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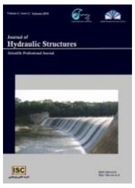

Experimental Investigation on the Deviated Sediment and Flow to Sediment Bypass Tunnels (SBTs) Using Submerged Plates

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Abstract

In recent decades, although dam construction has increased in number and multiplicity, unfortunately, most of these dams are subjected to sediment accumulation during their operation period. As a scientific way, Sediment Bypass Tunnels (SBTs) could be hired to solve this problem. They are deviant channels that convey the current containing sediments from the upstream of the reservoir to the downstream of the dam. In this research, the effect of hydraulic parameters of flow and changes in the angle of plates on sediment transport and deviated flow have been investigated through applying submerged plates on the entrance of a 90-degree diversion channel for sediment transport and then, compared with the state without using submerged plates. The experiments were conducted on a 10-meter-long laboratory flume, with a main channel of 60 cm width and a secondary channel of 30 cm width and a height of 75 cm. In this regard, the variables of Froude number and flow depth in three angles of 30, 45, and 60 degrees were assumed. The results of this study highlight that an increase in Froude number averagely reduced 22.2% and 53.3% the channel deviated flow and sediment to the secondary channel, respectively. The 60-degree angle of the plates was effective in decreasing the deviated flow while the 30-degree angle was responsible for the increased deviated sediments. With a decrease in Froude number and depth along with submerged plates with a 30-degree angle, the optimum condition in conveying sediments is achieved where the maximum amount of sediments is conveyed in the minimum flow rate. Based on experimental data, the best equation proposed to calculate the deviated sedimentation flow using the Genetic Algorithm (GA).

Keywords: sediment conveyance, Sediment Bypass Tunnel, performance, secondary flow, submerged plates.

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1. Introduction

Sedimentation, which hinders optimum consumption of water stored in the dam reservoir, is considered to be an important issue once the construction of dams is implemented. Hence, understanding the problem of sedimentation in dams and how to deal with it is very essential. In recent decades, although dam construction has increased in number, unfortunately, most of these dams encounter sedimentation problems during their service lives [1]. The effective storage capacity of water is decreased due to the entry of sediments and their accumulation in the dam reservoir. This accumulation of sediments, in turn, will reduce hydroelectric power and irrigated land and will devastate flood moderation capacity. If sediments reach the dam body, they could be accumulated in the outlets and could block the intake valves of the power plant and deep outlets. In addition, sediments that reach the hydroelectric power plant outlets can erode and corrode turbines and tank bottom valves. Moreover, the load on the dam will also increase. In this situation, different scientific solutions such as hydraulic flushing, sluicing, density current venting, siphoning, and sediment bypass tunnels can be used for management of reservoir sedimentation ([2]-[4]). Sediment Bypass Tunnels (SBTs) are deviant channels that convey the current containing sediments from the upstream to the downstream of the reservoir. In this system, either by moving the sediments pre-accumulated in the reservoir to the entry of these tunnels or by entering the sediments deposited by the river into these tunnels, the sediments will be transmitted to the downstream of the reservoir [5]. The first SBTs were constructed in Japan and Switzerland in the early 20th century, and a decade was dedicated to reducing their construction rates [6]. SBTs Type 1 of Lake Ashi in Japan has significantly reduced the volume of sediments formed after its construction in 1998 and even during a major flood occurred in 2011 due to hurricane, SBTs effectively limit the internal current of sediments inside the reservoir [7]. Recent studies focus on the resistance of tunnels against hydraulic erosion as well as the combination of laboratory research and numerical models. For example, Boes et al. [7] and Cajot et al. [8] studied the characteristics and concentration of suspended sediments in an experimental model with a scale of its actual sample, and their research has become a tool for calibrating previous numerical models. Emamgholizadeh and Samadi [9] conducted a study on the using of SBT method at the upstream of the Dez Reservoir Dam and concluded that construction of a submerged dam at a distance of 9 km from the dam as well as building a tunnel with a diameter of 28.8 m and a length 15 km could improve the possibility to discharge 11.3 million cubic meters of sediment. According to the Auel and Boes [10], SBTs should be sufficiently sloped to prevent sedimentation, and at the same time, their slope should be as gentle as possible to prevent their erosion by limiting the flow rate. So far, no research has been conducted on the amount of sediment entry into SBTs while numerous studies have been carried out to determine the sediment input into the intake where these investigations and experiments were aimed at reducing the incoming sediment. The variation of the sediment ratio to the ratio of deviated flow on the direct intake in Barkdoll [11] research had a maximum deviated flow of 38%. Obviously, the experiments of this researcher were conducted under conditions without sediment injection. Therefore, by carrying bed sediments and increasing depth, the power of transport of the flow decreased, and by increasing the deviated discharge ratio, the ratio of the sediment input to the intake reached to zero. The study of Barkdoll et al. [12] on lateral intake in direct channel and 90-degree dewatering angles revealed that the deviated flow ratio had the most effect on the deviation ratio. Izadpanah and Salehi Neishabouri [13] conducted laboratory experiments on a 90-degree bend via changing the location of the intake led to conclusion that less sediments would be deviated by the 75 degrees' bend compare to those of 65 and 70-degree ones. By conducting experiments at different angles of the canal with different positions and Froude numbers, Pirestani [14] concluded that an angle of 60 degrees for a position of 115 degrees in a 180-degree bend was appropriate. Research by Abbasi [15] on intake in the direct direction of the river showed that the presence of the sill would reduce the width of the vortex at the beginning of the intake and, as a result, reduce sediment entry and sediment width in the inlet entrance, and the effect of the sill on high deviation ratios compared to low deviation ratios is more effective.

