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Numerical Investigation of Successive Sluice Gates Performance in Regulating Flow Rate in Channels

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Abstract

Successive sluice gates are designed to maintain a stable discharge rate in open channels despite variations in upstream water levels. This study numerically investigates the hydraulic performance of successive sluice gates under different operational conditions. Four gate configurations and five upstream flow depths were simulated to analyze their flow regulation efficiency. The numerical results were validated against experimental data, revealing differences in outlet discharge of less than 10%, indicating that the simulation model provides reliable accuracy. Following model validation, the computed outflow rates for each configuration were compared with the corresponding design discharge, showing an average deviation of approximately 8% in all tested cases. These results confirm that successive sluice gates are capable of maintaining a nearly constant flow rate, even under fluctuating upstream water levels. Moreover, energy dissipation analysis showed that losses were negligible when only the first gate was active. However, as the upstream depth increased and additional gates were engaged, energy dissipation rose to about 15–22%. Overall, the findings demonstrate that successive sluice gate systems can effectively combine precise flow regulation with adequate energy dissipation, making them suitable for hydraulic structures requiring stable discharge control under variable inflow conditions.

Keywords:
Energy dissipation, FLOW-3D software, Successive sluice gates, Free surface flow.

1. INTRODUCTION

Efficient management of water resources is critical, particularly in the agricultural sector, which accounts for a substantial portion of freshwater consumption. A significant fraction of this water is conveyed through open channels, making effective flow regulation essential to mitigate water scarcity and ensure optimal utilization of available resources [1]. Hydraulic engineers commonly address this challenge by designing and implementing regulating structures such as sluice gates.

For vertical gates under free-flow conditions, the flow rate is often estimated using the Rajaratnam and Subramanya (1967) equation [2]:

$$Q = C_d w b \sqrt{2 g y_0} \quad (1)$$

where $Q$is the discharge, $C_d$is the discharge coefficient, $w$and $b$are the gate opening height and width, g is the gravitational acceleration, and y_0 is the upstream water depth. This relationship indicates that the flow rate per unit width depends not only on the gate dimensions and discharge coefficient but also on the upstream water depth, which varies under different hydraulic conditions [2].

To achieve more precise flow control, successive sluice gates have been introduced. These structures, first proposed by Larsen and Mishra (1990), consist of multiple vertical gates arranged sequentially with increasing heights downstream and decreasing openings [3]. Mishra et al. (1990) developed a three-gate structure to investigate successive gate performance, although the first gate had minimal effect on regulation [4]. Anwar (1999) enhanced this design by implementing the flow coefficient equation proposed by Swamee (1992), thereby ensuring that the first gate also plays an effective role in regulating the flow rate [5,6]. Bijan Khan et al. (2010) and Yarizadeh and Kouchakzadeh (2011) explored design optimization, hydraulic sensitivity, and the impact of floating debris on flow performance [7,8]. Barghi Khosrow et al. (2016) and Mehrzad et al. (2014) further improved gate module designs to minimize deviations from target discharge over varying upstream water depths [9,10].

Numerical modeling and computational fluid dynamics (CFD) have been widely applied to investigate sluice gate hydraulics [11, 12]. Kim (2007), Helmi and El-Gamal (2011) demonstrated that CFD simulations accurately predict flow behavior, including contraction, pressure distribution, and discharge coefficients, when validated against experimental data [13,14].

Recent advancements in hydraulic engineering have introduced various structural modifications to improve the discharge performance beneath sluice gates. Among these, the sill has been widely recognized for its effectiveness in enhancing flow rate by influencing the flow contraction and pressure distribution. Studies involving different sill geometries and channel widths have consistently reported an increase in discharge efficiency. However, limited research has addressed the role of the sill in downstream energy dissipation and its implications for hydraulic stability [15, 16, 17, 18, 19, 20].

Despite these advances, successive gates remain relatively underexplored [4].

This study presents a novel numerical investigation of successive sluice gates as high-efficiency flow regulators under a range of hydraulic conditions, with validation against established experimental data. Various gate configurations were systematically modeled to provide a comprehensive analysis of flow dynamics, energy distribution, and hydraulic performance. The study offers new insights into the optimization of gate arrangements for improved flow control, reduced energy loss, and enhanced system stability, highlighting its potential application in efficient water management and flood mitigation strategies.

2. MATERIALS and METHODS

In this research, Flow3D software was used to numerically simulate the flow through successive gates in 4 different models with varying distances between the gates. The channel dimensions and one of the models under investigation were taken from the experimental model of for validation, and 3 other models were investigated with different distances between the gates [4]. The modular range, i.e., the range of upstream depth variation, was considered to be 15 to 25 cm for all models. Each model was simulated and investigated for input flow depths of 15, 17.5, 20, 22.5, and 25 cm. All three gates have the same thickness of 2 cm, but their lengths and openings are different, such that the opening decreases and the gate length increases in the flow direction.

