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Experimental Investigation on Hydraulic Efficiency of Vertical Drop Equipped with Vertical Screens

Rasoul DANESHFARAZ[1]
Sina SADEGHFAM[2]
Vadoud HASANNIYA[3]
John ABRAHAM[4]
Reza NOROUZI[5]

ABSTRACT

In the present study, vertical screens were utilized at downstream of vertical drops to increase the energy dissipation of subcritical flow. The experiments were carried out using screens with two different porosity ratios (40% and 50%) and three different distances from the drop brink (30, 60 and 90 cm). The results reveal that drops equipped with screens increase the relative downstream depth, the relative pool depth, and the relative energy dissipation compared with a plain vertical drop. By increasing porosity ratios and the screen distance from the drop brink, the relative downstream depth and relative energy dissipation increase, whereas the relative pool depth decreases. Also, by increasing the relative critical depth, the relative energy dissipation of the vertical drop decreases, whereas the energy dissipation related to the screens increases. However, increasing the relative critical depth initially increases and then decreases the performance of the hydraulic jump in terms of total energy dissipation.

Keywords: Energy dissipation, hydraulic jump, screen, vertical drop.

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1 Department of Civil Engineering, University of Maragheh, East Azerbaijan, Iran
daneshfaraz@maragheh.ac.ir - https://orcid.org/0000-0003-1012-8342

2 Department of Civil Engineering, University of Maragheh, East Azerbaijan, Iran
s.sadeghfam@maragheh.ac.ir - https://orcid.org/0000-0002-9018-547X

3 Department of Civil Engineering, University of Maragheh, East Azerbaijan, Iran
vadoodh733@gmail.com - https://orcid.org/0000-0002-8200-582X

4 School of Engineering, University of St. Thomas, St Paul, MN, USA
jpabraham@stthomas.edu - https://orcid.org/0000-0002-3818-8681

5 Department of Water Engineering, University of Tabriz, East Azerbaijan, Iran
rezanorouzi1992@tabrizu.ac.ir - https://orcid.org/0000-0002-3756-8746

1. INTRODUCTION

Screens have been introduced by Rajaratnam and Hurtig [1] as a new method to enhance effectiveness of energy dissipation in rivers and downstream of hydraulic structures. These structures are located perpendicular to the flow direction to impose regime transformation by a hydraulic jump and consequently dissipate energy. Screens are commonly used downstream of drops to reduce energy. Also, vertical drops are commonly used as the structure to dissipate the energy of flow in rivers and open channels. This study combines drops with screens to achieve a higher performance in terms of energy dissipation.

When the natural slope in a river is high, drops compensate for differences between the existing slope and the desired slope for controlling the energy of the flow. Rouse' [2] was one of the first research studies on this; he derived an equation to estimate the discharge by measuring the brink depth. The results by Rouse [2] were later modified by Blasidell [3] and Rajaratnam and Chamani [4]. Rajaratnam and Chamani [4] used the data developed in prior studies of Moore [5] and Rand [6] to derive an equation relating to energy dissipation and pool depth. Chamani and Beirami [7] investigated the effect of supercritical flow upstream of a vertical drop on the hydraulic parameters. They revealed that increasing the Froude number for a constant discharge decreases the relative pool depth, the relative downstream depth, and the relative energy dissipation. Chamani et al. [8] presented an equation for the relative energy dissipation using shear layer theory and a fully developed surface jet.

A literature review also highlights studies that investigated the geometry of drops and adjunct structures. Esen et al. [9] evaluated the performance of a step with different dimensions downstream of a vertical drop and revealed that increasing the height of step increases the energy dissipation. Hong et al. [10] investigated the effect of downstream slope on hydraulic performance. Their results showed that increasing the downstream slope of a drop increases the drop length and the collision forces. Liu et al. [11] studied the effect of the upstream slope of a drop on hydraulic performance. Their results revealed that increasing the Froude number and the upstream slope will decrease the values of brink depth, the depth of water in the pool, and the angle of jet collision.

In recent years, many theoretical and empirical studies have been conducted to understand the energy dissipation process through screens (e.g., Rajaratnam and Hurtig [1]; Daneshfaraz et al. [12]; Bozkus et al. [13]; Şimsek et al. [14] and Sadeghfamet al. [15]). Rajaratnam and Hurtig [1] investigated the energy dissipation through screens and revealed that screens with 40% porosity can efficiently dissipate energy. Sadeghfam et al. [16] evaluated the performance of screens when a submerged hydraulic jump occurs and revealed that screens successfully perform in both free and submerged hydraulic jumps. On the other hand, they observed that the gap between screens had an insignificant effect on energy dissipation. Daneshfaraz et al. [17] investigated the energy dissipation through screens equipped with baffles. They observed that screens with 40% porosity reduce more energy compared to screens with 50% porosity. Also, their results revealed that screens equipped with baffles exhibit a greater energy dissipation compared to plain screens. investigated the behaviour of screens in movable-bed channels. They derived a set of equations to describe the dimensions of a scouring pit induced by screens.

Sharif and Kabiri-Samani [18] investigated a drop equipped with a horizontal screen in subcritical flow. They observed two types of bubble impinging jet flow regimes and a surface flow regime occur downstream of drops equipped with screens. They also found that when the relative downstream depth is increased, air/water mixing decreases the relative length of the first jet collision point. However, it increases the relative pool depth. Norouzi et al. [19] studied energy dissipation through vertical screens downstream of inclined drops. Their results showed that screens cause a significant increase (between 400-900%) in the total relative energy dissipation compared to a plain inclined drop. Daneshfaraz et al. [20] investigated the performance of a drop equipped with dual horizontal screens. They observed that dual horizontal screens transformed supercritical flow to subcritical downstream of the drop. Daneshfaraz et al. [21] studied the efficiency of support vector machine for predicting vertical drop with dual horizontal screens. The results showed that capacity for this approach to predict the hydraulic performance of these systems with accuracy. Using vertical screens with two porosity ratios located downstream of inclined drops was investigated by Daneshfaraz et al. [22] investigated an inclined drop equipped with a screen in subcritical flow. Results revealed that compared to a plane inclined drop, the screen also caused an increase of at least 407% and up to 903% in total relative energy dissipation.

From this prior research, the use of screens can improve energy dissipation. However, there are limited studies have been performed for investigating energy dissipation on drops equipped with screens. Jet collisions with the pool floor have not been performed in the previous studies. So, the aim of this study is to investigate the performance of drop with vertical screen and pool downstream of the drop. Then, the hydraulic parameters of the drop with vertical screen such as the relative pool depth, the relative downstream depth and average percentage of the energy dissipation contribution for each of the components will be examined. The results of this study will also be compared with the results of the others.

