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Maximum energy loss in a vertical drop equipped with horizontal screen with downstream rough and smooth bed

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ABSTRACT

Screens are one of the recent energy dissipator structures that can be used downstream of small hydraulic structures. In this study, screens were used horizontally at the brinks of the vertical drop with downstream smooth and rough bed to investigate the energy loss of the drop. Experiments were performed on two porosities of screens, a relative critical depth of 0.13–0.39 and a median size of 1.9 cm aggregates. The results showed that for a relative critical depth of more than 0.3 in a vertical drop equipped with a screen with a rough bed, the drop length with respect to smooth bed increases. Compared to applying a Type I stilling basin, a vertical drop equipped with a screen with downstream smooth and rough bed reduces the drop length by approximately 50%. Although a rough bed increases air entrainment, it has no effect on the energy loss and pool depth of a vertical drop equipped with a horizontal screen with smooth bed. The use of horizontal screens at the brinks of the vertical drop causes maximum energy loss in the downstream of drop. Equations were provided to estimate the flow parameters with a R^2 value of more than 0.925 and a normalized root mean square error of less than 0.04.

Key words: energy loss, rough and smooth bed, screen, vertical drop

HIGHLIGHTS

- Introducing a relatively new structure to create energy loss is presented.
- The importance of energy loss in open channels flow is stated.
- Using accurate laboratory results, the amount of energy loss in the channels has been investigated.
- To understand the problem, proper hydraulic analysis is done.
- The results of this research can be generalized in the design of hydraulic structures.

NOTATION

The following symbols are used in this paper:

B	flume width (m)
Q	flow discharge (m^3/s)
g	acceleration due to gravity (m/s^2)
ρ	density of water (kg/m^3)
μ	dynamic viscosity (kg/m·s)
E_u	total energy upstream of the drop (m)
E_d	downstream specific energy (m)
L_{ds}	total drop length (m)
L_d	drop length (m)
L_b	basin length (m)
P	screen porosity (-)
y_c	critical depth (m)
q	unit discharge of flow (m^3/s·m)

h drop height (m)
y_u upstream depth of drop (m)
y_d downstream depth of drop (m)
y_p pool depth (m)
L_{wet} wetting length of screen (m)
ΔE energy loss (m)
Fr_u upstream Froude number (–)
Fr_d downstream Froude number (–)
Re_u Reynolds number (–)
k_s median size of rough bed sands (m)
σ surface tension (ML^{-1})

INTRODUCTION

Vertical drops are among the most commonly used water management structures because of their ease of construction compared to options. Vertical drops are commonly used in mountainous areas to reduce steep slopes. Flow downstream of the drop often has a destructive kinetic energy. If this destructive energy is not controlled and reduced, downstream structures will be exposed to erosion and potential damage. A hydraulic jump in the stilling basin is commonly used to reduce this energy, as discussed, for example, in Daneshfaraz *et al.* (2020a) and Abbaspour *et al.* (2019).

The first studies of vertical drops with the upstream subcritical flow were made by Bakhmeteff (1932). He presented an equation to calculate the downstream depth of the drop by assuming a hydrostatic pressure distribution and a uniform velocity distribution in the energy equation. Subsequently, extensive experimental studies have been performed to characterize the flow over a simple vertical drop. Many of these researchers investigated the total energy loss and the hydraulic parameters for plain vertical drops (Gill 1979; Rajaratnam & Chamani 1995; Chamani *et al.* 2008).

Square steps with different heights were investigated by Esen *et al.* (2004). The results of that study showed that as the step height increased, energy loss and the vertical downstream depth of the drop also increased. Hong *et al.* (2010) utilized a positive slope in the downstream bed of a drop and showed that by increasing the bed slope, the drop length and force on the downstream bed is increased.

Chiu *et al.* (2017) carried out a numerical investigation on the various plunge pool lengths with a vertical drop and found that the three types of flow regimes (skimming, nappe and periodic oscillatory flows) occurred. The flow regime depends on the discharge and geometry of the pool. Kabiri-Samani *et al.* (2017) performed experiments to study energy loss for a vertical drop equipped with grid dissipaters. They showed that using a dissipater increased the energy loss and the authors proposed equations to predict energy loss.

Abrari *et al.* (2017) developed a theoretical method to investigate the brink depth for a vertical drop in an inverted semi-circular channel with a steep slope. The results of that study provided an equation to estimate the discharge using brink depth. The influence of tailwater depth on the vertical hydraulic performance of a vertical drop equipped with grid dissipaters was also studied experimentally by Sharif & Kabiri-Samani (2018). The results showed that as the tailwater depth increases, air entrainment decreased. Recently, Shubing & Sheng (2019) developed a theoretical model of a vertical drop with a steep slope and bed friction. Their predictions of the water surface profile, discharge, and brink depth were in good agreement with the laboratory results.

Air entrainment is a phenomenon commonly employed to cause energy loss. In fact, the use of vertical screens promotes air–water mixing and two-phase flow has been one of the methods in recent years (Daneshfaraz *et al.* 2017). The first studies on vertical screens were carried out by Rajaratnam & Hurtig (2000). They showed that the Froude number downstream of the screens was approximately 1.65 for all laboratory conditions. Results also showed that the thickness of the screen had no effect on the energy loss, but modifications to the number of screens and the shape of the apertures did have an impact (Mahmoud *et al.* 2013; Daneshfaraz *et al.* 2017; Sadeghfam *et al.* 2019).

Recently, the application of a horizontal screen at the brink of a vertical drop has been considered as an energy dissipater. Horizontal screens increase energy loss by creating several falling jets and increasing downstream turbulence. Daneshfaraz *et al.* (2021a) investigated the effect of a horizontal screen on the energy loss of a vertical drop with the upstream subcritical flow. The experiments were performed with a 15 cm drop height, screens whose porosity was 40 and 50%, and a relative critical depth that ranged from 0.128 to 0.4. The results show that the utilization of a horizontal screen at the brink of a vertical drop increases the flow energy loss.