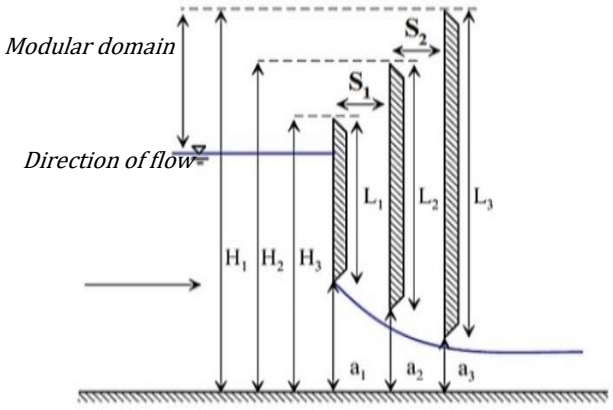

Figure 1. Schematic shape of the structure of sequential valves.

According to the experimental data of, the gates were placed in a channel with a length of 100 cm, a width of 10 cm, and a height of 50 cm, 32 cm upstream. The specifications of the simulated models are shown in Figure 1 and Table 1, [4].

Table 1 shows that the opening and length values of the gates are the same in all models. However, the distance between the gates varies to investigate the effect of this parameter on the structure's performance within the modular range.

Table 1. Specifications of simulation models

Model	Opening Values (cm)			Length Valves (cm)			Distance Between Valves (cm)	
	a_1	a_2	a_3	L_1	L_2	L_3	S_1	S_2
1	5.5	4.7	4.1	9.5	14.7	20.9	2	2
2	5.5	4.7	4.1	9.5	14.7	20.9	2	4
3	5.5	4.7	4.1	9.5	14.7	20.9	4	2
4	5.5	4.7	4.1	9.5	14.7	20.9	4	4

3. RESULTS AND DISCUSSION

In this research, the flow through successive gates in 4 different models has been simulated and investigated. The primary function of this structure is to deliver a nearly constant flow rate downstream despite variations in the upstream water depth. This is achieved by designing the successive gates with specific openings for a target flow rate. The expectation is that as the flow depth changes within the modular range, the output flow rate will remain relatively stable and close to the design flow rate. This constant discharge delivery capability aligns with the principles outlined by Larsen and Mishra [3], who developed constant discharge devices for field irrigation applications. In this study, data and experimental results from Mishra et al. (1990) were used for model simulation.

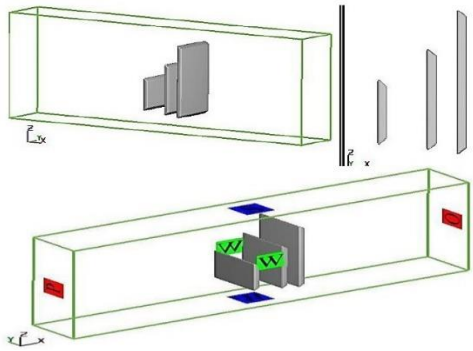

Figure 2. Computational network and boundary conditions applied to Consecutive S_{42} Model Valves

3.1. Validation of The Model

One of the most critical parts of research involving numerical methods is the validation and verification of the numerical model. To this end, the numerical results are compared with experimental data under identical conditions. In this study, for validation purposes, the output flow rates for the S_{22} model were compared with the experimental data of for a design flow rate of 0.5 liters per second per centimeter and gate spacing of 2 cm [4].

Table 2 and Figure 3 present the comparison of numerical results from the present study with the corresponding experimental data of Mishra et al. (1990) for the S_{22} model at different input flow depths.

Table 2. Calculation of Relative Percentage Error and Mean Absolute Error (MAE) of Output Flow Rate Values per Unit Width of Numerical and Experimental Results

$Z_{0.0}$	Results		$\% E_{cal}$	MAE
	Numerical	Experimental		
15	0.5369	0.4875	9.203	0.0494
17.5	0.5346	0.4983	6.785	0.0363
20	0.5225	0.5178	0.895	0.0047
22.5	0.5312	0.5269	0.809	0.0043
25	0.5448	0.5328	2.204	0,012

$Z_{0.0}$: Input Flow Depth (at x=0.0) (cm)