2. MATERIALS AND METHODS

2.1. Experimental Set-up

Experiments were conducted on a flume with 5m length, 0.3m width and 0.55m depth in the hydraulic laboratory at the University of Maragheh. The flume is horizontal and has a rectangular cross-section. Figure 1 illustrates the flume. The flow was supplied via two pumps with a flow rate capacity of 900 liters per minute. The discharge was measured using two rotameters which were located at the outlet of the pumps and have a ±2% accuracy. The flow depth was measured using a point gauge with ±1% accuracy.

The body of the drop was made of plexiglass planes with 0.3m width and 0.15m height. Screens were made of polyethylene planes with a thickness of 1cm and porosity ratios of 40% and 50% through circular holes. All screens were located perpendicular to the flow direction at downstream of the drop with 30, 60 and 90 cm distance from the drop brink. The Range of variables used illustrated in Table 1.

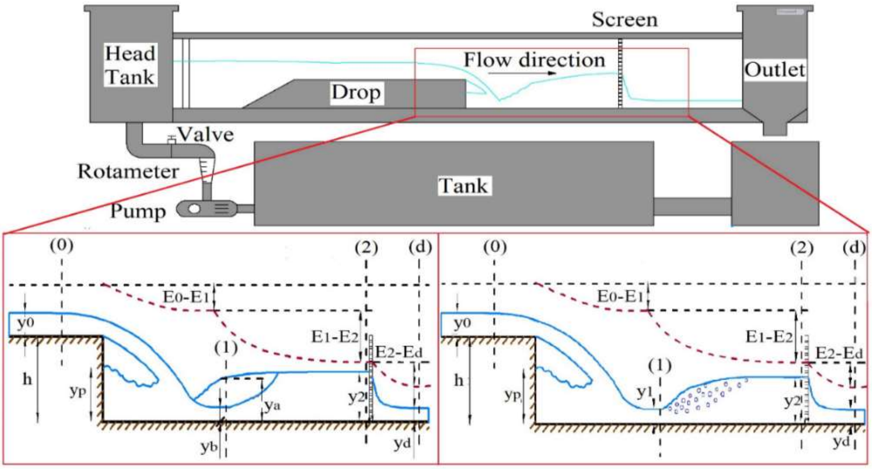

Figure 1 - Schematic of experimental setup and water circulation system

Table 1 - Range of variables used in the experimental study

Measured variables	Range of variables				
	Drop	Drop equipped with vertical screen in different distances			
		p (%)	d/h=2	d/h=4	d/h=6
Q (l/min)	150-850	40	150-850	150-850	150-850
		50	150-850	150-850	150-850
y_0(cm)	2.45-6.86	40	2.34-7.6	2.38-6.98	2.33-7
		50	2.35-7.2	2.39-7.1	2.39-7.1
y_b(cm)	1.38-4.12	40	1.3-4.22	1.27-4.27	1.28-4.25
		50	1.32-4.22	1.33-4.28	1.32-4.22
y_p(cm)	3.78-8.97	40	4.15-14	4-13.02	3.88-12.4
		50	3.9-11.48	3.9-10.43	3.78-9.99
y_d(cm)	0.62-2.55	40	1.35-4.08	1.39-4.33	1.45-4.37
		50	1.48-4.22	1.46-4.61	1.51-4.62

2.2. Specific Energy Dissipation

The specific energy at upstream of the drop is calculated using $E_0=h+1.5y_c$ and specific energy at downstream (after the screen) of the drop is calculated as follows:

$$E_d=y_d+\frac{q^2}{2gy_d^2} \tag{1}$$

where E_0 is the energy at upstream; h is the drop height; y_c is the critical depth; E_d is the energy downstream of the drop; q is the discharge per unit width; g is the gravitational acceleration; and y_d is the flow depth downstream of the drop measured approximately 20 to 30 cm after screen.

The relative energy dissipation of the total system is calculated as follows:

$$\frac{\Delta E}{E_0}=1-\frac{E_d}{E_0} \tag{2}$$

where ΔE is the energy that has been dissipated. The energy dissipation efficiency of the drop equipped with screens compared to a plain vertical drop (η) can be calculated as follows:

$$\eta=\frac{\Delta E_{\text{with screen}}-\Delta E_{\text{without screen}}}{\Delta E_{\text{without screen}}} \tag{3}$$

By measuring the flow depth at the location where the jet collides with the pool floor and the depths before and after screen, and also by calculating the energy at each section, the relative energy dissipation in each component of energy dissipation can be calculated as follows:

$$\frac{\Delta E_{(\text{Energy dissipator systems})}}{E_0}=\frac{E_n-E_{n-1}}{E_0} \tag{4}$$

where E_n is energy at n^{th} component and E_{n-1} is energy at $(n\text{-}1)^{\text{th}}$ component. The energy of the jet at the collision point with the floor for a submerged hydraulic jump is calculated as follows (see Fig. 1).

$$E=y_a+\frac{q^2}{2gy_b^2} \tag{5}$$

2.3. Dimensional Analysis

The equation describing energy dissipation as a function of independent parameters can be written as follows:

$$\Delta E=f_1(\rho,\mu,g,Q,B,h,p,t,d,y_c,y_0,y_b,y_1,y_2,y_d) \tag{6}$$

where ρ is the density of water [ML^{-3}]; μ is the dynamic viscosity of water [$ML^{-1}T^{-1}$]; g is gravitational acceleration [LT^{-2}]; Q is the flow discharge [L^3T^{-1}]; B is the channel width [L]; h is the drop height [L]; p is the porosity of screen [-]; t represents thickness of the screen [L]; d is the distance of the screen from the drop brink [L]; y_c is the critical depth [L]; y_0 is the depth of flow at upstream depth of drop [L]; y_b is the drop brink depth [L]; y_1 is the depth of water after the jet collides with the floor [L]; y_2 is the depth of water at upstream of screen

[L]; y_d is the depth of water at downstream screen [L]; and y_p is the pool depth under the falling jet [L].

Upstream energy and downstream Froude number can be expressed by Eqs. (7) and (8):

$$E_0=f_2(g,Q,B,h,y_0) \tag{7}$$

$$Fr_d=f_3(g,Q,B,y_d) \tag{8}$$

Since the channel width is fixed, 30 cm, in all experiments it can be ignored. So, Eq. (6) can be rewritten as follows:

$$\Delta E=f_4(\rho,\mu,g,Q,h,p,t,d,y_c,y_0,y_b,y_1,y_2,Fr_d) \tag{9}$$

Considering y_0, ρ and g as the repeating variables, the dimensionless Eq. (10) is obtained through Buckingham π theorem as follows:

$$\frac{\Delta E}{E_0}=f_5(Re_0,Fr_0,\frac{h}{y_0},p,\frac{t}{y_0},\frac{d}{y_0},\frac{y_c}{y_0},\frac{y_b}{y_0},\frac{y_1}{y_0},\frac{y_2}{y_0},Fr_d) \tag{10}$$

where Re_0 is upstream Reynolds number, Fr_0 is upstream Froude number and Fr_d is downstream Froude number of the drop. After simplifications, Eq. (11) is obtained as follows:

$$\frac{\Delta E}{E_0}=f_6(Re_0,Fr_0,p,\frac{t}{h},\frac{d}{h},\frac{y_c}{h},\frac{y_b}{y_c},\frac{y_2}{y_1},Fr_d) \tag{11}$$

Since the Reynolds number varied in the range of 7000 to 34000 in the present study, the flow was turbulent and viscosity effects can be neglected [23]. It was also observed that the Froude number (Fr_0) varied in the range of 0.68 to 0.84. Considering the small range of Froude numbers, the effect of this parameter on the hydraulic characteristics was neglected. The thickness of the screens was also identified as an insignificant parameter Cakir [24] and Balkis [25].

