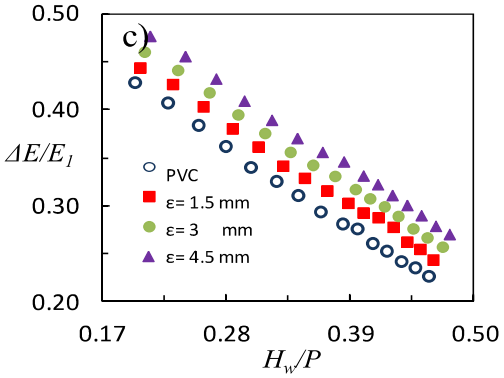


Fig. 16. Relative energy loss over the cylindrical weirs for various surface roughnesses and weir diameters, a) D=0.15 m, b) D=0.2 m, and c) D=0.25 m

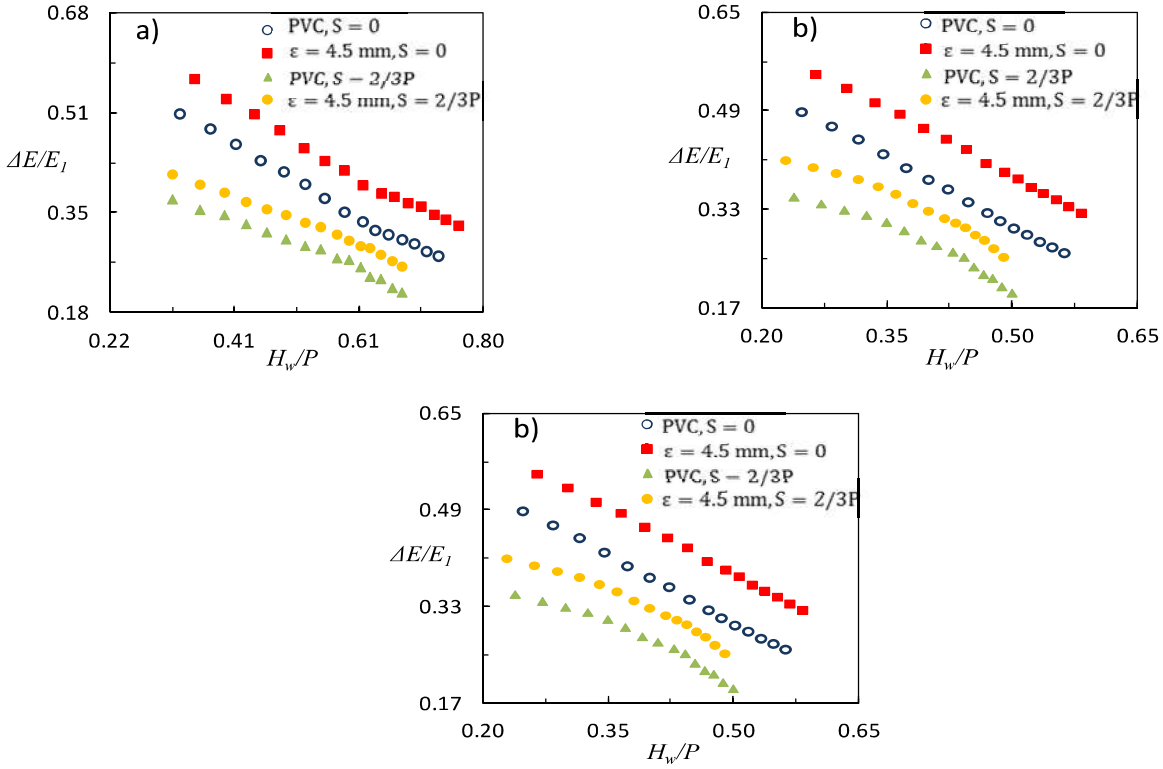


Fig. 17. The effect of roughness and sedimentation on relative energy loss over the cylindrical weirs, a) D=0.15 m, b) D=0.2 m, and c) D=0.25 m

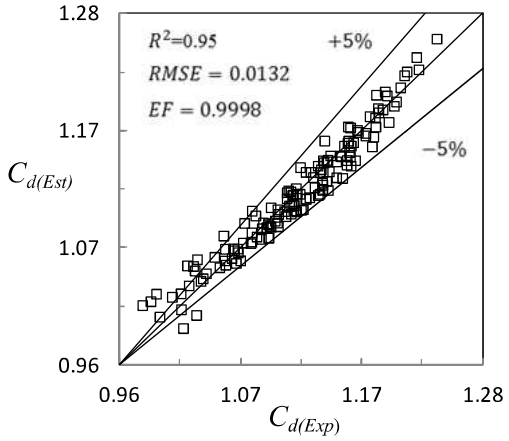


Fig. 18. The comparison of regression model output and corresponding experimental data