$\% E_{cal}$: Calculated Percentage Error

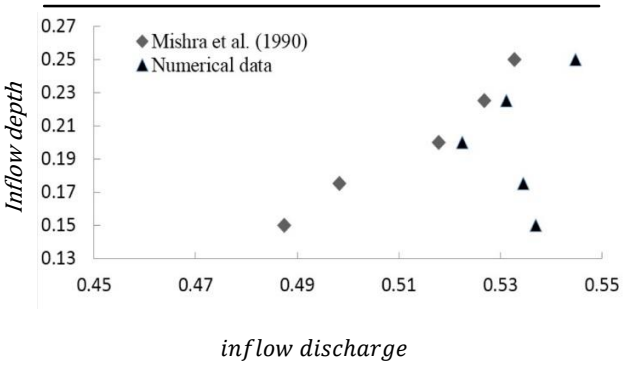

Figure 3. Comparison of Numerical Solution Results with Laboratory Data S_{22} Model

A noteworthy point in these data is that, unlike the experimental data, the numerical results show a higher output flow rate than the design flow rate for all input flow depths. Furthermore, the positive percentage error indicates that the numerical data are consistently higher than the experimental data, which could be attributed to factors such as mesh resolution, the method of defining the water surface profile in the software, and the application of boundary conditions.

As shown in Figure 3, the difference between the numerical solution data and the experimental results of is larger at lower input flow depths [4]. However, as the input flow depth increases, the numerical results become closer to the experimental data, and the model's percentage error decreases. Overall, the percentage error remains below 10%, indicating that the simulated model has acceptable accuracy.

3.2. Analysis of Numerical Solution Results

Considering that the primary function of successive gates is to deliver a relatively constant flow rate downstream despite variations in the input flow depth, the most critical parameter to analyze is the downstream output flow rate. The final output flow rate is the sum of the flow rates from overflow over gates 1 and 2, plus the flow rate passing under gate 3. While the contribution of each flow component can be examined, this section focuses on the total output flow rate.

Figure 4 illustrates the two-dimensional plots of flow depth and velocity variations along the channel for the S_{24} model with an input flow depth of 22.5 cm. It's important to note that the values shown in these figures for depth and velocity variations are

in meters and meters per second, respectively. In calculating the output flow rate, the software's output values were converted to the desired units, and the flow rate per unit width was compared with the design flow rate of 0.5 liters per second per centimeter. Table 3 presents the output flow rate values for the S_{24} model and their percentage error relative to the design flow rate.

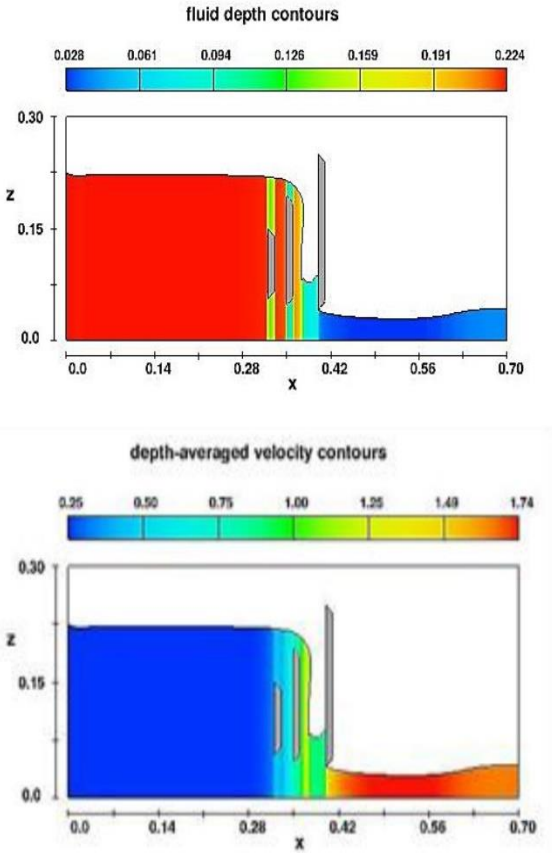

Figure 4. Two-Dimensional Plots of Flow Depth and Velocity Variations for the S_{24} Model with 22.5 cm Input Flow Depth

The percentage error values indicate that the output flow rate in the S_{24} model is close to the design flow rate, with an error of less than 7%. This performance is in line with Anwar's findings, which showed that under various upstream situations, multi-baffle module designs could maintain discharge within allowable deviation ranges [5].

Similarly, the output flow rates for the S_{44} model were calculated using the depth and velocity data from the software and compared with the design flow rate. Figure 5 shows the flow rate values for both the S_{24} and S_{44} models. The percentage error of the S_{44} model relative to the design flow rate is presented in Table 3.