Although the parameters y_b/y_c and y_2/y_1 can be included in the experiments, quantifying their impact is beyond the scope of the present study. Therefore, relative energy dissipation can be described as a function of the reduced set of non-dimensional parameters as follows:

$$\frac{\Delta E}{E_0}=f_7(p,\frac{d}{h},\frac{y_c}{h}) \tag{12}$$

The relative pool depth and relative downstream depth are expressed in terms of the dimensionless parameters are found as follows:

$$\frac{y_p}{h}=f_8(p,\frac{d}{h},\frac{y_c}{h}) \tag{13}$$

$$\frac{y_d}{h}=f_9(p,\frac{d}{h},\frac{y_c}{h}) \tag{14}$$

In this study, 48 experiments were conducted based on the non-dimensional parameters *p*, *d/h,* and y_c/h. Also, eight experiments were conducted for the case of drops without screens. The non-dimensional parameters of the porosity ratios of the screens are 40% or 50%; the distance to height (*d/h*) equals 2, 4 and 6; and relative critical depth (y_c/h) are in the range (0.13-0.406). All the experiments required 15 minutes to warrant a steady-state condition.

2.4. Performance Metrics

Three performance metrics were used to evaluate the results. RMSE is the Root Mean Square Error, R^2 is the determination coefficient, and *RE* is the relative error (see Table 2).

Table 2 - Performance Metrics for Evaluation Results

Performance Metrics	Equation
Root Mean Square Error	$\mathrm{RMSE}=\sqrt{\frac{1}{n}\sum_{1}^{n}\left(X_{exp}-X_{cal}\right)^2}$
Determination coefficient	$R^2=\left(\frac{n\sum X_{exp}X_{Cal}-\left(\sum X_{exp}\right)\left(\sum X_{cal}\right)}{\sqrt{n(\sum X_{exp}^2)-(\sum X_{exp})^2}\sqrt{n(\sum X_{cal}^2)-(\sum X_{cal})^2}}\right)^2$
Relative Error	$\mathrm{RE}=\frac{\lvert X_{exp}-X_{cal}\rvert}{X_{exp}}$

X_{exp} is an experimental value and X_{cal} is calculated values.

3. RESULTS AND DISCUSSIONS

While the flow regime is subcritical upstream of the drop, the flow regime changes initially to critical and then supercritical near the drop brink. After the brink, due to gravity, the flow falls and impacts the pool. The flow then is divided into two parts, part of which flows towards the pool and the other part flows downstream [26]. The presence of a returned rotating flow leads to greater pool depth. Fluctuations, air/water mixing and the presence of a returned flow inside the pool result in a non-hydrostatic pressure distribution [27]. Also, turbulence inside the pool reduces the energy of flow [26, 28]. The flow regime becomes supercritical by moving downstream (Fig. 2).

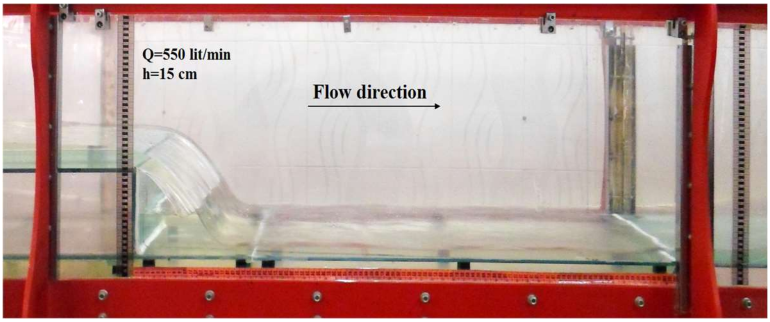

Figure 2 - Flow overview in plain vertical drop

3.1. The Drop Relative Depth

Previous studies on subcritical flow upstream of vertical drops indicated that the fluid depth is initially greater than the critical depth and as the flow approaches the drop brink, the flow depth decreases and reaches the critical flow depth. Then, at a slight distance upstream of the drop brink it reaches a supercritical depth [26]. Laboratory observations in the present study confirm these findings. Also, experiments conducted on the vertical drop equipped with screens show that screens had an insignificant effect on the general behavior of flow at upstream of the drop. The equation $y_c = \sqrt[3]{\frac{q2}{g}}$ can be useful to relate the critical depth and discharge values. Table 3 presents a comparison between the present drop brink and critical depths with prior studies. It is observed that the drop relative depth in the present study agrees with previous studies. Therefore, it can be concluded that the results of the present study and the experimental findings are accurate.

Table 3 - Comparison of the drop brink depth and the critical depth of the present study with previous studies

Studies	Diskin [29]	Andersen [30]	Strelkoff and Moayeri [31]	Present study
y_b/y_c	0.667	0.694	0.672	0.674

After the flow passes through the drop brink, it collides with the downstream bed. When the jet moves further downstream towards the screen, the screen acts as a barrier against the flow and increases the flow depth just upstream of the screen and consequently causes a hydraulic jump between the screen and the collision location. Laboratory observations revealed that hydraulic jump increases turbulence and roller flows and air/water mixing between the screen and the collision location. Figure 3 shows the behavior of the flow along with the screen and hydraulic jump formation.

Figure 3 - Vertical drop equipped with a screen and hydraulic jump formation

It was observed that for low discharges, the free hydraulic jump occurred, and the toe of jump formed a slight distance upstream of the screens. By increasing the discharge, the toe of hydraulic jump moves towards the drop and ultimately reaches the collision location of a jet, which forms a submerged hydraulic jump. For all the cases where the hydraulic jump was submerged, it was observed that pool depth increased. It was also observed that flow passing through the screens produce severe air/water mixing.