Behbahani and Shafaei Bajestan [16] conducted experiments on water intakes with 75 and 90-degree bends and concluded that the deviation flow rate was mostly dependent on the Froude number at the upstream water intake, and the deviation rate at 75 ° with similar conditions was estimated less than the discharge ratio of the SBTs at 90 degrees. Also, the longitudinal dimension of the detachment surface in the deviation of 90 ° with the variable rate of the deviation flow did not show significant changes and in the width dimension, the detachment surface at a deviation angle of 75 °, had a greater width where with increased deviation flow ratios, the separation surface was decreased.

Sediment entry from the main channel with trapezoid cross-section to the 30-degree water intake was investigated experimentally by Karami et al. [17]. The results indicated that decreasing depth would result in reduced power of secondary flow and consequently reduced sediment load into the reservoir. Salemnia and Shafaei-Bajestan [18] examined the effect of dewatering change on the sediment loading rate of the submerged bed in a trapezoidal channel with a 60-degree dewatering angle compared to the flow direction with and without the installation of submerged plates. The results of this study demonstrated that by increasing the dewatering ratio from 7.5 to 16 percent, the amount of sediment input to the reservoir in both cases with and without submerged plates increased by an average of 23 percent. An experimental study conducted by Jafari-Mianaei and Ayyoubzadeh [19] on the effect of the slope of the main channel wall on the amount of sediment input to the lateral intake with and without the installation of submerged plates proved that application of submerged plates in both the vertical wall and the sloping channel of the main channel decreased the amount of sediment input to the catchment; however, this reduction in steep wall conditions, specifically in low water absorption ratios compared to the vertical wall condition, was considerably higher wherein sloped wall conditions, the amount of sediment input to the intake decreased by 100% with installation of submerged plates and a diversion ratio of 12%. Hashid et al. [20] studied the characteristics of the flow of circular lateral intake and concluded that the flow rate of this type of pond depended on Froude number and the ratio of the outlet to the width of the main channel.

By concluding previous studies, it is evident that most studies related to SBTs were either field or case studies and most of them focused on the intake channels, and dedicated the flow pattern in deviated channels and optimization of the sub-channel angle and incorporation of sediment control structures to reduce the sedimentation rate. Hence, to convey more sediment in lower deviation flows, it is crucial to conduct experiments to study the effect of different parameters on the performance of the SBTs. Therefore, in this research, by changing the angle of submerged plates, it has been attempted to study the effect of hydraulic parameters of the flow on the sediment transport compared to the condition without submerged plates.

2. Materials and Methods

Experiments were conducted in Hydraulics Laboratory of Islamic Azad University, Shahrood Branch on a fluctuating research flume with a length of 10 meters, the main channel width of 60 cm and a width of 30 cm and a height of 75 cm. The bed material was made of painted metal plate, and the walls were made of glass with 8 mm thickness (Fig. 2a). The secondary channel location, which is a rectangular canal with a length of 2.2 m, is at a distance of 4 meters from the beginning of the main channel. By employing hydraulic and geometric variables effective on the input flow behavior of SBTs, one could find a relationship to determine deviated sediment ratio. To achieve this, first, by using dimensional analysis, the non-dimensional variables effective in this region are determined, and then, their effect will be examined. Independent and effective variables in this area are: main channel width (B), secondary channel width (b), longitudinal slope of main channel (S_0) and submerged plate angle (ϴ), average speed of flow in the main channel (U) and flow depth in the main channel (y), Q_m flow rate in the main channel, Q_l flow rate in the secondary channel, Q_r the deviated flow ratio, Q_{sm} sedimentation flow in the main channel, Q_{sl} sedimentation flow and Q_s the deviated sedimentation flow in the secondary channel, average material diameter (d_{50}), sediment specific weight (ρ_s) and the standard deviation of the distribution of aggregate size (σ_g), water specific weight (ρ), gravitational acceleration (g), and fluid kinematic viscosity (ν).

By defining the parameters $Q_r = {}^{Q_l}/_{Q_m}$ and $Q_s = {}^{Q_{sl}}/_{Q_{sm}}$ equation (1) is obtained:

$$f(Q_r, Q_s, U, S0, b, y, B, \Theta, d50, \sigma g, \nu, \rho, \rho s, g) = 0 \tag{1}$$

Using the Buckingham-π theorem and removing the constant parameters, the following dimensionless equation is achieved:

$$Q_s = f(Q_r, Fr, \Theta) \tag{2}$$

Before carrying out of each experiment, firstly, the sediment was sieved with a uniform diameter of about 1.1 mm at the bottom of the canal and in a layer at a thickness of 5 cm. Figure 1 shows the grain-size distribution curve of the substrate particles.