The stability of rivers and channels is often related to the stability of its bed. Creating a natural rough bed is a method that increases bed roughness and decreases the flow rate, thereby protecting against erosion (Keller 2004). Rough beds were first studied in 1968 (Rajaratnam 1968). Subsequently, various researchers have studied the effect of a rough bed on a hydraulic jump and have showed that height, density, and the shape of roughness elements can affect the hydraulic jump (Ead & Rajaratnam 2002; Tokyay 2005; Carollo *et al.* 2007; AboulAtta *et al.* 2011; Parsamehr *et al.* 2017).

By simultaneously applying a vertical drop and a horizontal screen, we hope to show a significant increase in energy loss downstream of these structures. On the other hand, no studies have been carried out on vertical drop equipped with a horizontal screen and a downstream rough bed. This combination is expected to increase energy loss and reduce bed erosion. Consequently, this combination will be the focus of the current study.

METHODOLOGY

Building and testing hydraulic models is one of the important study and experimental tools. For this purpose, in the present study, experiments were performed to investigate the energy loss of a vertical drop equipped with a horizontal screen on a downstream rough bed. First, effective parameters were identified and dimensional analysis was performed. Subsequently, the laboratory model was constructed based on the considered conditions. After making the model, the relevant experiments were performed and the data were measured. Finally, the obtained data were analyzed. Figure 1 shows the methodology flowchart of the present study.

Dimension analysis

Figure 2 is prepared to illustrate physical and hydraulic parameters of the flow; these parameters are indicated in Equation (1).

$$\Delta E = f_1(\sigma, \rho, \mu, g, q, B, h, P, y_c, y_u, k_s, E_u) \quad (1)$$

Here, σ is the surface tension (ML^{-1}), ρ is the density of water (ML^{-3}), μ is the dynamic viscosity ($ML^{-1}T^{-1}$), g is gravitational acceleration (LT^{-2}), q is the unit discharge of flow (L^2T^{-1}), B is the flume width (L), h is the drop height (L), P is the screen porosity ratio (–), y_c is the critical depth (L), y_u is the upstream depth of drop (L), k_s is the median size of rough bed sands (L) and E_u is the total energy upstream of the drop (L) ($E_u = h + 15y_c$). Using the π- Buckingham's theorem, the total

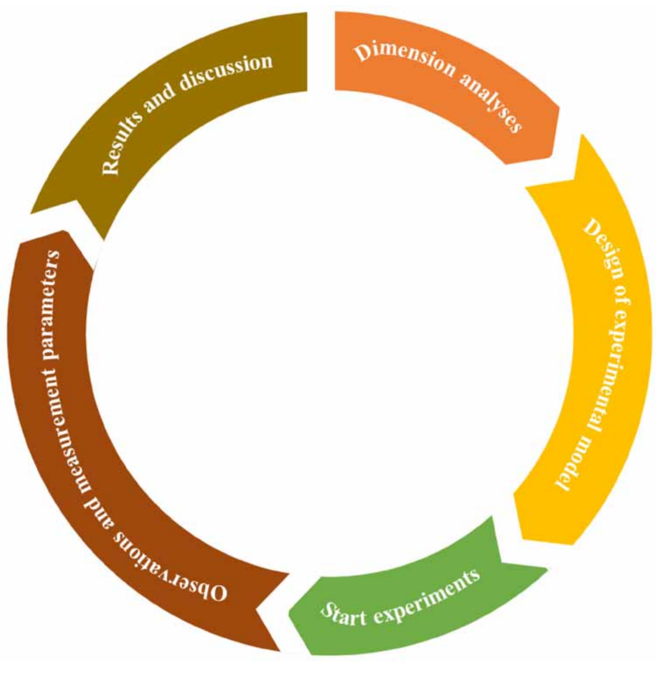

Figure 1 | The methodology flowchart.

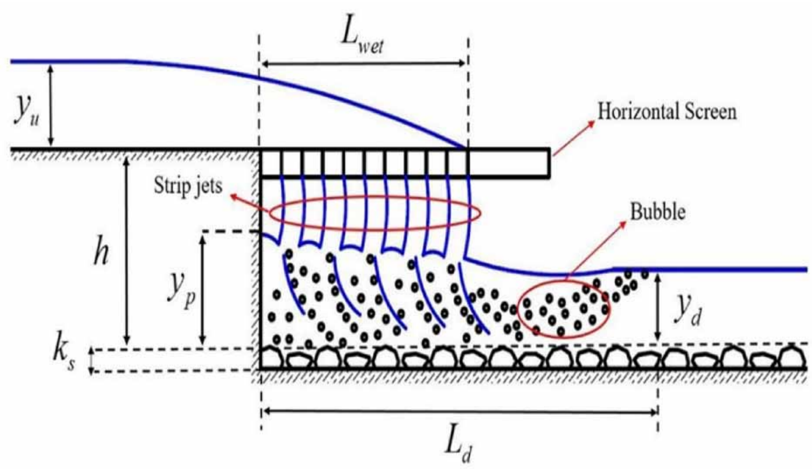

Figure 2 | Illustration of the flow features.

relative energy loss was obtained on the basis of the independent dimensionless parameters in Equation (2):

$$\frac{\Delta E}{E_u} = f_2\left(\frac{y_c}{h}, P, \frac{k_s}{h}, Fr_u, \mathrm{Re}_u, We\right) \tag{2}$$

By applying the same method, Equation (3) was obtained for the wetted length of horizontal screens, the depth of the pool, and the drop length:

$$\frac{y_p}{h}, \frac{L_{wet}}{y_c}, \frac{L_d}{h} = f_3\left(\frac{y_c}{h}, P, \frac{k_s}{h}, Fr_u, \mathrm{Re}_u, We\right) \tag{3}$$