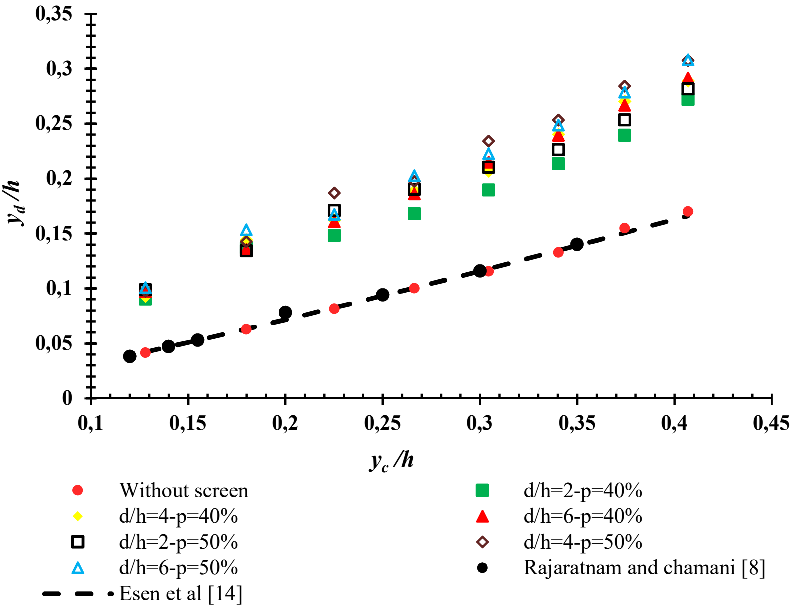

Figure 4 - Effect of screens on the relative downstream depth

3.2. Relative Downstream Depth

Figure 4 shows the effect of screens on the relative downstream depth versus the relative critical depth. According to the figure, y_d/h increases by increasing y_c/h. The figure also shows that screens downstream of the vertical drop increase the relative downstream depth compared to a plain vertical drop. Also, increasing screen porosity and the downstream location of screens from the drop brink increase the relative downstream depth.

During the experiments, it was observed that the downstream Froude number decreases from a range of 3.5-5.5 to a range of 1.25-2.1. Notably, the downstream Froude number has a direct relationship with the destructive energy of flow. In some experiments, it was also observed that at low relative critical depth, an undular jump is formed.

Table 4 presents the reduction of downstream Froude number for vertical drops equipped with screens compared to plain vertical drops. The table shows that the increase in screen porosity decreases the Froude number. Also, with the increase in distance of screens from 2h to 4h, the Froude number increases. However, there is no significant difference in the results for screens which are located at 4h to 6h. *h* is the height of drop.

Table 4 - Reduction of downstream Froude number for vertical drops equipped with screens compared to plain vertical drops

Location	Decrease in Froude number for the screen with 40% porosity (%)	Decrease in Froude number for the screen with 50% porosity (%)
2h	56.6	61.1
4h	62	65.5
6h	62	65.1

3.4. Relative Pool Depth

The depth of the pool behind the falling jet was measured as an important parameter in the design of vertical drops. By estimating this parameter, it is possible to control submergence of the drop. Figure 5 shows a comparison of the relative pool depth in the present and previous studies for vertical drops equipped with screens. The figure also shows that screens in vertical drops increase the relative pool depth compared to plain vertical drops.

A submerged hydraulic jump occurred for all relative critical depths and all locations of screens with a porosity of 40%, while a free hydraulic jump occurred for the screen with a porosity of 50%. Therefore, experimental results provide evidence that a vertical drop equipped with a screen with a porosity of 50% located at a distance of 6h from the drop brink is appropriate for preventing drop submergence. However, by increasing the relative critical depth of submergence, the backflow moves to the pool and thus the pool depth increases in both cases. Furthermore, by increasing the screen distance from the drop brink, the submergence depth and the relative pool depth decreases. Table 5 shows the increase in relative pool depth for vertical drops equipped with screens compared to the plain vertical drop.

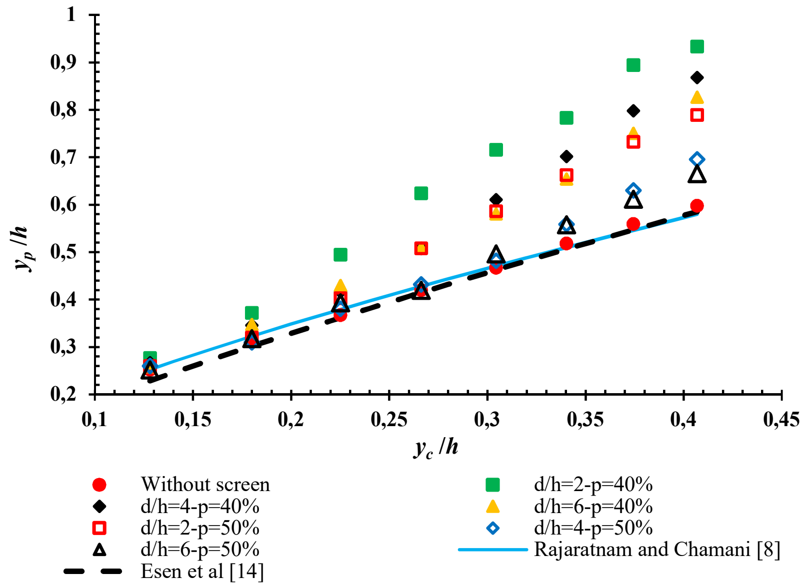

Figure 5 - Effect of screens on the relative pool depth for a drop equipped with a screen

Table 5- Increase in relative pool depth for the vertical drop equipped with screens relative to the plain vertical drop

Location	Increase in relative pool depth for the screen with 40% porosity (%)	Increase in relative pool depth for the screen with 50% porosity (%)
2h	41.5	19
4h	25.5	6
6h	21.8	5.4

In order to derive an empirical equation for describing relative pool depth, experimental data were divided randomly into calibration and validation sets with ratios of 80% and 20%, respectively. Then, Eq. (15) were derived by using a Generalized Reduced Gradient (GRG) algorithm as one of the most robust nonlinear programming methods (see [32]). Figure 6 compares the experimental and estimated values of the relative pool depth. According to the figure, the average relative error is 3.9% and the maximum error between experimental and the estimated values is 10.5%.

$$\frac{y_p}{h}=1.31\left(\frac{y_c}{h}\right)^{1.4}\left(\frac{d}{h}\right)^{-0.193}(p)^{-1.058}+0.1164 \qquad R^2=0.9952 \quad \text{and} \quad \text{RMSE}=0.019 \tag{15}$$