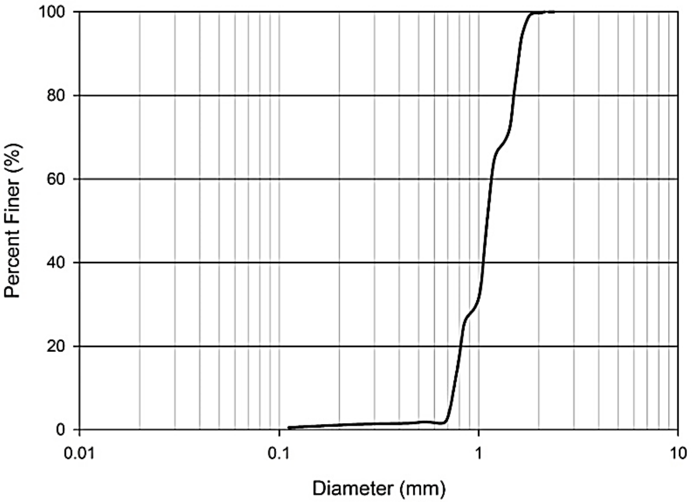
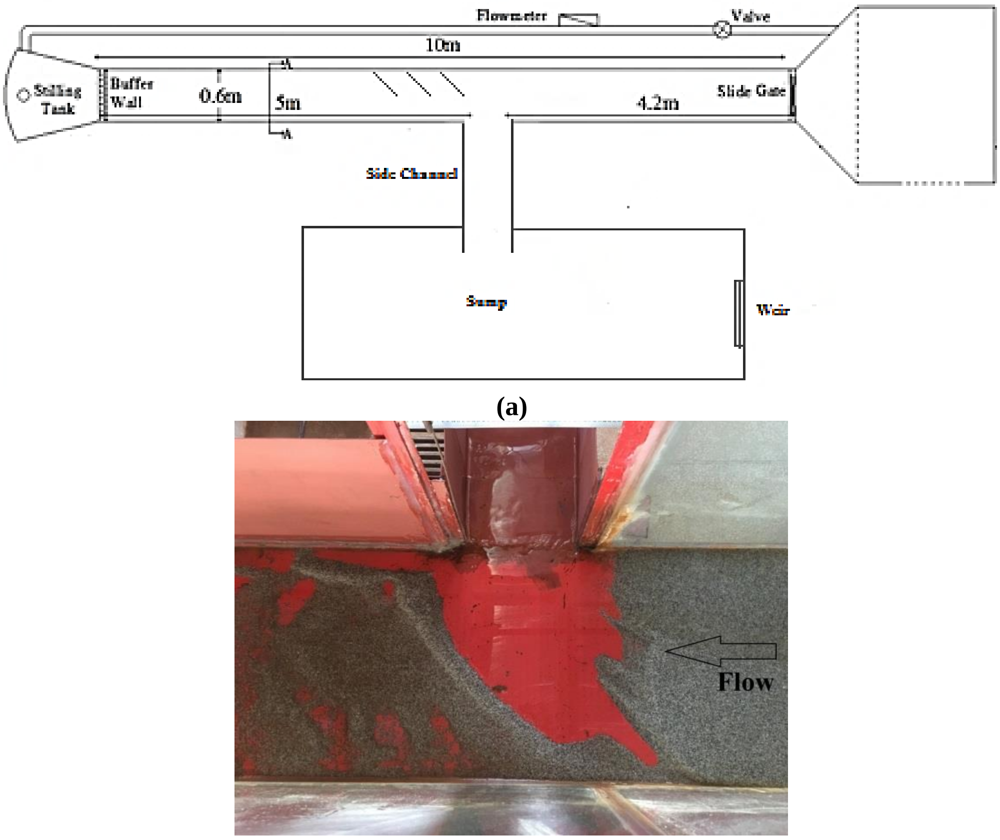


Figure 1. Grain-Size Distribution Curve of Experiments

Substrate sloping was then performed using the marker on the Flume wall indicating the slope and was controlled with the help of the hydraulic corrector. After leveling and preparing the bed, the water slowly entered the upstream stilling basin and then entered the Flume. First, with the help of the control valves on the inlet pipes, a small flow entered the Flume so that it does not move the substrate and that the bed remained constant. By holding down the downstream valves, the water level was raised inside the Flume. After increasing the depth of water, the flow rate was increased with the help of the inlet valves of the flow and simultaneously with the change of the downstream valves, the depth of flow and the main channel flow was adjusted using altimeters installed on the main channel and upstream of the spillway. Flow change and downstream valve adjustment continued until the preferred depth and discharge were achieved for the test. Eventually, after reaching the desired flow and depth, the experiment continued until complete washing out of the sediments. (Figure 2b)



(a)

(b)

Figure 2.a) Schematic Diagram for the Laboratory flume,
b) Washing out the sediments in the main channel

The sediments were then collected at the end of the main channel and the Deviated channel and were drained in special sieves, and after placement in the oven, the weight of the sediments was measured. In order to determine the effect of using submerged plates, three metal sheets with a height of 5 mm were hired. The sheets were placed in one-third of the width of the main channel adhering to the wall in front of the secondary channel (Fig. 3). The experiments were carried out in three angles of submerged plates 30, 45 and 60 degrees relative to the axis of flow, with constant holding of 50, 70 and 98-mm depth for each of 5 different discharges, which led to 5 different Froude numbers and the results were compared with the condition without using submerged plates. Table 1 demonstrates the values of the variables in the experiments and the number of experiments performed. According to Table 1, 60 tests were conducted to compare different situations.