Since the wetted length of the horizontal screen is independent of the drop height and the roughness of the downstream bed and also it is influenced by the upstream of drop, Equations (2) and (3) can be modified to

$$\frac{y_p}{h}, \frac{L_d}{h}, \frac{\Delta E}{E_u} = f_4\left(\frac{y_c}{h}, P, \frac{k_s}{h}, Fr_u, \mathrm{Re}_u, We\right) \tag{4}$$

$$\frac{L_{wet}}{y_c} = f_5(P, Fr_u, \mathrm{Re}_u, We) \tag{5}$$

In these equations, $\Delta E/E_u$ is the total energy loss, y_c/h is the relative critical depth, P is the screen porosity, y_p/h is the relative pool depth, L_{wet}/y_c is the relative wetting length of screen, L_d/h is the relative drop length, k_s/h is the relative grain height of rough bed, Fr_u is the Froude number at the upstream of drop, Re_u is the upstream Reynolds number and We is the Weber number. Since the Reynolds number range is between 8,335 and 38,900, the flow is quite turbulent, viscosity and surface tension effects can be neglected (Hager & Bremen 1989; Bagherzadeh *et al.* 2022). The flow upstream of the drop is subcritical, and the Froude numbers are low ($0.69 < Fr_u < 0.86$), so the effect of this parameter on Equation (4) is neglected (Daneshfaraz *et al.* 2021b, 2021c). Finally, Equations (4) and (5) are modified as follows:

$$\frac{y_p}{h}, \frac{L_d}{h}, \frac{\Delta E}{E_u} = f_6\left(\frac{y_c}{h}, P, \frac{k_s}{h}\right) \tag{6}$$

$$\frac{L_{wet}}{y_c} = f_7(P, Fr_u) \tag{7}$$

The relative critical depth in the present study ranged from 0.13 to 0.39.

Laboratory characteristics

In the present study, a rectangular laboratory flume with length, width, and height of 5, 0.3, and 0.45 m was used. In this flume, water from a reservoir under the flume is introduced into the inlet tank by two pumps with a minimum and maximum discharge of 2.5 and 7.5 L/s. At the end of the flume, there is an outlet tank that returns the incoming water to the flume to the lower tank after a length of 5 m. A glass with 6 mm thickness with a length of 1.2 m was used to construct a vertical drop at the beginning of the flume. In order to create a rough bed, sand with a median grain size of 1.9 cm was used (All sand was passed through a sieve of 0.75 in and remained on a sieve of 0.5 in.). Sand grains were adhered to the glass and located on flume bed, and horizontal screens were prepared with circular apertures of 1 cm diameter arranged in a zigzag pattern. In this way, 40 and 50% porosity screens were created (Daneshfaraz *et al.* 2020a, 2020b, 2021a). The distance between screen holes and its edge is half the diameter of its hole (5 mm). Figure 3 shows a schematic of the experimental model in the present study.

After constructing the laboratory model and installing the horizontal screen, the pump was turned on. Then, when stable flow conditions were achieved, the parameters of discharge (Q), upstream drop depth (y_u), wetted length of the horizontal screen (L_{wet}), the pool depth (y_p), drop length (L_d), and downstream depth (y_d) were measured. A rotameter installed on the pump was used to measure the discharge. For measuring depth, a point gauge with an accuracy of 1 mm was used and the desired depth was measured at five locations along a traverse and the average value was determined. A ruler with 1 mm accuracy was used to measure the wetted length and drop length. In all experiments, the upstream flow of the drop was considered subcritical. In total, 108 different experiments were carried on rough and smooth bed; the ranges of variables are presented in Table 1.

Drop length theory

The downstream Froude number (Fr_d) is calculated by using Equation (8) (Rand 1955):

$$Fr_d = \left(\frac{y_c/h}{y_d/h}\right)^{1.5} \tag{8}$$

Figure 3 | Schematic of the laboratory model on rough bed.

Table 1 | Range of measured variables

P	Q (L/s)	y_u (cm)	L_{wet} (cm)	y_p (cm)	L_d (cm)	y_d (cm)
40%	2.5–13.3	2.45–6.5	9–45	3.6–10.2	18–56	2.6–7.1
50%	2.5–13.3	2.45–6.5	8–37.5	3.7–10.3	16–55.5	2.6–7.1

Prior researchers, for instance, Esen *et al.* (2004) have presented predictive calculations for the relative downstream depth as in Equation (9).

$$\frac{y_d}{h} = 0.4824\left(\frac{y_c}{h}\right)^{1.1854} \tag{9}$$

Using these equations, the Froude number downstream of the plain vertical drop can be expressed as:

$$Fr_d = 2.985\left(\frac{y_c}{h}\right)^{-0.278} \tag{10}$$

In the present study, the relative critical depth range is between 0.13 and 0.39, so the range of the downstream Froude number for the plain vertical drop is between 3.9 and 5.3. If a Type I stilling basin is installed downstream of the drop to dissipate the flow energy, the total drop length is obtained from Equation (11) (see in Figure 4):

$$\frac{L_d}{h} = \frac{L_{ds}}{h} + \frac{L_b}{h} \tag{11}$$

In the above equation, L_{ds}/h and L_b/h are the relative lengths of the plain vertical drop and the stilling basin downstream of the drop, respectively. They can be calculated from the following equations:

$$\frac{L_{ds}}{h} = 4.3\left(\frac{y_c}{h}\right)^{0.81} \tag{12}$$

$$\frac{L_b}{h} = \frac{220 y_d \tanh\left(\frac{Fr_d - 1}{22}\right)}{h} \tag{13}$$

RESULTS AND DISCUSSION

Laboratory observations show that by applying a horizontal screen on the brink of vertical drop, a single failing jet is converted into several strip jets. This causes the formation of numerous submerged small hydraulic jumps (a succession hydraulic jumps) and increased air entrainment. Due to the high turbulence and the submerged hydraulic jump formation, the initial depth, roller length and jump length could not be measured. The presence of a downstream rough bed also increased air entrainment compared to the smooth bed (Figure 5). Following the experiments, the relevant calculations were performed, and the wetted length, pool depth, drop length, and energy loss were evaluated.