Table3. Output Flow Rate Values for the S_{24} Model and Their Percentage Error with the Design Flow Rate

$Z_{0.0}$	$Z_{0.7}$	V_O	q_{Cal}	q_{Des}	% E
15	3.76	142.3	0.535	0.5	6.55
17.5	3.50	152.8	0.535	0.5	6.51
20	3.13	166.7	0.522	0.5	4.17
22.5	3.15	167.4	0.527	0.5	5.17
25	2.87	187.9	0.539	0.5	7.28

q_{Cal}: Calculated Flow Rate per Unit Width (L/cm·s)

q_{Des}: Design Flow Rate per Unit Width (L/cm·s)

$Z_{0.0}$: Input Flow Depth (at x=0.0) (cm)

$Z_{0.7}$: Output Flow Depth (at x=0.7) (cm)

V_O : Average Flow Velocity at Outlet Section (cm/s)

% E : Relative Percentage Error

The percentage error values for the S_{44} model are similar to those of the previous models, with a maximum difference of approximately 8% from the design flow rate.

Comparing the output flow rates of the four models shows that their percentage errors relative to the design flow rate are nearly the same.

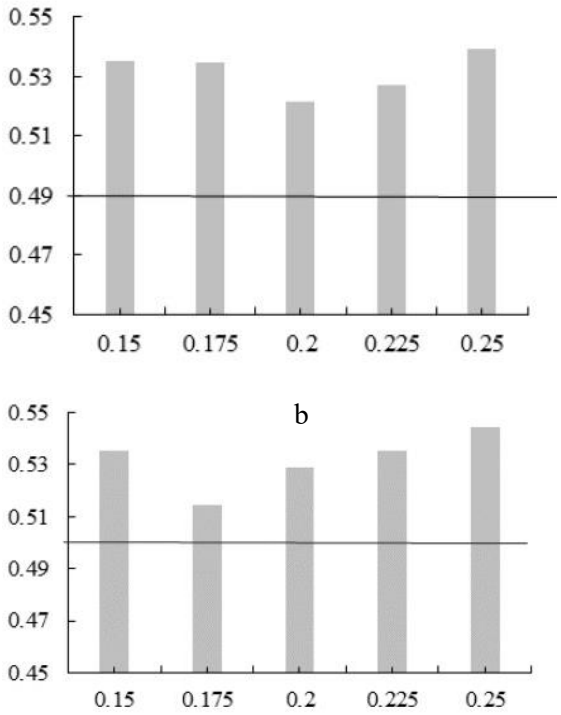

Figure 5. Output Flow Rate Values for (a) S_{24}Model, (b) S_{44} Model

Therefore, the spacing between the successive gates has a negligible effect on their performance and can be disregarded. Mehrzad et al., who developed design standards for parallel baffle modules and showed that spacing factors within specific ranges had no effect on discharge control performance, concur with this conclusion [10]. The model error with the design flow rate is given in Table 4.

Table4. Output Flow Rate Values for the S_{44} Model and Their Percentage Error with the Design Flow Rate

$Z_{0.0}$	$Z_{0.7}$	V_O	q_{Cal}	q_{Des}
15	3.76	0.535	0.5	6.55
17.5	3.38	0.514	0.5	2.81
20	3.18	0.529	0.5	5.45
22.5	3.01	0.535	0.5	6.57
25	2.77	0.544	0.5	8.14

The results indicate that the successive gate structure performs well in regulating flow in all four studied configurations, making it suitable for application in irrigation networks. These results corroborate the findings of Larsen and Mishra and Mishra et al. about how well baffle-sluice modules work to maintain steady discharge for irrigation applications [3-4].

Figure 6 compares the output flow rates of the models. This figure shows that the output flow rates do not differ significantly, and the performance of the models is similar.