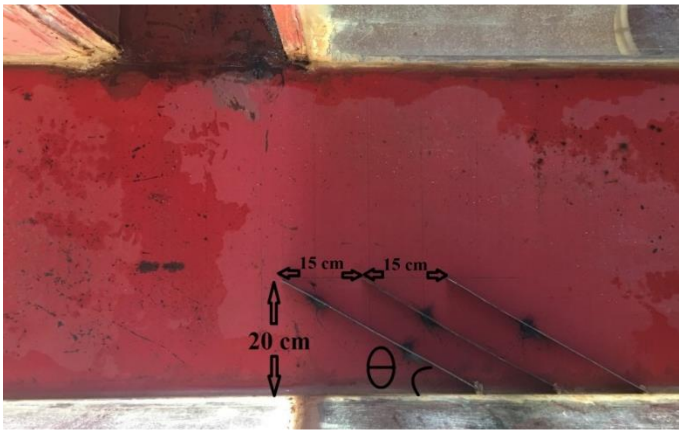


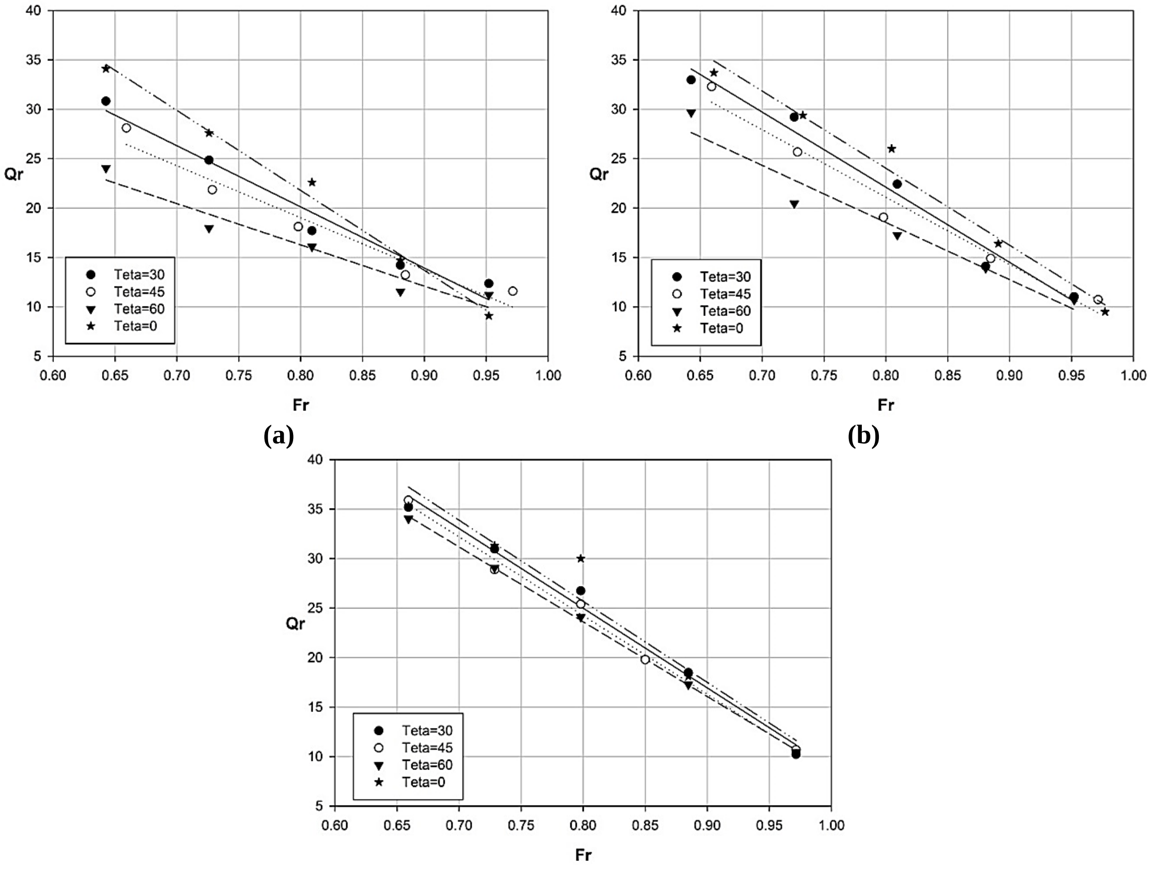
Figure 3.Dimensions of submerged plates in the main channel

Table 1. Values of variables for tests without submerged plates and submerged plates with angles 30, 45 and 60 degrees

