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Scour Control in Stepped Spillways Using Semicircular Baffle Blocks: Experiments and Predictive Modeling

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Abstract
This study explored the effectiveness of semicircular baffle blocks (SBBs) in mitigating scour downstream of stepped spillway stilling basins and demonstrated the potential of genetic programming (GP) for accurate scour prediction. Laboratory experiments under varying hydraulic and geometric conditions showed that optimal SBB placement within the first third of the stilling basin (xo = 0.21), combined with an intermediate height ratio (ho ≈ 0.375), reduced scour depth by nearly 90%. Building on these findings, a GP model was developed to capture the nonlinear interactions between flow and geometric parameters. The model achieved excellent predictive performance, with coefficients of determination of 0.92 (training) and 0.885 (testing), alongside low error metrics. These results confirmed the capability of GP to provide robust, data-driven predictions of scour depth, offering a valuable complement to physical experimentation. The integration of experimental optimization and GP-based modeling support more reliable and sustainable hydraulic structure design.

Article highlights

- Optimal SBB design reduced scour depth by nearly 90% in stepped spillways.
- Block height proved most critical; block width had negligible effect.
- GP modeling outperformed regression, providing robust scour predictions.

Keywords: Stepped spillway, Baffle Block, hydraulic structure, Regression, GP.

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1. Introduction

The erosion of bed materials, known as scour, is a critical factor influencing the safety and service life of dams and spillways. Despite their energy-dissipating design, stepped spillways are particularly vulnerable to local scour near the toe, (Rajaratnam,1990; Hoffmans & Pilarczyk, 1995). To address this problem, a range of mitigation strategies has been proposed. Structural modifications in stilling basins, such as flow deflectors and baffle blocks, have proven effective in altering flow characteristics and limiting scour (Negm et al., 2007, 2008). Previous experiments have demonstrated the benefits of structural countermeasures. For example, semicircular baffles were shown to significantly reduce scour (Barlock, 2013), while corrugated aprons helped dissipate jet energy and limit scour in submerged hydraulic jumps (Ali et al., 2014), underscoring the role of surface roughness. Numerous experimental studies have further examined the impacts of apron length, step geometry, baffling devices, and flow aeration on scour behavior, consistently reinforcing the significance of hydraulic and geometric factors (e.g., Hayder and Jafar, 2015; Hong et al., 2015; Elnikhely, 2018; Aminpour et al., 2018; Ghaderi et al., 2020; Eghlidi et al., 2020; Schleiss et al., 2023; Abdi et al., 2024; Cahya et al., 2024, Mei et al., 2025; Sharif, 2025; Bekheet, et al. 2025). Despite these efforts, predicting scour remains a complex task, as it depends on highly variable hydraulic conditions. This has motivated the application of computational and data-driven approaches. Early studies employed artificial neural networks (ANNs), gene expression programming (GEP), and genetic programming (GP) to predict scour in trapezoidal channels, spillways, and bridge piers (Guven & Gunal, 2008; Azamathulla et al., 2010; Moussa, 2013; Sattar et al., 2013; Mesbahi et al., 2016; Fuladipanah et al., 2023; Abdi Chooplou et al., 2024). Critical review for detecting and mitigating scour handle by Sharafati et al., 2020 and Tola et al. 2023. More recent research demonstrates that machine learning (ML) methods including Support Vector Machines (SVM), XGBoost, CatBoost, and gradient boosting ensembles can outperform empirical equations in scour prediction. For example, Le & Hien (2024) found XGBoost superior for sluice outlets, Kaushik et al. (2025) validated SVM models for river pipelines, and Ghanim et al. (2025) reported gradient boosting models with coefficients of determination exceeding 0.96 for submerged weirs. These advances reflect a clear shift toward hybrid approaches that integrate hydraulic knowledge with AI-based models to improve reliability and design efficiency. The scope of ML-based scour prediction has also expanded across diverse hydraulic environments, including spur dikes (Tabassum et al., 2024), sluice outlets (Le, 2024), weirs (Sharafati et al. 2020, and Ghanim et al., 2025), and river pipelines (Kaushik et al., 2025). This study aims to (i) experimentally assess the effectiveness of semicircular baffle blocks in stepped spillway stilling basins for reducing local scour, and (ii) develop regression- and GP-based predictive models for scour depth, provide a practical framework for simulating scour and improve hydraulic design.