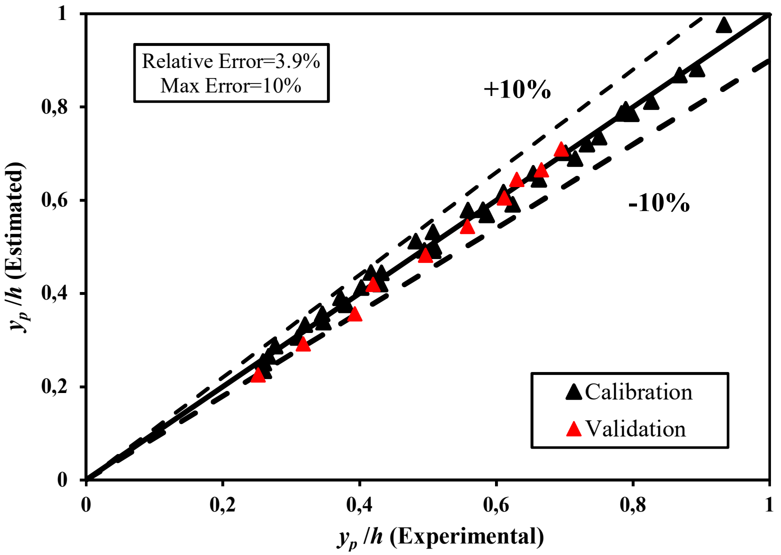

Figure 6 - Comparison between experimental values of y_p/h and estimated values

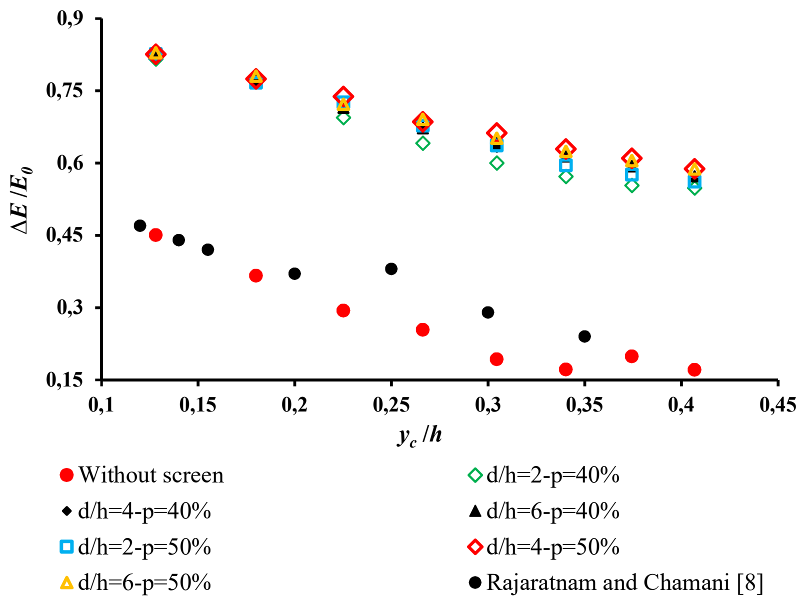

Figure 7 - Effect of screens on relative energy dissipation

3.5. Relative Energy Loss

Energy dissipation in vertical drops with the subcritical flow in upstream of the drop, usually occurs due to the collision effect of the jet to floor of pool and flow turbulence in the pool below the jet [26]. Figure 7 compares the relative energy dissipation versus changes in the relative critical depth in the present and prior studies. According to the figure, the relative energy dissipation decreases with increasing relative critical depth for plain vertical drops and vertical drops equipped with screens by varying porosities and locations. The figure provided evidence that using screen increases the relative energy dissipation compared with the plain vertical drop. Also, it is observed that increasing porosity and downstream position both increase the relative energy dissipation.

Similar to Section 3.3, the GRG algorithm was used to derive Eq. (16) for describing the relative energy dissipation in vertical drops equipped with screens. Figure 8 compares the estimated and experimental values for the relative energy dissipation. It is seen that the average relative error is 1.61% and the maximum error between experimental and estimated values is 3.29%.

The energy dissipation efficiency (the ratio of the energy dissipation difference of the plain vertical drop with screens to the energy dissipation of the plain vertical drop) is presented in Table 6 for different models versus changes in the relative critical depth.

$$\frac{\Delta E}{E_0}=1.023\left(\frac{y_c}{h}\right)^{0.4853}\left(\frac{d}{h}\right)^{-0.05} p^{-0.088}+0.252 \quad R^2=0.9934 \quad \text{and} \quad RMSE=0.012 \qquad (16)$$

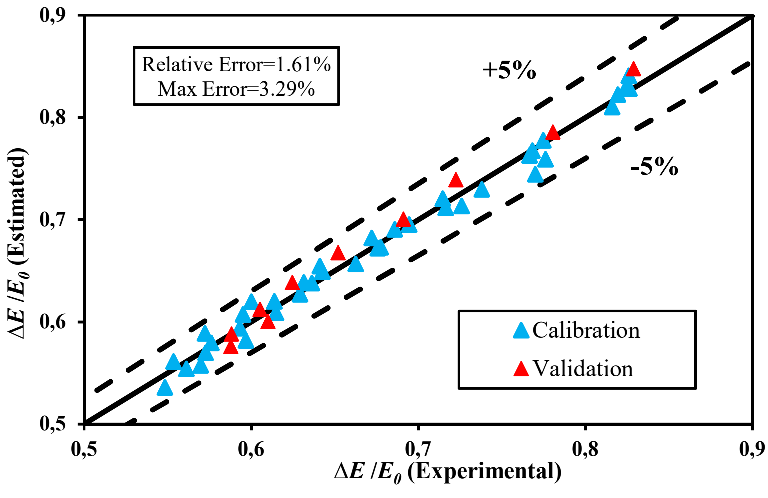

Figure 8 - Comparison of experimental values of $\Delta E/E_0$ and estimated values

Table 6 - Summary of the loss efficiency for the vertical drop equipped with energy dissipate

y_c/h	The efficiency of the energy dissipation increases in the screen with a porosity of 40% at various downstream locations			The efficiency of the energy dissipation increases in the screen with a porosity of 50% at various downstream locations		
	2h	4h	6h	2h	4h	6h
0.13	0.81	0.82	0.83	0.83	0.83	0.84
0.18	1.1	1.12	1.1	1.09	1.11	1.13
0.225	1.36	1.44	1.43	1.47	1.5	1.46
0.266	1.52	1.66	1.64	1.66	1.7	1.72
0.3	2.1	2.27	2.33	2.29	2.4	2.38
0.34	2.34	2.59	2.58	2.47	2.67	2.65
0.37	1.78	2	1.98	1.89	2.06	2.04
0.406	2.36	2.33	2.35	2.28	2.44	2.45

According to Table 6, it can be concluded that by increasing the relative critical depth, the efficiency of energy dissipation increases for all distances and different porosities. It is also observed that energy dissipation efficiency increases with increasing screen distance from the drop brink and by increasing the porosity of the screen for a constant relative critical depth. Figure 9 shows the average energy dissipation efficiency versus the relative critical depth and ratio of distance to drop height.