Froude Number	Main Channel Discharge (liters/sec)	Flow Depth (cm)	Test No.
0.64	13.5	50	1
0.73	15.25	50	2
0.81	17	50	3
0.88	18.5	50	4
0.95	20	50	5
0.66	23	70	6
0.73	25.5	70	7
0.8	28	70	8
0.88	30.5	70	9
0.95	33	70	10
0.66	38	98	11
0.73	42	98	12
0.8	46	98	13
0.88	51	98	14
0.97	56	98	15

3. Results and Discussion

Figure 4 shows the effect of the attack angle of the submerged plates on the amount of deviated flow at different depths. As can be seen, with an increase in the angle of the submerged plates, the amount of water deviations to the secondary channel decreases slightly, and as the flow depth increases, this change becomes subtle. The reason for this is that as the angle of the plates increase, the length of the plates decreases and the interaction of the flow and plates is decreased and centrifugal force decrease slightly and smaller amounts of flow are introduced into the secondary channel. Comparison of the results with the non-use of submerged plates ($\theta = 0$) indicates that the amount of flow diverted to the secondary channel decreases if submerged plates are used and the larger the angle of the plates, the lower the amount of flow deviation. The Froude number has an important effect on the amount of flow deviation into the SBTs. As the Froude number increases, the deviation rate decreases for all scenarios. The increase in the Froude number of mainstream flood at the upstream will increase the speed of the main channel (at a constant depth) and increasing the speed will reduce the centrifugal force and the power of the rotation of the current towards the secondary channel. A precise investigation of results reveals that an increase in Froude number, on average, would lead to a reduction of 22.2% of the deviated flow to the secondary channel. In the highest Froude numbers, the deviated flow values are almost constant, but there is a difference in the percentage of deviation in the lowest Froude numbers. By applying submerged plates at a 60-degree angle, the deviation flow rate of the non-submerged plate condition was 10% for y / B = 0.83 and 4% for y / B = 1.17 and decreased by 1.3% for y / B = 1.63. According to the results, it can be stated that the incorporation of submerged plates at a 60-degree angle along with an increase in the Froude number was effective in reducing the deviated flow to the secondary channel.

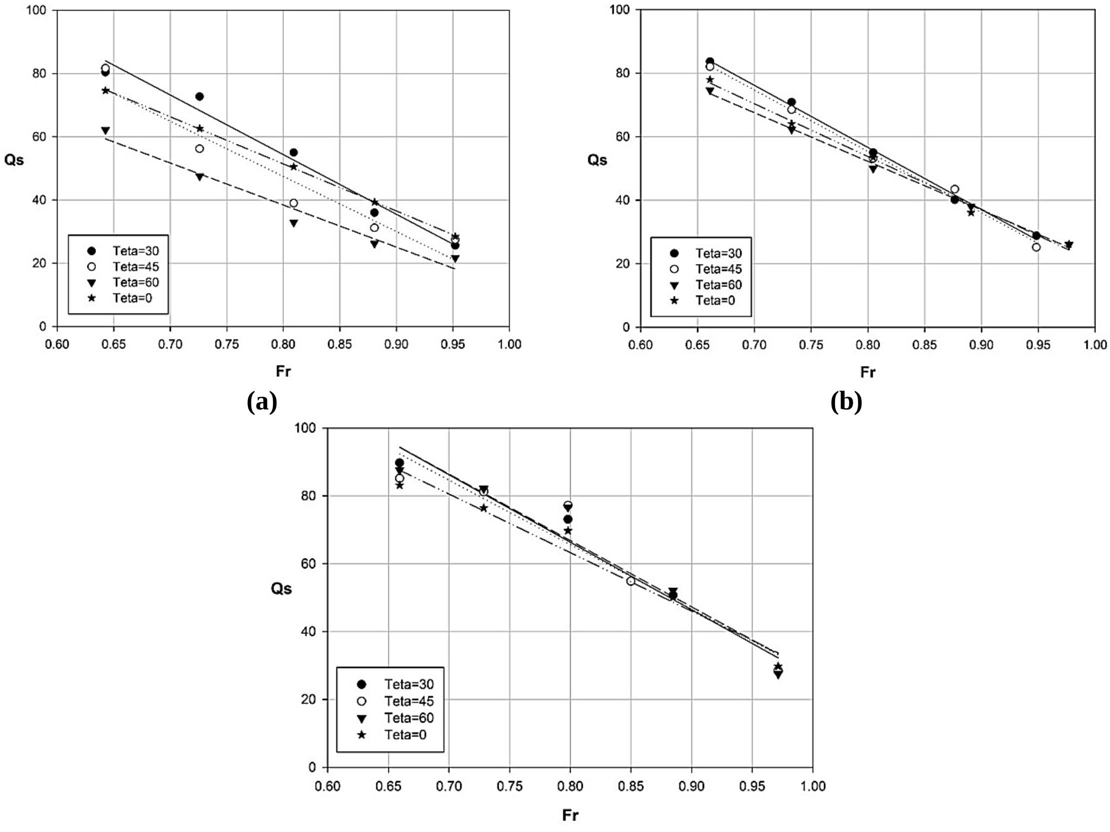


(a) (b)