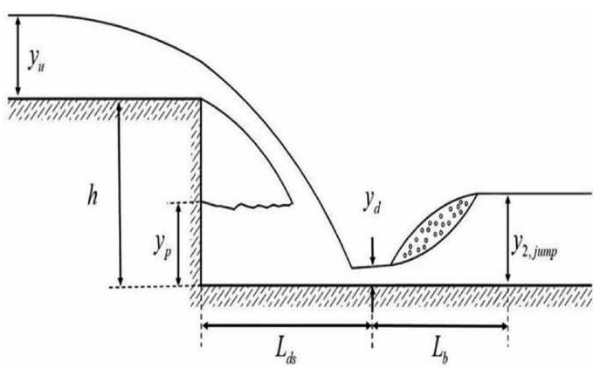

Figure 4 | Vertical drop schematics equipped with a downstream stilling basin.

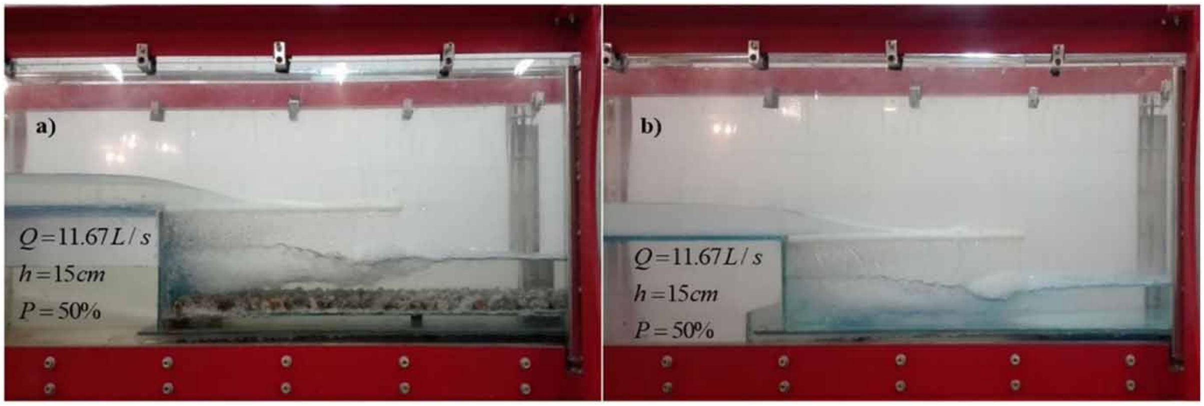

Figure 5 | Air entrainment created in the present study: (a) rough bed and (b) smooth bed.

Wetted length of a horizontally oriented screen

The length of a horizontal screen soaked by flow is known as the wetted length. Figure 6 shows the changes of relative wetted length of screen versus the upstream Froude number.

It is concluded from Figure 5 that when the Froude number increases, the wetted length also increases. Increasing the Froude number drives the flow away from the brink of the vertical drop and results in an increase in the wetted length. Also, for a constant Froude number as shown in Figure 6, the screens with 50% porosity have more apertures than a 40% porous screen, more flow passes through their apertures and they have a lesser wetted length. A comparison of the wetted length of horizontal screens for the two porosities shows that on average, the horizontal screen with 40% porosity increases the wetted length by about 14% compared to the 50% porous screens. Equation (14) was used to estimate the relative wetted length of the horizontal screens of the present study.

$$\frac{L_{wet}}{y_c} = 5.97 Fr_u^{2.09} P^{-0.646} \tag{14}$$

Figure 7 shows the comparison between the laboratory and calculated values of the relative wetted length. According to the figure, it can be seen that Equation (14) estimates the relative wetted length with an error of less than 10%. Also, the given

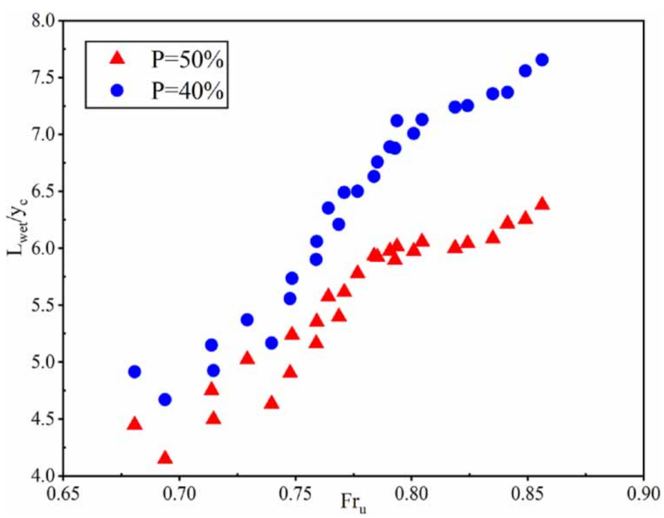

Figure 6 | The changes in the relative wetted length relative to the upstream Froude number.