2. Experimental Work

The experiments were carried out in a flume measuring 16.2 m in length, 65 cm in depth, and 66 cm in width (Fig.1). The experiments were conducted in the Hydraulics Laboratory at Zagazig University between June and august 2023. The flow from the flume was directed into a drain located in a lower channel, equipped with a weir for discharge measurement. A wooden spillway model was built and placed at the flume's midpoint, featuring a contraction ratio of 20%. The spillway measures 32 cm in height (H_s), 54 cm in width (W_s), and has 8 cm high steps (H_s). The downstream side of the spillway is inclined at a 30-degree angle. A 120 cm long stilling basin (L) was used to contain the free hydraulic jump occurring above it. Downstream of the basin, a 3.5-meter-long mobile bed was constructed using a 20 cm thick layer of stone. The fine gravel sample, with a median size (d_{50}) of 3.1 mm and a uniformity coefficient of 1.68, indicates a uniformly graded soil composition. Each experiment was allocated 2 hours, with a discharge rate of 35 L/s. These initial trials confirmed that 2 hours were sufficient to achieve over 90% of the maximum equilibrium scour depth. Each experiment was conducted for 2 hours at a discharge of 35 L/s, a duration shown in preliminary trials to achieve more than 90% of the equilibrium scour depth, in agreement with the methodology adopted by Mohamed et al. (2015). All experiments were performed under clear-water conditions, with the free hydraulic jump occurring downstream of the stepped spillway in each run. Scour depth downstream of the stilling basin was measured with an accuracy of ±0.1 mm using a 2 cm by 2 cm grid mesh. A point gauge was employed to measure the scour depth at each grid point. The same point gauge was also used to measure water depths both upstream and downstream of the spillway. A total of 80 experimental runs were conducted. A range of experimental configurations, featuring various semi-circular baffle block (SBB) arrangements fixed at different positions over the stilling basin with varying widths and heights, are detailed in Table 2 and illustrated in Fig. 2. Flow velocities over the stilling basin and mobile bed were measured using an electromagnetic current meter based on Faraday's law of induction. The instrument offers an accuracy of approximately ±0.01 m/s (Elnikhely, 2018; Aminpour et al. 2018; Ghaderi et al. 2020). Measurements were taken at each vertical, with the probe positioned 1.5 cm above the bed to represent near-bed velocity values.

3. Analysis and discussions

3.1 Effect of SBB Location on Scour Development

Fig. 3 illustrated the influence of the semicircular baffle block (SBB) location on relative scour depth, where the location was expressed by the non-dimensional parameter $x_o = x/L$ (with as the streamwise distance from the channel entrance and as the total basin length). The results showed that placing the SBB within the first third of the stepped spillway stilling basin significantly reduced scour depth, achieving an average reduction of about 75% compared to the case without an SBB. Comparison with earlier studies (Novak, 1961; Elnikhely, 2018) showed close agreement, with deviations averaging about ±7%, largely attributable to minor differences in experimental setup and boundary conditions. The maximum reduction of relative scour occurred at , where the scour depth decreased by nearly 85%. As the SBB was positioned farther downstream, beyond the first third of the stilling basin, its effectiveness diminished, with the reduction in scour depth decreasing to about 35% at . The reasons for this trend were examined in the following section through an analysis of near-bed velocity vectors within the stilling basin and the scour contours observed downstream. Near-bed velocity distributions and scour contours downstream of the stilling basin were presented for different scenarios: without semicircular baffle blocks (SBB) and with SBBs installed at various positions ($x_o = 0.1 - 0.67$). Fig.4 illustrated the case without countermeasures, where the maximum near-bed velocity reached 1.3 m/s at the point of maximum scour depth (5 cm), located 16 cm downstream of the stilling basin. With an SBB placed at $x_o = 0.21$ (Fig. 5), the redistribution of velocity vectors enhanced energy dissipation, reducing the maximum velocity to 0.9 m/s and limiting the scour depth to 1.6 cm near the side of the open channel, about 3 cm downstream of the stilling basin. These results emphasized the significant role of SBBs in controlling and mitigating scour hole dimensions. With the SBB fixed at $x_o = 0.34$ (Fig. 6), the baffle remained effective in dissipating energy by damping velocity vectors at the end of the stepped spillway's stilling basin, although its influence was less pronounced compared to the case with . In this configuration, a scour hole developed with a depth of 2.4 cm, located about 11 cm downstream of the stilling basin, subjected to a near-bed velocity of 1.0 m/s. When the SBB was placed farther downstream at $x_o = 0.67$ (Fig. 7), it remained effective in dissipating energy, with reduced near-bed velocities compared to the case without an SBB. At this position, the baffle caused the flow to concentrate along both sides of the open channel, where near-bed velocities reached 1.16 m/s on the right side and 1.15 m/s on the left side. The maximum scour depth observed in this configuration was 4 cm, located about 10 cm downstream of the stilling basin. These results collectively demonstrated that SBBs were effective in mitigating scour and reducing near-bed velocities, with the most significant improvement observed at $x_o = 0.21$.