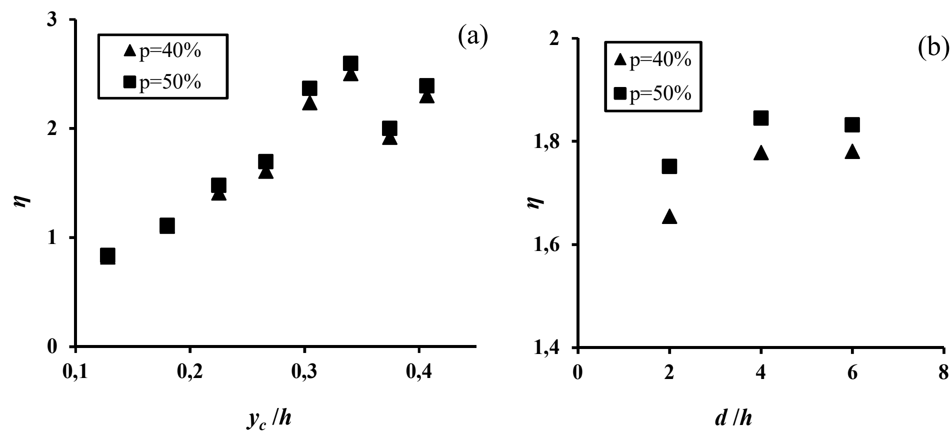

*Figure 9 - Variation of energy dissipation efficiency versus **(a)** Relative critical depth; and **(b)** ratio of distance to screen height*

Figure 9(a) shows that the average energy-loss efficiency increases by increasing relative critical depth, in general. However, there are fluctuations due to the high turbulence of flow for the relative critical depth greater than 0.3. As shown in Fig. 9(b), the energy-loss efficiency generally increases with the increase in the ratio of the distance from drop height. Also, both figures show that the energy dissipation efficiency for vertical drops equipped with screens with a porosity of 50% is higher than screens with the porosity of 40%.

3.6. Contribution of Different Components in Energy Dissipation

Three components play major roles in dissipating flow energy in a vertical drop: (1) the drop structure; (2) the hydraulic jump imposed by the screen; and (3) turbulence as fluid passes through a screen. Figure 10 depicts the contributions of these components in energy dissipation. The relative energy dissipation of the drop equipped with the screen is significantly greater than that for the plain vertical drop, while the total relative energy dissipation of a vertical drop equipped with the screen is smaller than that of the plain vertical drop. It can be concluded that for a drop equipped with a screen, an increase in critical depth can cause the hydraulic jump to become submerged and the pool depth to increase. This factor reduces the impact of the jet on the pool floor and thereby reduces the energy dissipation. On the other hand, by investigating the hydraulic jump mechanism for a vertical drop equipped with a screen, it can be concluded that a free hydraulic jump is formed at low discharge. By increasing the discharge, the toe of jump moves upstream and reaches the collision location of the jet with the floor and the relative energy dissipation of hydraulic jump reaches a maximum value. With further increase in the discharge, the hydraulic jump becomes submerged and its relative energy dissipation is reduced.

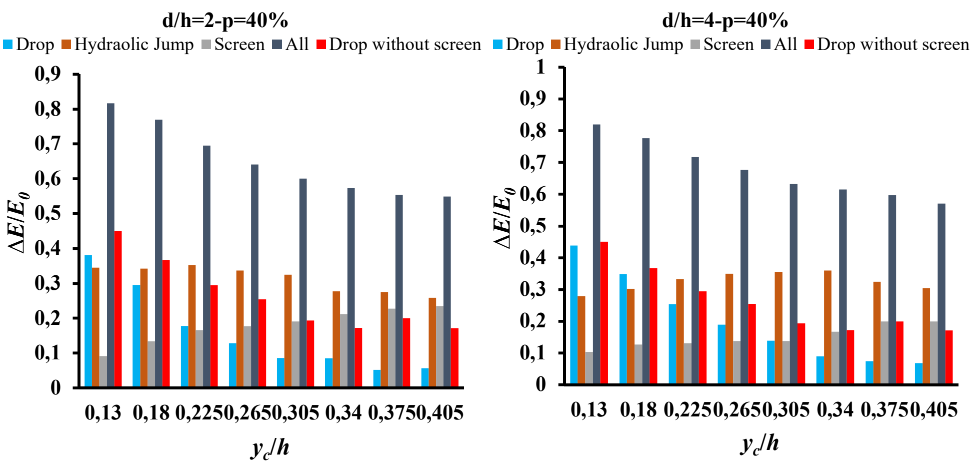

Figure 10- Contribution of different components in energy dissipation

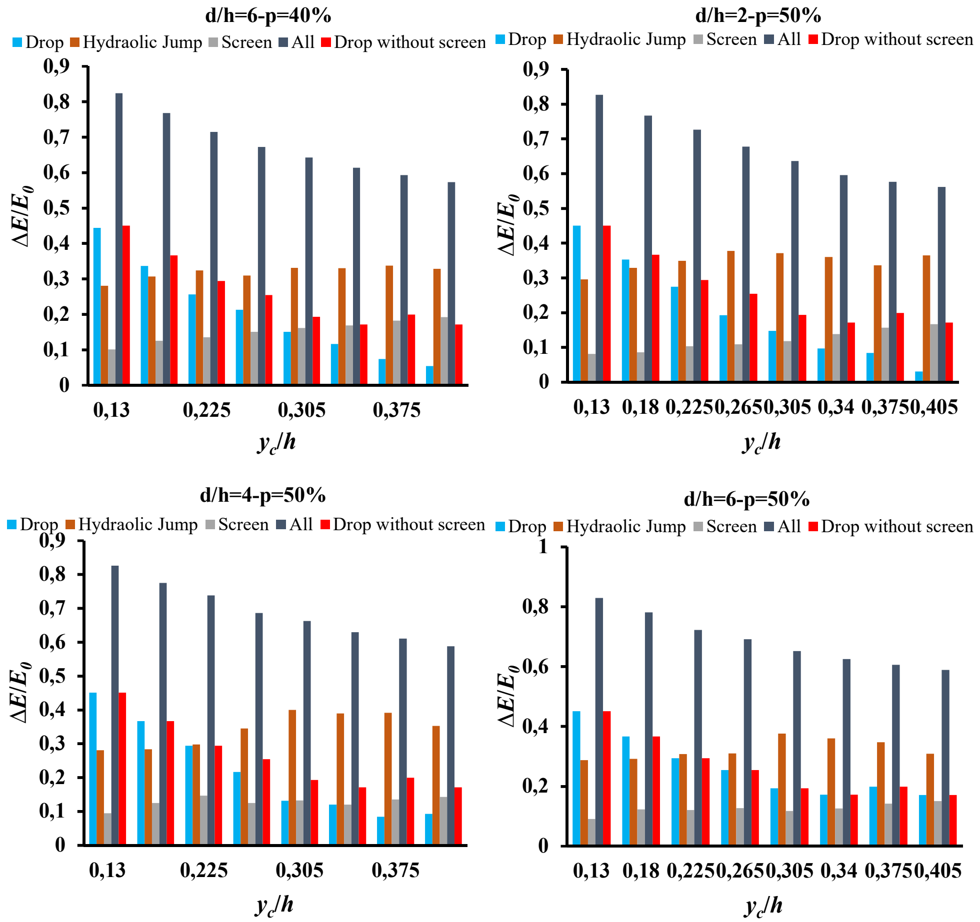

Figure 10- Contribution of different components in energy dissipation (continue)

Figure 11 shows the average percentage contribution for each of the components of the energy dissipation. It can be observed that by increasing the distance of the screens from the drop brink, the average contribution of the energy dissipation for a vertical drop increases. Furthermore, increase in the screen distance reduces the contribution in total energy dissipation of hydraulic jump and screen components.