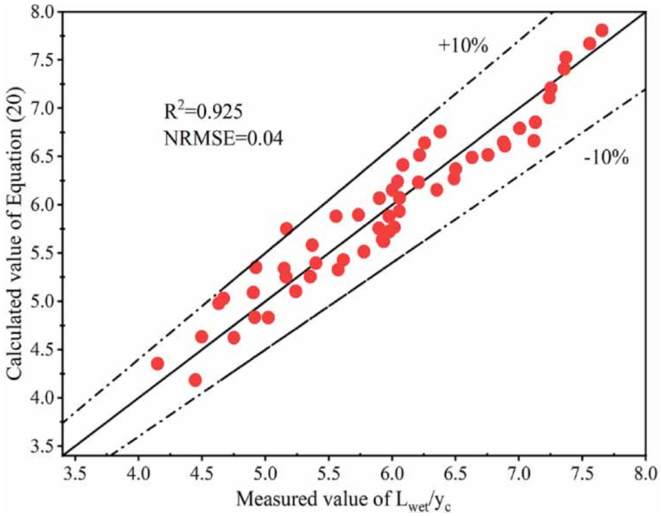

Figure 7 | Comparison of the measured and calculated values using Equation (14) for the relative wetted length.

equation has a determination coefficient (R^2) and normalized root mean square error (NRMSE) that are equal to 0.925 and 0.04, respectively.

Pool depth

The falling jets, after impacting with the downstream bed, causes some flow to return upstream to the vertical drop wall and form a pool behind the jet. The depth formed by the back flow near the wall of the vertical drop structure is called the pool depth. The pool depth values of the present study, along with the results of simple drop, are shown in Figure 8.

As seen in Figure 8, for the vertical drop with a horizontal screen with and without rough beds and for both screen porosities, the pool depth is an adaptation with results of Daneshfaraz *et al.* (2021a) and is increased compared to the simple vertical drop. This increase is due to the increase in the angle of the falling jet for the vertical drop equipped with a horizontal screen, compared to the absence of screens. Horizontal screens positioned at the brink of a vertical drop create a large number of submerged jumps in the pool and these submerged jumps also increase the relative pool depth. The average increase in the relative pool depth in the present study for porosities of 40 and 50% was 13.5 and 9.5%, respectively,

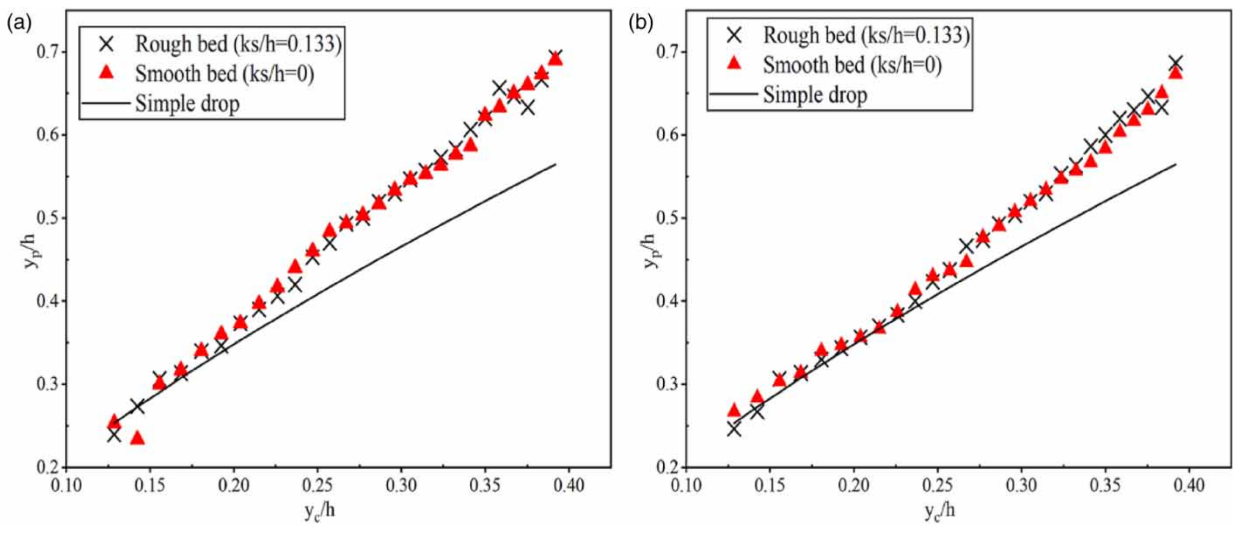

Figure 8 | Relative pool depth changes versus relative critical depth: (a) $P = 40\%$ and (b) $P = 50\%$.

compared to the plain vertical drop situation. Also, the relative pool depth of the rough bed, compared to smooth bed in both porosities, is not different.

Figure 8(a) and 8(b) compare the relative pool depths for a constant relative critical depth. It is seen that the lower porosity screens lead to a greater pool depth. The less porous screens have longer wetted lengths and the submerged jumps extend for a greater length. Equation (15), which can be used for predicting the pool depth of this study, is presented as follows:

$$\frac{y_p}{h} = 1.4\left(\frac{y_c}{h}\right)^{0.924} P^{-0.165} \tag{15}$$

Figure 9 shows that Equation (15) estimates the relative pool depth accurately. According to the figure, the Equation (15) has a relative error, R^2 and NRMSE that are equal to 8%, 0.99 and 0.021, respectively. It is worth noting that due to non effect of bed roughness on the pool depth of drop, k_s/h has not been considered in the presented equation.

Drop length

Passing strip jets through the horizontal screen and colliding them with the flume bed cause numerous jumps in the pool and create a uniform depth downstream of the falling jets. The longitudinal distance from the brink of the drop to the downstream depth of the drop is called the 'drop length' or the 'mixing length'. This length is always greater than the wetted length of the screens (Figure 2).