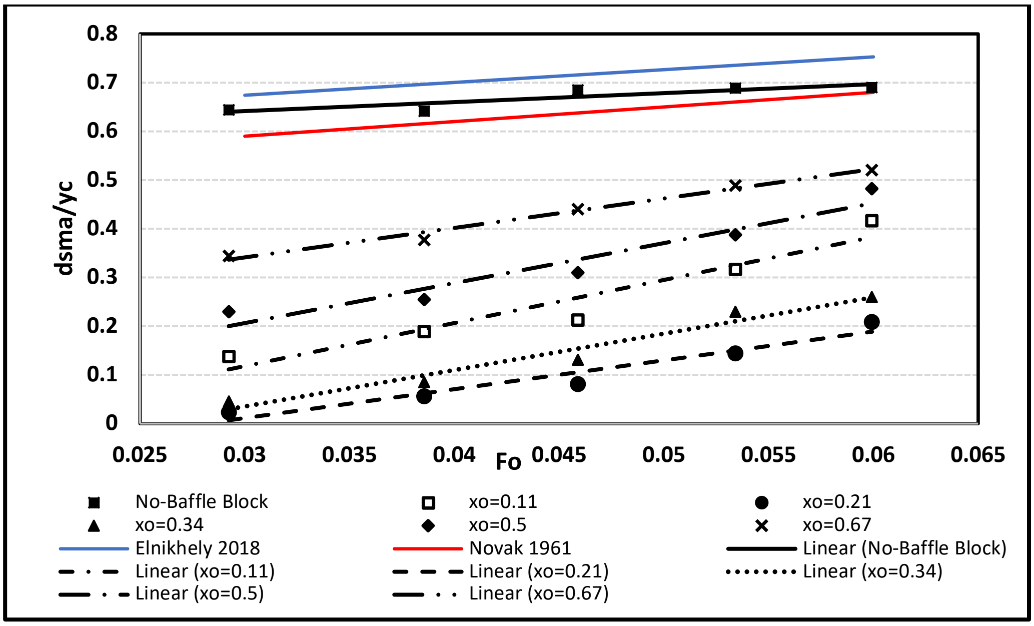

Fig. 3 Variation of Relative Scour Depth with Froude Number for Different SBB Locations (xo).

Fig. 1. General view of the laboratory flume.