(c)

Figure 4. Changes in the ratio of deviated flow to the main flow with Froude number: a) y/B = 0.83, b) y/B = 1.17, c) y/B =1.63

Figure 5 shows the effect of changing the angle of submerged plates on deviated sediments in different depths. As can be seen, with an increase of the angle of the submerged plates in the ratio of y/B=0.83, the amount of deviated sediments decreased, but with increasing flow depth to y/B = 1.63, no change in deviated sediments rate was observed. The high-speed flow at the water level, as compared to the low-speed flow at the bottom of the channel, requires more power to change direction. The higher the ratio of the velocity of the intake flow to the current velocity in the main channel, the more power is added to the secondary flow of the secondary channel which is an effective factor in sediment conveyance. Increasing the angle of the plates caused a sudden decrease in the velocity of the intake flow to the secondary channel, thereby reduced the centrifugal force, which eventually reduced the sediment conveyance to the secondary channel. But at higher levels, the effect of the plates on the flow velocity in the upper layers decreased and caused the angular changes to be ineffective in changing the amount of deviated sediments. Increasing the Froude number due to reduced centrifugal force reduced the input velocity to the secondary channel, which reduced the power of the secondary flow generated in the secondary channel and also the transfer of sediments in it. A numerical study of the results highlights that the increase in the Froude number would mean an average of 53.3 percent of the deviated sediment to the secondary channel. In experiments with the highest Froude numbers, deviated sediment values were almost constant, while in the lowest Froude number values, the difference in deviated sediments was evident for lower depths and by applying submerged plates at a 60-degree angle, the deviated sediment amount compared to non-submerged plate conditions decreased by 12.4% for y/B=0.83 and decreased by 3.4% for y/B=1.17 and increased by 4.4% for y/B=1.63. According to the results, it can be said that the increase in the Froude number was effective in reducing the sediment deviations to the secondary channel, but the incorporation of plates with a 60-degree angle only affected the higher depths to a negligible amount, and a 30-degree angle resulted in better sediment transport.

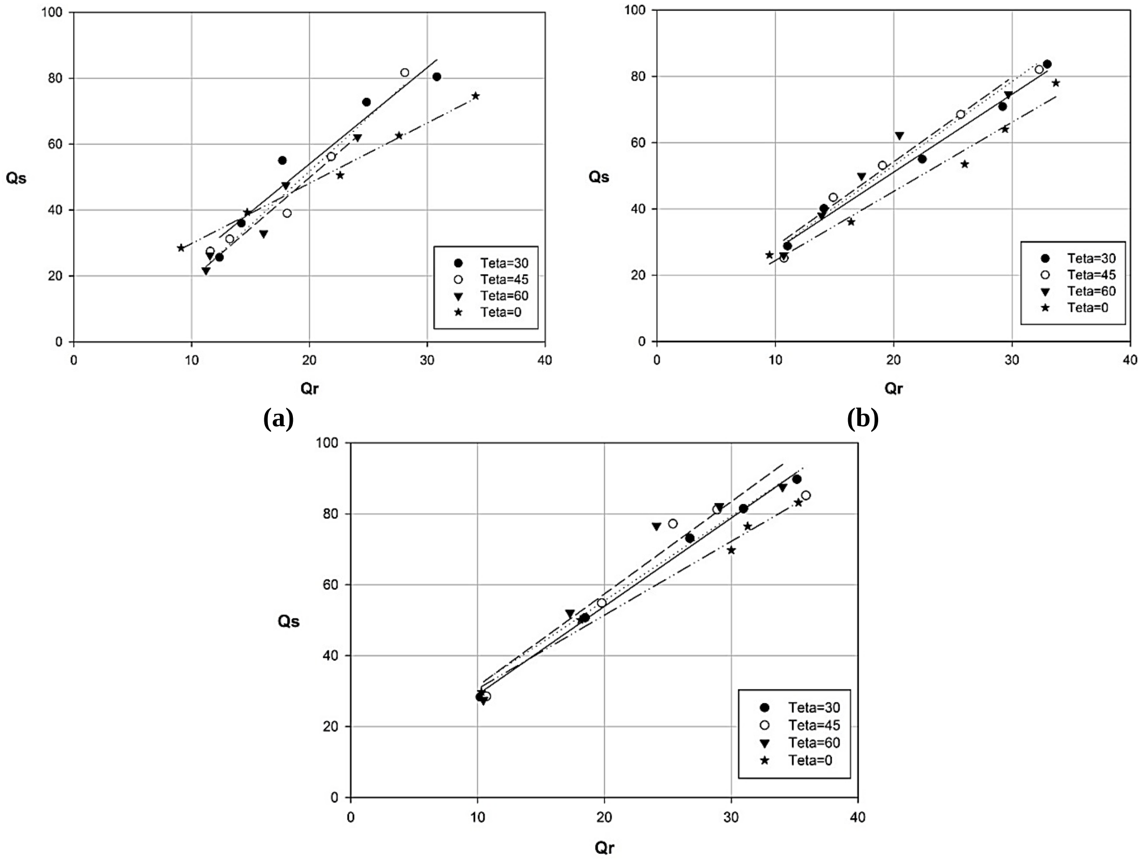


(a) (b)