The drop lengths versus relative critical depth for both 40 and 50% porosity screens are shown in Figure 10. It should be noted that the length of the vertical drop for a Type I stilling basin was calculated based on Equation (11). The drop length versus relative critical depth for both 40 and 50% porosity screens is shown in Figure 10. It should be noted that the length of the vertical drop for a Type I stilling basin was calculated based on Equation (11). As shown in Figure 10, when the relative critical depth increases, the drop lengths for all models increase. In both screen porosities for critical depths less than 0.3, the results of drop lengths in the present study for a rough and smooth bed are correspond with the results of Daneshfaraz *et al.* (2021a). Also, for values of relative critical depth greater than 0.3, the drop length of rough bed is slightly increased compared to smooth bed and results of Daneshfaraz *et al.* (2021a). The reason for this behavior is the increase in air entrainment due to the collision of falling jets with the rough bed. The air bubbles created by the air entrainment tend to move along with the flow, the movement of these bubbles to downstream causes and the increase in the drop length (Figure 5).

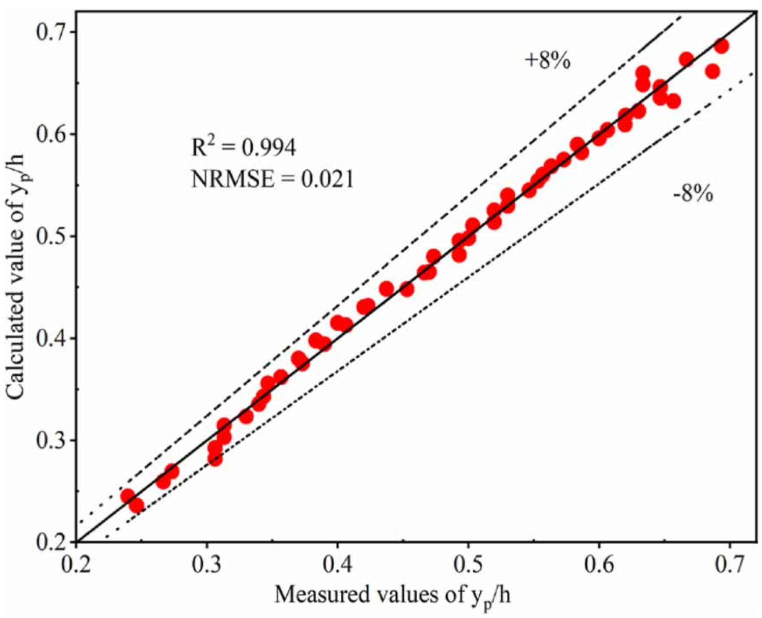

Figure 9 | Comparison of the measured and calculated values from Equation (15) for the relative pool depth.

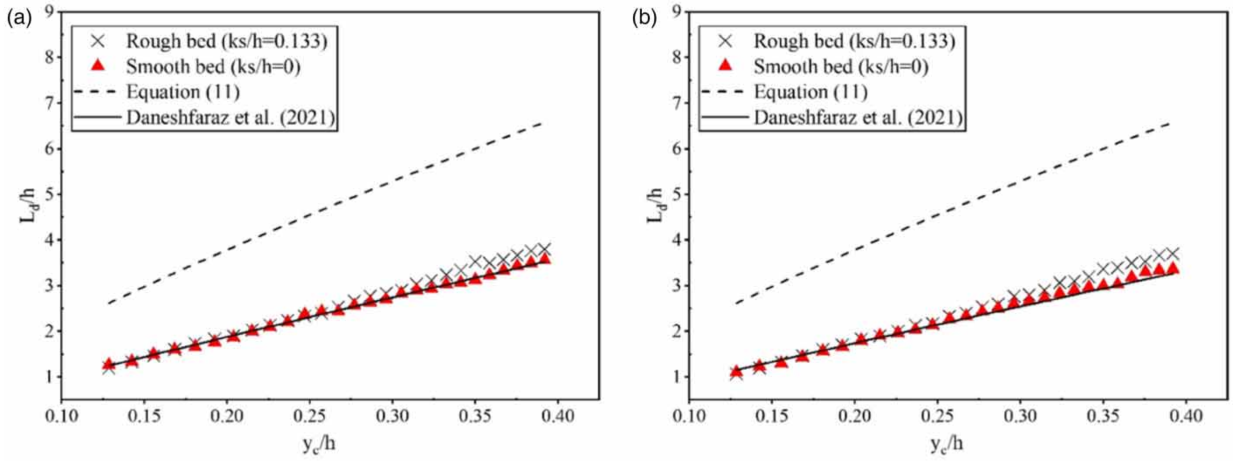

Figure 10 | Drop length variations versus relative critical depth: (a) $P = 40\%$ and (b) $P = 50\%$.

In Figure 10, it is observed that the utilization of screens significantly reduces the drop length compared to a Type 1 stilling basin. Also, the vertical drop length gradient of the present study is also lower than the vertical drop with a Type 1 stilling basin. This means that the greatest decrease in the length of the vertical drop occurs in the higher critical depths compared to using a stilling basin. Comparison of the values of the horizontal screen drop length for the two porosities in Figure 10(a) and 10(b) also shows that a 40% horizontal screen causes a larger drop length than a more porous screen. As noted earlier, the drop length created inside the pool is influenced by the wetted length of the horizontal screen. The results also show that vertical drops equipped with horizontal screens decrease the drop length by about 47.5 and 49.5%, respectively, for the 40 and 50% porosities (compared to a Type I stilling basin).

Equations (16) and (17), which can be used for predicting the vertical drop length of the present study with rough and smooth bed, are presented as follows:

$$\left(\frac{L_d}{h}\right)_{\text{Rough}} = 8.94\left(\frac{y_c}{h}\right)^{1.81} P^{-0.19} \quad (16)$$

$$\left(\frac{L_d}{h}\right)_{\text{Smooth}} = 7.06\left(\frac{y_c}{h}\right)^{0.97} P^{-0.25} \quad (17)$$

Figure 11 depicts the comparison between the laboratory and calculated values of the relative drop length. As seen, results determine that Equation (17) estimates the laboratory values accurately and has a good overlap with the laboratory data, so that its maximum relative error is equal to 10% and its R^2 and NRMSE are equal to 0.997 and 0.02, respectively.