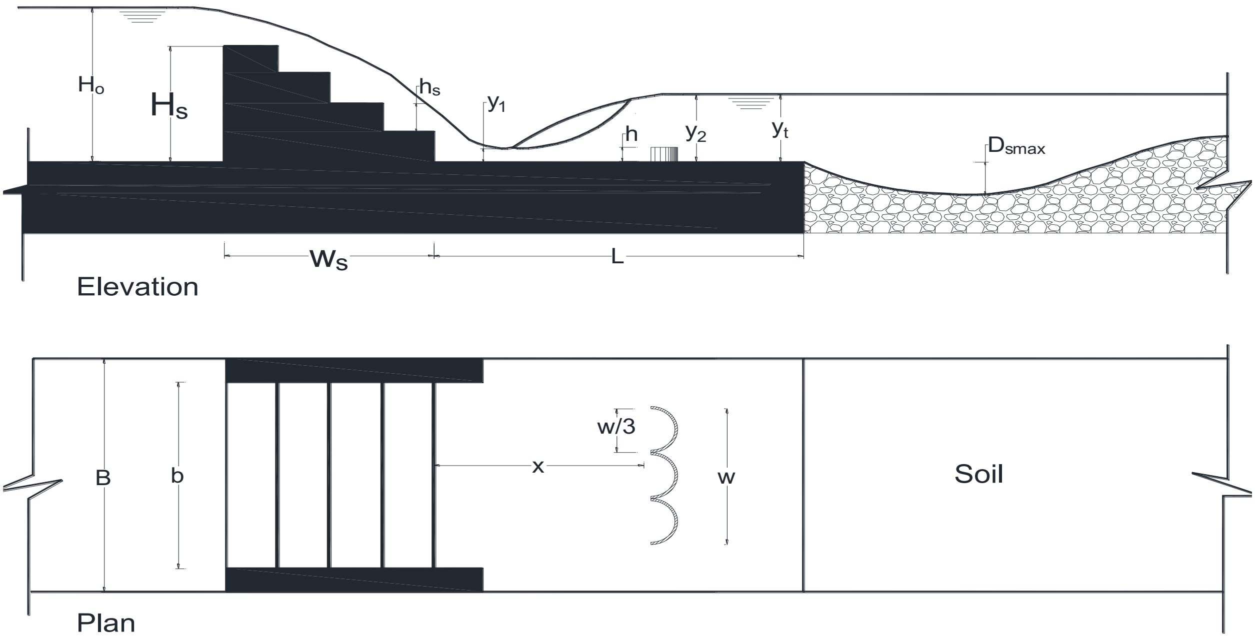

Fig. 2 Configuration sketch of the experimental setup

Table 1 Detailed specifications of the experimental setup

Flow rate, Q , Upstream flow depth, H	Q= 15-35 l/s , H = 35-42 cm
Spillway dimensions	Height, Hs = 32 cm; width, Ws = 54 cm; consisting of 4 steps, each with a height of hs= 8 cm.
Contraction (b/B)	20%
Distance (x) from last step to the semicircular baffle block (SBB)	x = 13.5, 25.5, 40.5, 60.5, and 80.5 cm
Heights of SBB, h	h= 2, 3, 4, 5, 6, 8, 10 cm
Width of SBB, w	w= 30, 45, and 66cm

3.2 Effect of SBB Height and Width on Scour Development

In this section, the SBB location was fixed at x_o = ***0.21*** while its height (h_o) was varied within the range 0.25–1.25 to evaluate its influence on flow structure and scour development downstream of the stepped spillway stilling basin (Fig. 8). At the smallest height (h_o = ***0.25***), only a modest reduction in scour depth was achieved (approximately 21%). The baffle was too small to significantly alter the velocity field, allowing high near-bed velocities to persist over the mobile bed and resulting in a pronounced scour hole, 4.1 cm deep, located 28 cm downstream of the basin (Fig. 9). This demonstrated that insufficient baffle height provided little resistance against the strong jet action and high-energy flow. As the height increased to h_o = ***0.375***, the SBB became much more effective in dissipating energy. The flow deceleration was evident in the reduced near-bed velocity of 0.7 m/s, and the scour depth decreased markedly to 1.2 cm, localized to one side of the open channel (Fig. 10). This case illustrated the beneficial effect of a moderately sized baffle in stabilizing the flow and protecting the bed. A similar trend was observed for h_o = ***0.5***, where scour reduction remained significant, with an average reduction of about 87% compared to the no-SBB condition. The optimum performance occurred at h_o = ***0.375***, where the relative scour depth was reduced by nearly 89%. Beyond this range, however, the influence of SBB height became counterproductive. At h_o = ***0.5*** and especially h_o = ***1.25***, the interaction between the jet and the taller baffle generated strong recirculating zones and complex velocity patterns, producing asymmetric flow structures. As a result, scour activity intensified. In the case of h_o = ***0.625***, a scour hole 5 cm deep developed on the right side of the channel, 25 cm downstream of the basin (Fig. 11), while additional scour holes formed along both channel sides for h_o = ***1.25*** (Fig. 12). In this case, near-bed velocities reached up to 1.55 m/s, leading to a maximum scour depth of 6.3 cm. Overall, the results indicated that while very small baffles had minimal hydraulic effect, and excessively tall baffles disrupted the flow and promoted severe localized scour, an optimally sized SBB (h_o ≈ ***0.375***) effectively dissipated energy, stabilized flow patterns, and significantly reduced scour downstream. This highlighted the importance of careful height selection to achieve stable and efficient hydraulic performance. The influence of varying the SBB width at the optimal position and height was illustrated in Fig. 13 (h_o = ***0.375***, x_o = ***0.21***). The width was tested at w_o = ***0.45, 0.68***, and 1.0. Within this range, variations in had no appreciable impact on scour reduction, with an average reduction of approximately 91% observed in all cases. This indicated that, once the optimal height and position were established, the effect of width became secondary, as the dominant mechanisms of energy dissipation and scour control were primarily governed by the SBB's vertical dimension and placement.