(c)

Figure 5. Changes of the ratio of deviated sediments to total sediments with Froude number: a) y/B = 0.83, b) y/B = 1.17, c) y/B =1.63

According to the results, it can be said that the higher the deviated sediments and the lower the deviated flow, the better the results and the better the performance. In other words, in the case of better hydraulic conditions and placement of submerged plates, the best results will be obtained if, in lower deviated flows, higher amounts of sediments are deviated. Therefore, by defining the parameter Eta (the ratio of deviated sediments to the deviated flow, Q_s/Q_r) as a function, the conditions of the experiments were investigated. Figure 6 shows a comparison of secondary channel performance in the abovementioned states. Regarding the gradient shape of each graph, the value of the parameter of the function will be expressed, and the higher the amount, the secondary channel deviates more sediments and fewer flows. Once the performance parameter is greater than 1, the optimum condition is achieved. According to the results, it can be seen that in all cases, the values of the performance parameter were greater than 1 and ranged from 1.84 to 3.4. Therefore, a 90-degree secondary channel had a good performance in sediment transport. According to the results, it can be concluded that incorporation of submerged plates can increase the performance parameter of the secondary channel, but the angle changes do not have much effect on the performance parameter.



(a) (b)

(c)

Figure 6.Changes in the ratio of deviated sediments to total sediments with the ratio of deviated flow to the main flow :
a) y/B = 0.83, b) y/B = 1.17, c) y/B =1.63

The slope of the line shown in Fig. 6 represents the mean performance value of the SBT in the range of the Froude number of the experiments. Therefore, to determine the optimal mode, the performance value for each model (the slope of each of the graphs in Fig. 5) was calculated, and its variations were plotted in terms of dimensionless parameters in Fig. 7. This shape actually indicates the interaction of deviated flow and deviated sediments in terms of flow depth.

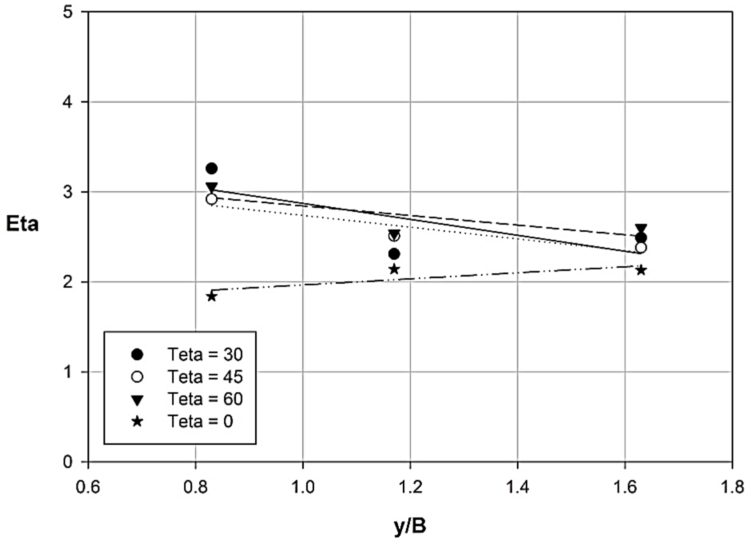


Figure 7. Performance parameter variations in terms of flow depth for different angles of submerged plates

As can be seen in Fig. 7, increasing the flow depth will improve performance in the non-submerged mode and will reduce performance in the use of submerged plates. But concerning Figure 7, incorporation of submerged plates will be more beneficial than not using them. On the other hand, changes in the angle of the submerged plates do not have a significant impact on the performance value, which makes fitting close in the Eta – y/B diagrams for different angles of the plates. Therefore, according to the results obtained in Figs. 4 and 5, it can be seen that the 30-degree angle of the plates provided the best option for the deposition of sediments. Therefore, by decreasing the Froude number and the depth and using submerged plates with a 30-degree angle, it is possible to optimize the sediment transport in such a way that maximum sediments are conveyed in minimum deviated flows.

After analyzing the results, this section presents a formula using Response Surface Methodology (RSM) in combination with two optimization methods, including GA and hessian gradient. The main reason for using this combination is the weakness of RSM or other curve fitting methods in minimizing a wide range of error functions. In fact, many of regression methods designed based on minimizing Mean Squared Error (MSE) and is not optimum for other error terms. The advantage of all hybrid methods is their ability to implement any error term or goodness of fit criterion as cost function.

For this purpose, based on the measurements, the parameters of the Froude number (Fr), the ratio of the width of the secondary channel to the main channel (b / B), the ratio of the flow depth to the main channel width (y / B), the angle of the submerged plates (θ) and the deviation flow rate Qr were considered as inputs and the sedimentation flow rate Qs was considered as output.