Energy loss

Energy loss in vertical drops can be expressed as follows (Rajaratnam & Chamani 1995):

$$\frac{\Delta E}{E_u} = \frac{E_u - E_d}{E_u} \quad (18)$$

For a constant upstream flow of energy (E_u), if the flow energy downstream, (E_d) is a minimum value ($E_{min} = E_d$), and Equation (18) will have its maximum value. So, for the rectangular channel:

$$\left(\frac{\Delta E}{E_u}\right)_{\max} = \frac{(h + 1.5y_c) - 1.5y_c}{h + 1.5y_c} = \frac{h}{E_u} \quad (19)$$

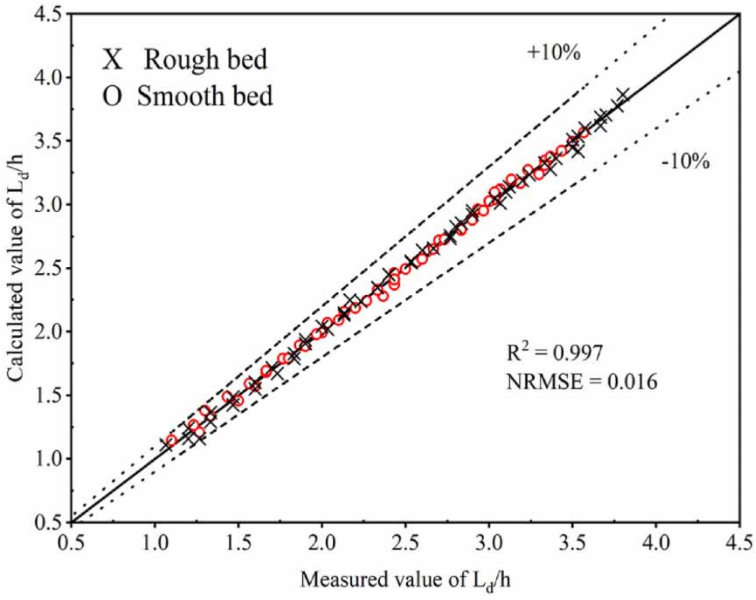

Figure 11 | Comparison of the measured and calculated values of drop length.

Equation (19) provides an estimate for the maximum energy loss that can occur in a vertical drop. The energy loss from the present study, Kabiri-Samani *et al.* (2017) and Daneshfaraz *et al.* (2021) is shown in Figure 12. A comparison of the energy loss in the figures shows that the porosity of the screens does not have as large of an effect on the energy loss.

In Figure 12(a), it is seen that the energy loss for a vertical drop equipped with a 40% horizontal screen and with a downstream rough bed compared to the smooth bed and results of Daneshfaraz *et al.* (2021a) overlap each other. The bed roughness has little effect on the energy loss of a vertical drop equipped with a horizontal screen in comparison to the smooth bed. This is due to the maximum energy loss that occurs in the vertical drop (Equation (19)). Also, it can be seen that energy loss from Kabiri-Samani *et al.* (2017) is greater than the maximum amount that can occur in vertical drops and is not in agreement with predictions from Equation (19). It seems that the approach presented by Kabiri-Samani *et al.* (2017) is not capable of accurately estimating the flow energy loss and this failure needs further investigation.

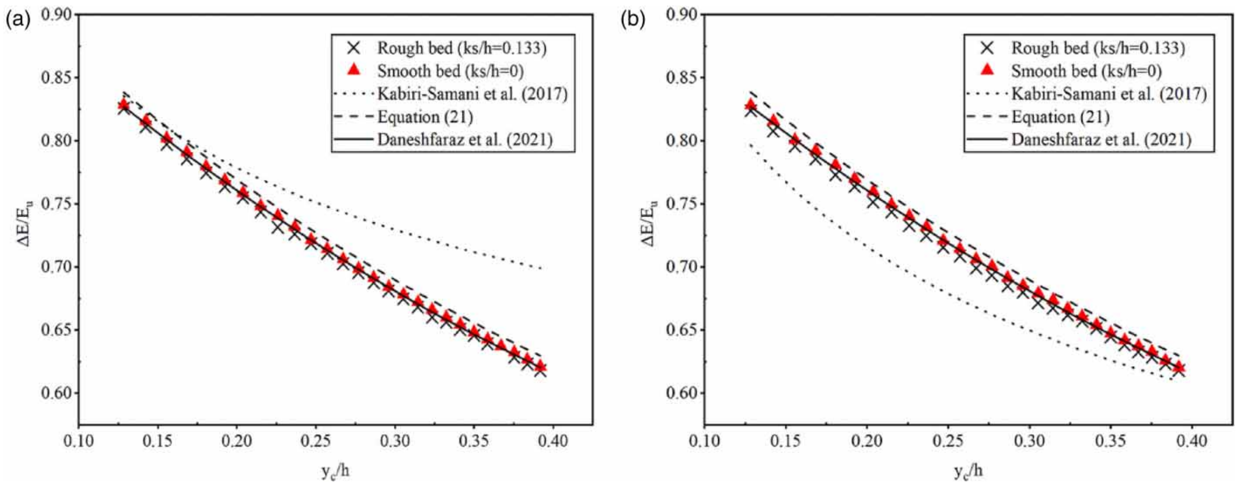

Figure 12 | Energy loss changes versus relative critical depth: (a) $P = 40\%$ and (b) $P = 50\%$.