It is seen that by increasing screen porosity, both the contribution in total energy dissipation of the vertical drop and hydraulic jump increase while contribution of the screen decreases. Generally, the results show that the hydraulic jump provides the greatest contribution to total energy dissipation.

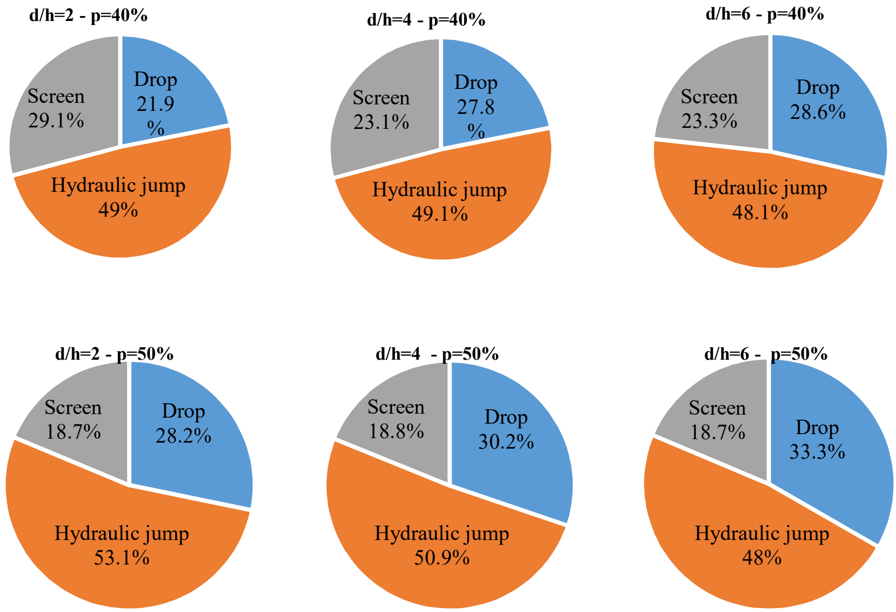

Figure 11 - Variation of energy dissipation percentage for different components

4. DISCUSSION

Recent studies confirm that using screens downstream of small hydraulic structures can increase energy dissipation by imposing a hydraulic jump and turbulence and thereby control erosion and scouring on rivers beds and open channels. The present study suggests that screens can be utilized along with drops as one of the common structures to achieve higher energy dissipation and control the hydraulic jump location. This system is a step towards less polluted water and provide an important environmental benefit by aeration mechanism.

However, screen-type dissipaters have been used less in practice and research is ongoing in this field. One of the major obstacles to the use of these systems is the potential of clogging or blocking of pores with natural material and sediment. Therefore, the determination of pore diameters and pore shapes are critical and require further attention. Maintenance systems are needed to control the possible blocking if the system is to be used in practices. On the other hand, this feature can be useful to remove unfavorable floating or submerged objects in the flow.

The present study is a step towards providing a guideline to design such systems. For example, the pool depth under the falling jet is an important parameter for determining the amount of the submergence in the vertical drop design. The results of this study show that the use of screens downstream of a vertical drop increases the pool depth and decreases the performance of the drop structures. However, according to the design regulations, the drop structure should not be totally submerged. Equations are developed to calculate the relative pool depth in vertical drops equipped with screens. These equations can be used in the design of this system.

A comparison of the screen porosity on energy dissipation has shown that a screen with a porosity of 40% dissipates more energy than screens with a porosity of 50% in the hydraulic jump, in agreement with [1] and [16]. However, since submergence of the jump reduces the performance of energy dissipating in the drop and screen with porosity of 40% leads to submergence, a vertical drop equipped with a screen of porosity of 50% leads to more energy dissipation than a screen of porosity of 40%.

Screens are another type of energy dissipation structure whose performance is based on a relative critical depth, as shown in Fig. 10. By increasing water height behind the screen the amount of air/water mixing and energy dissipation increase. Therefore, by increasing the discharge and thus increasing the depth at upstream of the screen, the screen performance increases.

5. CONCLUSION

The present study investigates the effect of using screens in vertical drops to increase energy dissipation. The experiments were run for a vertical drop equipped with screens with two porosity ratios, 40% and 50% and three different screen locations, 30 cm, 60 cm, and 90cm downstream the drop brink. It was observed that a screen installed at downstream of a vertical drop imposes a hydraulic jump between the jet collision position and the screen and provides the depth necessary to create a hydraulic jump. This phenomenon increases energy dissipation. The screen also increases energy dissipation by enhanced air/water mixing. The results show that the use of screens increases the relative downstream depth, the relative pool depth, and the relative energy dissipation. It was also found that by increasing porosity and the distance of screens from the drop brink, the relative downstream depth and the energy dissipation are increased, and the relative pool depth is decreased. It was also found that by increasing relative critical depth, the relative energy dissipation of the drop component decreaseds, the contribution of hydraulic jump initially increases upto a certain point and then decreases, and the contribution of energy dissipation of the screen increases. Also, by increasing the distance of the screen from the drop brink, the energy dissipation in the vertical drop increases and the contributions to energy dissipation by the hydraulic jump and the screen decreases. It was also found that hydraulic jump provides the greatest contributions (~50%) in total energy dissipation followed by almost equal contributions from vertical drop and screen.

Notation

The following symbols are used in this paper:

B= channel width (m)

d= the distance of the screen from the drop brink (m)

E_0= Energy at the upstream(m)

E_1= energy at cross-section (1) (m)

E_2= energy at cross-section (2) (m)

E_d= energy at the downstream(m)

Fr_u= upstream Froude number (-)

g= gravitational acceleration (m/s^2)

h= drop height (m)

p= porosity of the screen (%)

Q= flow discharge (m^3/s)

q= discharge inflow per unit width (m^2/s)

Re_u= Reynolds number at upstream of screen (-)

t= represents the thickness of the screen (m)

y_u= upstream depth (m)

y_1= depth after the jet collides with the floor (m)

y_2= depth before the screen (m)

y_b= drop brink depth (m)

y_c= critical depth (m)

y_d= downstream depth (m)

y_p= pool depth under the falling jet (m)

ΔE = energy dissipation(m)

η = energy dissipation efficiency; (-)

ρ = density of water; (kg/m^3)

μ = the dynamic viscosity; (kg/m.s)

References

[1] Rajaratnam, N., Hurtig, K., Screen-type energy dissipator for hydraulic structures. Journal of Hydraulic Engineering, Vol 126, No (4), 310-312. 2000.