4. Conclusions

The present study investigated the effects of surface roughness of cylindrical weirs and upstream sedimentation levels on the rating curve, energy loss, and pressure variations under free and submerged flow conditions at the downstream. The comparison of the results showed that increasing the upstream sedimentation level to 2/3P reduced the upstream head of the weirs up to approximately 5 percent. The comparison of the discharge coefficient showed that by increasing the surface roughness of weirs to 4.5 mm, the discharge coefficient was decreased by 8 and 7 percent under free and submerged flow conditions at the downstream, respectively. Furthermore, the discharge coefficient of the weir under submerged flow conditions was reduced by 5 to 8 percent in comparison with free flow conditions at the downstream. In all cases, the static pressure decreased as the flow passed over the weir. The pressure variations along the weir at the upstream sedimentation level of 2/3P were similar to those obtained for S=0. However, the pressure values decreased as the upstream sedimentation level increased. In addition, increasing surface roughness of the weirs increased the pressure head over most parts of the weir surface. The comparison of the results showed that increasing the weir diameter from 0.15 to 0.25 m decreased energy loss by about 15 percent. In addition, increasing the surface roughness of the weirs from PVC to 4.5 mm increased energy loss by approximately 14 percent for all the considered weirs. Furthermore, an increase in the upstream sedimentation level to 2/3P reduced energy loss over the weirs by 22 percent. At upstream sedimentation level of 2/3P, increasing the roughness to 4.5 mm increased the energy loss by 10 to 16 percent. Ultimately, the regression analysis was used to derive a regression model for estimating the discharge coefficient of cylindrical weirs under different upstream sedimentation levels and surface roughness conditions.

5. References

1. Asgarinezhad, A. R. 2013. Laboratory investigation of the effect of sedimentation and weir's angle on discharge coefficient of triangular weirs. MSc Thesis. University of Tarbiat Modares, Tehran. In Persian
2. Bazin, H. 1898. Recent experiments on the flow of water over weirs. Mémoireset Documents. Annales des PontsetChaussées. Paris. France. 15, 151-264.
3. Beygipour, Gh. And Bina, M. 2005. Hydraulic characteristics of flow in cylindrical and circular crested weir.5th Iranian hydraulics conference. Shahid Bahonar University of Kerman. Kerman. Iran. (In Persian)
4. Bos, M.G. 1976. Discharge measurement structures. International Institute for Land Reclamation and Improvement, Wageningen. The Netherlands. pp. 394.
5. Chanson, H. and Montes, J. S. 1998. Overflow characteristics of circular weir. Journal of Irrigation and Drainage Engineering, ASCE, 124(3), 152–162
6. Creager, W.P. 1917. Engineering for masonry dams.John Wiley and Sons, New York, USA.pp. 289.
7. Dastorani, M. and Nasrabadi, M. 2012. The effect of sedimentation deposition behind of ogee weir on flow conditions. Iranian Water Research Journal, 6(10), 47-57. (In Persian)
8. Dizji, N. and Mahmoudkhani, A.M. 2009. Experimental investigation of effect of sedimentation on discharge coefficient in triangular, rectangular, ogee and over pass in open channel. Iranian Journal of Watershed Management Science and Engineering, 3(8), 50-39. (In Persian)
9. Emami, S. Arvanaghi, H. and Parsa, J. 2018. Effect of weir height on flow features of duckbill weir. Journal of Hydrosciences and Environment 1(3): 2018 46-50.

10. Esmaeili, K., Naghavi, B. KouroshVahid, F. and Yazdi, J. 2010. Experimental and numerical modeling of flow pattern on circular weir. Journal of Water and Soil, 24(1), 166-179. (In Persian)

11. Heidarpour, M. and Chamain, M. R. 2006. Velocity distribution over cylindrical weirs. Journal of Hydraulic Research, 44(5), 708-711. (In Persian)

12. Heidarpour, M., MohammadzadehHabili, J. and. Haghiabi, A. H. 2008. Application of potential flow to circular-crested weir. Journal of Hydraulic Research, 46(5), 699-702. (In Persian)

13. Kirkgöz, M.S., and Ardichoğlu, M. 1997. Velocity profiles of developing and developed open channel flow. Journal of Hydraul. Eng.-ASCE, 123(12), 1099-1105.

14. Masoudian, M. and Gharahgezlou, M. 2012. Flow Characteristics of cylindrical weirs in a small laboratory canal. Journal of Science Series Data Report, 4(4), 12- 23.

15. Othman, KH. I., Tahsen, A.CH. and Ebrahim, A. I. AL. H. 2010. Effect of size and surface roughness of cylindrical weirs on overflow characteristics. Journal of AL-Rafidain Engineering, 19(2), 77-89.

16. Parilcova, J., Řiha, J. and Zachoval, Z. 2012. The influence of roughness on the discharge coefficient of abroad-crested weir. Journal of Hydrology and Hydromechanics, P: 101-114.

17. Ramamurthy, A. S., Vo, N. D. and Vera, G. 1992. Momentum model of flow past weir. Journal of Irrigation and Drainage Engineering, ASCE, 118(6), 988-994.

18. Ramamurthy, A. S. and Vo, N. D. 1993b. Characteristics of circular crested weir. Journal of Hydraulic Engineering, ASCE, 119(9), 1055-1062.

19. Rehbok, T. 1929. The river hydraulic laboratory of the Technical University of Karlsruhe. Hydraulic laboratory practice. ASME, New York, N.Y, 111-242.

20. Shabanlou, S. and Khorami, E. 2013. Study of the hydraulic properties of the cylindrical crested weirs. Journal of Flow Measurement Institute, 33, 153–159. (In Persian)

21. Shafaattalab-Deghani. H., Esmaeili Varaki, M. and Ashrafzadeh, A. 2016. Experimental study on effect of geometry and upstream channel bed level on discharge coefficient of trapezoidal labyrinth weir. Iranian Journal of hydraulic, 11(2): 61-76. (In Persian)

22. Severi, A., Masoudian, M., Kordi, E., and Roettcher, K. 2015. Discharge coefficient of combined-free over-under flo on a cylindrical weir gate. ISH Journal of Hydraulic Engineering, 21(1) 42–52. doi:10.1080/09715010.2014.9 39503.