In Figure 12(b), for 50% porous screens, the energy loss of a vertical drop equipped with the horizontal screens with rough and smooth bed, and Daneshfaraz *et al.* (2021a) have values close to the maximum energy loss. When the energy loss for screens of 50% porosity is compared to the results of Kabiri-Samani *et al.* (2017), the comparison shows that a vertical drop equipped with a horizontal screen with a rough and smooth bed has greater energy loss. The differences in the shape and size of the aperture and the zig-zagging arrangement of the horizontal screen apertures in the present study are some of the parameters that might explain the increase in energy loss of the present study compared to Kabiri-Samani *et al.* (2017).

In order to estimate the energy loss of the vertical drop equipped with the horizontal screen with a rough and smooth bed, Equation (20) with the coefficient of determination of 0.987 and the NRMSE of 0.012 is presented (Figure 13).

$$\frac{\Delta E}{E_u} = 0.48\left(\frac{y_c}{h}\right)^{-0.26} P^{-0.033} \tag{20}$$

Sensitivity analyzed

The results of sensitivity analysis are presented in the Table 2. In this table, for independent parameters, the amount of increase and decrease of 10–40% is considered, and based on the presented relationships, the sensitivity of the model to decrease and increase of the parameter is calculated. As can be seen, for all the studied parameters, the changes in the porosity of the screen have the least effect on the model compared to the other parameter and the maximum effect for the wetted length of the screen (Equation (14)) is related to the upstream Froude number of the drop. In addition, in other case (Equations (15) to (20)), the relative critical depth has the greatest impact on the model.

CONCLUSION

In the present study, the energy loss flow passing through vertical drops equipped with a horizontal screen with downstream rough and smooth bed was investigated. Experiments were performed using a constant drop height, two different screen porosities and a relative critical depth ranging from 0.13 to 0.39. The results show that by increasing the upstream Froude number and decreasing the screen porosity, the relative wetted length of screens increases. The results also show

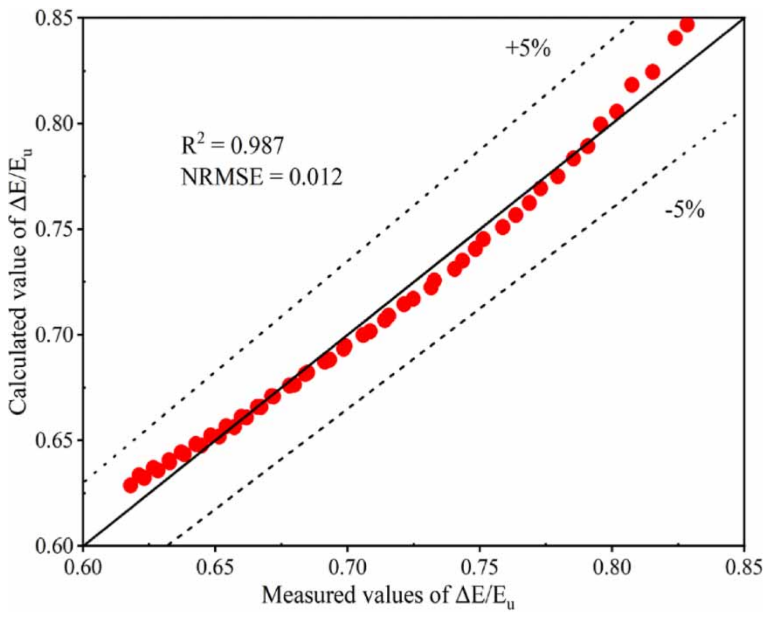

Figure 13 | Comparison of the measured and calculated values of Equation (20) for energy loss.

Table 2 | The results of sensitivity analysis

		Increase			Decrease		
		Parameters			Parameters		
Equation number	Percentages applied (%)	y_c/h	Fr_u	P	y_c/h	Fr_u	P
14	10	–	1.220	0.940	–	0.802	1.070
	20	–	1.464	0.889	–	0.627	1.155
	30	–	1.730	0.844	–	0.475	1.259
	40	–	2.020	0.805	–	0.344	1.391
15	10	1.092	–	0.984	0.907	–	1.018
	20	1.183	–	0.970	0.814	–	1.038
	30	1.274	–	0.958	0.719	–	1.061
	40	1.365	–	0.946	0.624	–	1.088
16 or 17	10	1.188	–	0.982	0.826	–	1.020
	20	1.391	–	0.966	0.668	–	1.043
	30	1.608	–	0.951	0.524	–	1.070
	40	1.839	–	0.938	0.397	–	1.102
20	10	0.976	–	0.997	1.028	–	1.003
	20	0.954	–	0.994	1.060	–	1.007
	30	0.934	–	0.991	1.097	–	1.012
	40	0.916	–	0.989	1.142	–	1.017

that a vertical drop equipped with a horizontal screen with rough bed had a negligible effect on the energy loss and pool depth compared to the smooth bed. However, for a relative critical depth of more than 0.3, the vertical drop length equipped with a horizontal screen with a rough bed increases compared to situations with smooth beds. Also, the use of horizontal screens at the brink of a vertical drop with a rough and smooth bed reduces the total drop length by approximately 50% compared to a Type 1 stilling basin and creates maximum energy loss. Another advantage of applying horizontal screens at the brink of a vertical drop is to avoid the need for a tailwater depth to form a hydraulic jump. A decrease in the screen performance due to blockage of their apertures by debris flow is a disadvantage that can occur with horizontal screens. If the pores can be prevented from being blocked, these screens can be a good alternative for a stilling basin downstream of the vertical drop. It should be noted that turbulence and air entrainment are increased through the use of horizontal screens. Such structures can be used for aeration in fish farming pools, mixing chemicals in water for water treatment and agricultural as well as in wastewater chlorination.

DATA AVAILABILITY STATEMENT

If needed, all data will be made available to the readers.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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