In both cases, the combination of training data and test data were 70% and 30%. The optimization criteria in both methods were to minimize the MSE firstly, and the second is to maximize the correlation coefficient between the output of the model and the actual output. Optimization of the model has been conducted on test data incorporating genetic algorithm and Hesssin gradient. The assumed parameters for GA are as follows: the GA was binary type, and 10 bits were assigned for each variable. In this way, the number of bits per chromosome was 60 bits. Initial starting points were randomly selected. The number of overlapping points according to the length of the chromosome was 5, and the mutation probability was assumed to be 0.01. The choice of the remaining samples was ideal. The number of replicates was 600, and the number of prototypes was 200. The selection of prototypes in search space was random. Eventually, four formulas were derived for the four assumed states where for each formula, relative error, Mean Squared Error (MSE) and the correlation coefficient for both training data and test data were computed (Table 2). A total of four implementations have been made (two times with a genetic algorithm for two different cost functions and two times with the Hessian gradient), and the results are presented in equations 3 to 6.

Equation Number		Mean Squared Error		Correlation Coefficient	
		Training data	Test data	Training data	Test data
(3)	Minimizing the Mean Squared Error (MSE), Genetic algorithm	33.189	29.570	0.957	0.964
(4)	Maximizing the correlation coefficient, Genetic algorithm	28.937	29.218	0.965	0.966
(5)	Minimizing the Mean Squared Error (MSE), Hessian gradient	33.169	29.948	0.957	0.964
(6)	Maximizing the correlation coefficient, Hessian gradient	28.946	29.222	0.963	0.964

$$Q_S(\%) = 35.25 - 49.98F_r + 12.9\frac{y}{B} + 2.27\tan\theta + 1.638Q_r \tag{3}$$

$$Q_S(\%) = 1.92\left(11.26 - 49.99F_r + 6.93\frac{y}{B} + 1.5\tan\theta + 0.544Q_r\right) + 127.24 \tag{4}$$

$$Q_S(\%) = 34.43 - 50F_r + 12.9\frac{y}{B} + 2.3\tan\theta + 1.65Q_r \tag{5}$$

$$Q_S(\%) = 62.65\left(0.1553 - 1.54F_r + 0.213\frac{y}{B} + 0.045\tan\theta + 0.0165Q_r\right) + 79.15 \tag{6}$$

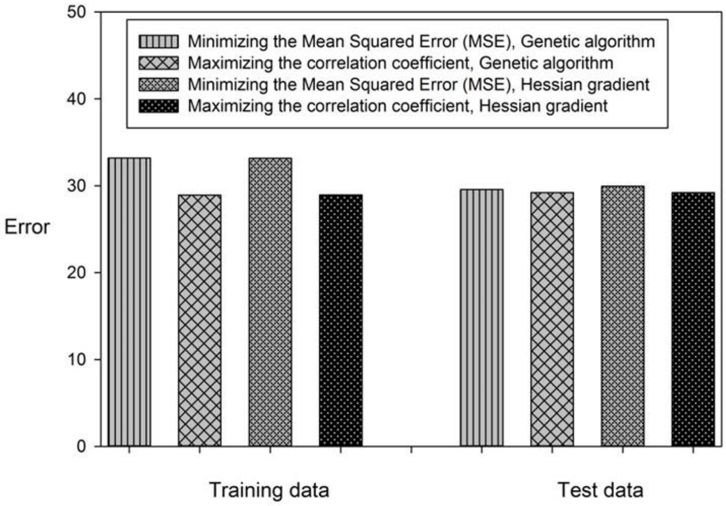


Figure 8.A comparison between different methods in training and test data categories

Figure 8 shows a comparison between the results of the error of different techniques where it can be concluded that the results of the genetic algorithm with the cost function of the correlation coefficient were better compared to other methods.

4. Applied Optimization techniques

In the present experimental study, the effect of the angle of the submerged plates on the amount of deviated flow and deviated sediments to the secondary channel were investigated, and the results were compared with the state without using the submerged plates. In this regard, three angles of 30, 45, and 60 degrees for the plates with different Froude numbers and flow depths were considered. The results of the research revealed that increasing the Froude number would reduce the deviated flow to the secondary channel by 22.2%. Incorporation of submerged plates with a 60-degree angle, along with increasing the Froude number, is effective in reducing the deviated flow to the secondary channel. Also, the increase in the Froude number on average leads to a reduction of 53.3% of the deviated sediments to the secondary channel and application of submerged plates with a 60-degree angle is only effective for higher depths and to a negligible amount to convey sediments, and the angle of 30 degrees would yield better results. In all cases, the values of the performance parameter were greater than 1 and varied from 1.84 to 3.26, and therefore, a 90° deviation channel had a proper performance in sediment transport. The use of submerged plates increased the performance parameter of the secondary channel, but angular variations did not have much effect on the performance parameter value. Also, by decreasing the Froude number and flow depth and using submerged plates with a 30-degree angle, it is possible to optimize the sediment transport in such a way that the maximum deviated sediments are obtained at minimum deviated flows. Based on test results, the best equation to calculate the deviated sedimentation flow (Qs) using the genetic algorithm is suggested as follows:

$$Q_s\,(\%) = 1.92\left(11.26 - 49.9F_r + 6.93\frac{y}{B} + 1.5\tan\theta + 0.544Q_r\right) + 127.24 \quad (7)$$

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