[2] Rouse, H., Discharge characteristics of the free overfall: Use of crest section as a control provides easy means of measuring discharge. Civil Engineering, Vol 6, No (4), 257-260. 1936.

[3] Blaisdell, F., Hydraulics of rectangular vertical drop structures. Journal of Hydraulic Research, Vol 17, No (4), 289-302. 1980.

[4] Rajaratnam, N., Chamani, M.R., Energy loss at drops. Journal of Hydraulic Research, Vol 33, No (3), 373-384. 1995.

[5] Moore, W.L. Energy loss at the base of a free overfall. in Proceedings of the American Society of Civil Engineers. ASCE, 1943.

[6] Rand, W. Flow geometry at straight drop spillways. in Proceedings of the American Society of Civil Engineers. ASCE, 1955.

[7] Chamani, M.R., Beirami, M., Flow characteristics at drops. journal of Hydraulic Engineering, Vol 128, No (8), 788-791. 2002.

[8] Chamani, M.R., Rajaratnam, N., Beirami, M., Turbulent jet energy dissipation at vertical drops. Journal of Hydraulic Engineering, Vol 134, No (10), 1532-1535. 2008.

[9] Esen, I.I., Alhumoud, J.M., Hannan, K.A., Energy Loss at a Drop Structure with a Step at the Base. Water international, Vol 29, No (4), 523-529. 2004.

[10] Hong, Y.M., Huang, H.S., Wan, S., Drop characteristics of free-falling nappe for aerated straight-drop spillway. Journal of Hydraulic Research, Vol 48, No (1), 125-129. 2010.

[11] Liu, S.-I., Chen, J.-Y., Hong, Y.-M., Huang, H.-S., Raikar, R.V., Impact characteristics of free over-fall in pool zone with upstream bed slope. Journal of Marine Science and Technology, Vol 22, No (4), 476-486. 2014.

[12] Daneshfaraz, R., Hasannia, V., Norouzi, R., Sihag, P., Sadeghfam, S., Abraham, J., Investigating the Effect of Horizontal Screen on Hydraulic Parameters of Vertical Drop. Iranian Journal of Science and Technology, Transactions of Civil Engineering. 2021.

[13] Bozkus, Z., Çakir, P., Ger, A.M., Energy dissipation by vertically placed screens. Canadian Journal of Civil Engineering, Vol 34, No (4), 557-564. 2007.

[14] Şimsek, O., Göksu Soydan, N., Gumus, V., Sami Akoz, M., Salih Kirkgoz, M., Numerical modeling of B-type hydraulic jump at an abrupt drop. Teknik Dergi, Vol 26, No (4), 7215-7240. 2015.

[15] Sadeghfam, S., Daneshfaraz, R., Khatibi, R., Minaei, O., Experimental studies on scour of supercritical flow jets in upstream of screens and modelling scouring dimensions using artificial intelligence to combine multiple models (AIMM). Journal of Hydroinformatics, Vol 21, No (5), 893-907. 2019.

[16] Sadeghfam, S., Akhtari, A.A., Daneshfaraz, R., Tayfur, G., Experimental investigation of screens as energy dissipaters in submerged hydraulic jump. Turkish Journal of Engineering and Environmental Sciences, Vol 38, No (2), 126-138. 2015.

[17] Daneshfaraz, R., Sadeghfam, S., Ghahramanzadeh, A., Three-dimensional numerical investigation of flow through screens as energy dissipators. Canadian Journal of Civil Engineering, Vol 44, No (10), 850-859. 2017.

[18] Sharif, M., Kabiri-Samani, A., Flow regimes at grid drop-type dissipators caused by changes in tail-water depth. Journal of Hydraulic Research, 1-12. 2018.

[19] Norouzi, R., Daneshfaraz, R., Bazyar, A., The Study of Energy Depreciation due to the use of Vertical Screen in the Downstream of Inclined Drops by Adaptive Neuro-Fuzzy Inference System (ANFIS). AUT Journal of Civil Engineering. 2019.

[20] Daneshfaraz, R., Majedi Asl, M., Razmi, S., Norouzi, R., Abraham, J., Experimental investigation of the effect of dual horizontal screens on the hydraulic performance of a vertical drop. International Journal of Environmental Science and Technology. 2020.

[21] Daneshfaraz, R., Bagherzadeh, M., Esmaeeli, R., Norouzi, R., Abraham, J., Study of the performance of support vector machine for predicting vertical drop hydraulic parameters in the presence of dual horizontal screens. Water Supply. 2020.

[22] Daneshfaraz, R., Majedi Asl, M., Bazyar, A., Abraham, J., Norouzi, R., The laboratory study of energy dissipation in inclined drops equipped with a screen. Journal of Applied Water Engineering and Research. 2020.

[23] Ghaderi, A., Daneshfaraz, R., Abraham, J., Torabi, A., Effect of Different Channels on Discharge Coefficient of Labyrinth Weirs. Teknik Dergi, Vol 32. 2021.

[24] Cakir, P., Experimental investigation of energy dissipation through screens in Department of Civil Engineering. Middle East Technical University: Ankara, Turkey, 2003.

[25] Balkis, G., Experimental investigation of energy dissipation through inclined screens in Department of Civil Engineering Middle East Technical University: Ankara,Turkey, 2004.

[26] Rajaratnam, N., Chamani, M., Energy loss at drops. Journal of Hydraulic Research, Vol 33, No (3), 373-384. 1995.

[27] Robinson, K., Predicting stress and pressure at an overfall. Transactions of the ASAE, Vol 35, No (2), 561-569. 1992.

[28] White, M., Discussion of moore. Tran. ASCE, Vol 108, 1361-1364. 1943.

[29] Diskin, M., End depth at a drop in trapezoidal channels. Journal of the Hydraulics Division, Vol 87, No (4), 11-32. 1961.

[30] Andersen, V.M., Non-uniform flow in front of a free overfall. Acta polytechnica scandinavica-civil engineering and building construction series, Vol 42, No (3). 1967.

[31] Strelkoff, T., Moayeri, M.S., Pattern of potential flow in a free overfall. Journal of the Hydraulics Division, Vol 96, No (4), 879-901. 1970.

[32] Lasdon, L.S., Fox, R.L., Ratner, M.W., Nonlinear optimization using the generalized reduced gradient method. Revue française d'automatique, informatique, recherche opérationnelle. Recherche opérationnelle, Vol 8, No (V3), 73-103. 1974.