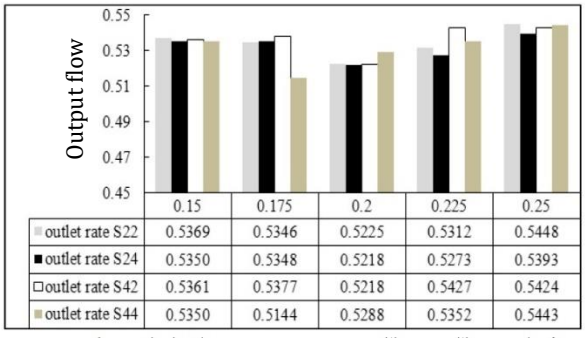

Figure 6. Comparison of Output Flow Rate Values of the Models

Analysis of Specific Energy of Flow Before and After Successive Gates

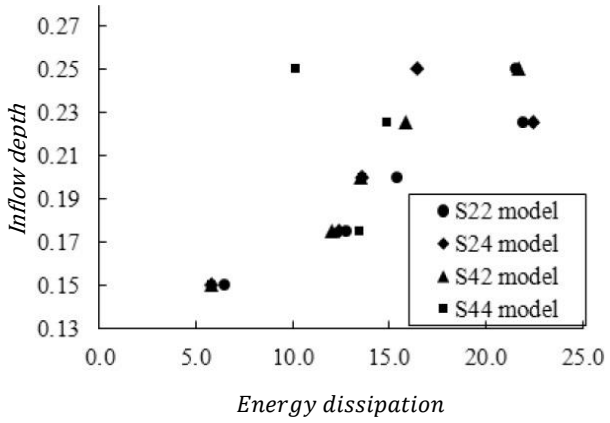

Figure 7. Comparison of Percentage of Energy Dissipation in the Models

Single vertical gates, in their typical application, are not very effective in energy dissipation, and the energy loss due to flow under the gate is generally disregarded. However, successive gate structures, due to the presence of three vertical gates in the flow path, can dissipate some of the flow energy.

Therefore, this section of the research investigates the energy dissipation in the models by calculating the specific energy of the flow (in meters) at two sections before and after the successive gates (sections A and B) using Equation 2:

$$E = y + \frac{v^2}{2g} \quad (2)$$

Where: E is the specific energy of the flow, y is the flow depth, and v is the flow velocity. The percentage of energy dissipation in the models is calculated using Equation 3:

$$\text{Energy Dissipation Percentage} = \frac{E_A - E_B}{E_A} \times 100 \quad (3)$$

Where: E_A is the specific energy of the flow before the successive gates, and E_B is the specific energy of the flow after the gates.

Table 5 and Figure 7 show the percentage of energy dissipation for the four models at different input flow depths.

Table 5. Percentage of Energy Dissipation in the Models

$Z_{0.0}$	Energy Dissipation by Each Model (%)			
	S_{22}	S_{24}	S_{42}	S_{44}
15	6.45	8.15	5.85	5.82
17.5	12.78	12.4	12.02	13.45
20	15.42	13.59	13.55	13.64
22.5	21.92	22.5	15.91	14.93
25	21.54	16.51	21.75	10.16

The results in the table indicate that the amount of energy dissipation increases with increasing input flow depth. Comparing the energy dissipation among the models shows that their performance is quite similar in this regard. However, the models with closer gate spacing exhibit slightly higher energy dissipation.

The energy dissipation and hydraulic jump characteristics beneath sluice gates with different sill configurations were examined by Daneshfaraz et al., and their findings are

similar to these patterns. Energy dissipation also rises with upstream flow depth and geometric changes, according to their analysis [18].

As shown in Table 5, for an input flow depth of 15 cm, where only the first gate is active, the energy dissipation is minimal, similar to single vertical gates, and can be considered negligible. This finding aligns with the observations of Abbaszadeh et al., who reported that energy dissipation characteristics are significantly influenced by the number of active flow control elements and their geometric arrangement [20]. Similarly, Gül et al., demonstrated that energy dissipating blocks configurations can substantially increase energy loss percentages, particularly under higher flow conditions [11].

4. CONCLUSION

Among water intake structures, successive sluice gates are designed to deliver a relatively constant flow rate for a range of water depth variations in the feeding channel, known as the modular range. In this study, the flow through successive gates was simulated and investigated using Flow3D software. To investigate the effect of the spacing between the gates on the structure's performance, 4 different models were simulated. The channel dimensions, gate openings, gate thickness, modular range, design flow rate, and the position of the first gate relative to the upstream of the channel were kept constant across all models. By comparing the numerical results with the corresponding experimental data of, it was observed that the differences in output flow rates were consistently less than 10% [4]. Therefore, the simulated model demonstrates acceptable accuracy, and the numerical solution results are applicable for analyzing the model's performance.

The most critical parameter in evaluating the performance of successive gate structures is the difference between the output flow rate of the structure and the design flow rate at various input flow depths. Comparison of numerical solution results with the design flow rate showed that the maximum difference was about 8%, indicating that successive gates perform well in delivering a relatively constant flow rate. The results also showed that the spacing between the gates has a negligible effect on the structure's performance within the modular range.

The investigation of energy dissipation in the models revealed that energy dissipation is negligible when only the first gate is active. However, with increasing input flow

depth and the activation of subsequent gates, the energy dissipation increases, reaching 15-22% when all three gates are active. This indicates that successive gates, in addition to their primary function of flow regulation, are also effective in energy dissipation, which can be considered a secondary function of this structure.

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