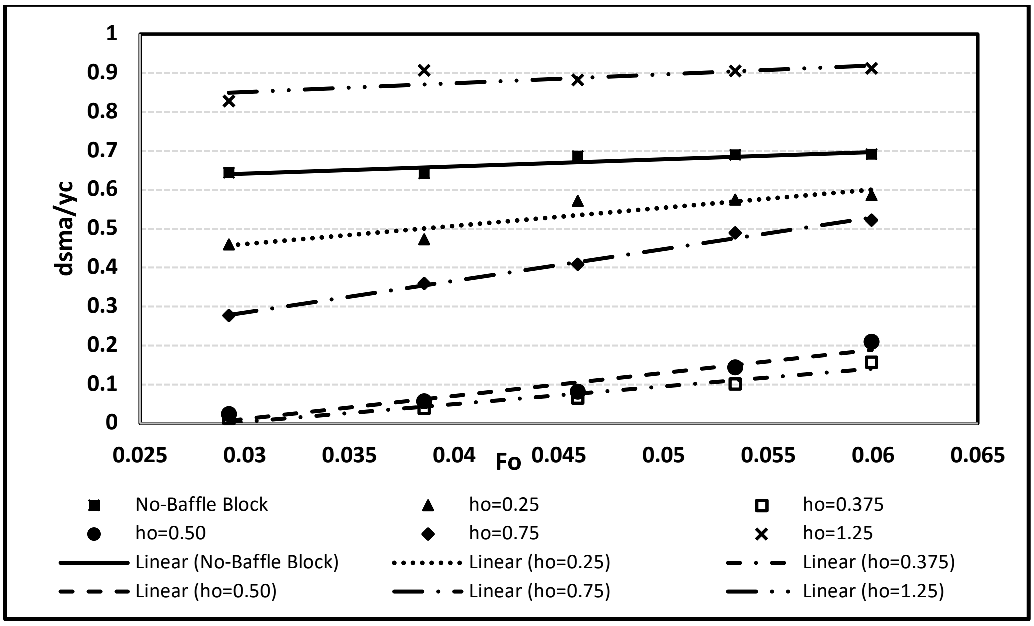

Fig. 8 Variation of Relative Scour Depth with Froude Number for Different SBB Heights (ho)

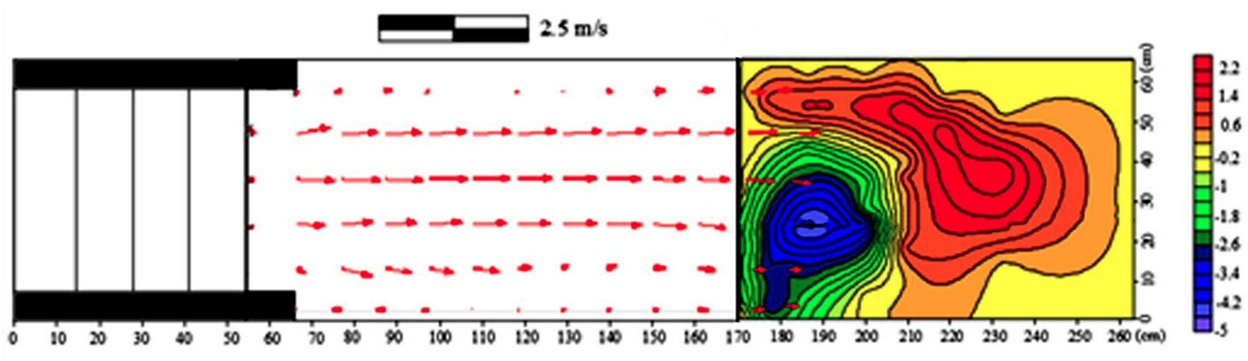

Fig. 4 Near-bed velocity distribution and scour morphology downstream of stilling basin without SBB, Fo = 0.08.

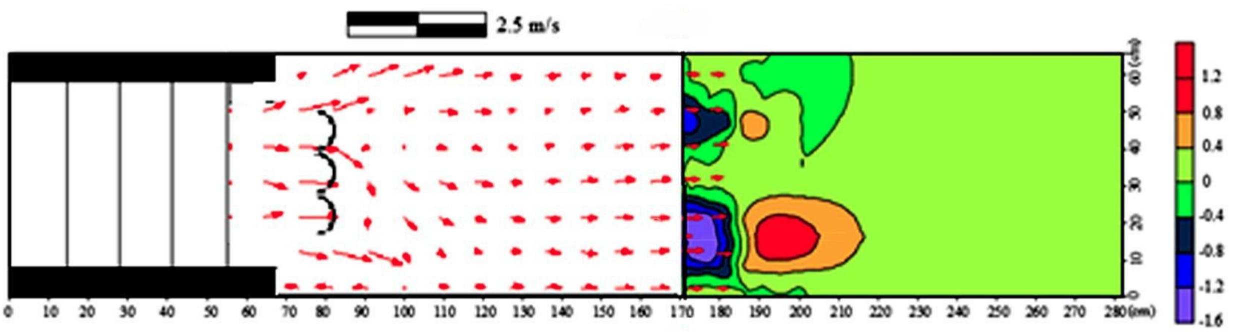

Fig. 5 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (xo = 0.21, Fo = 0.08).

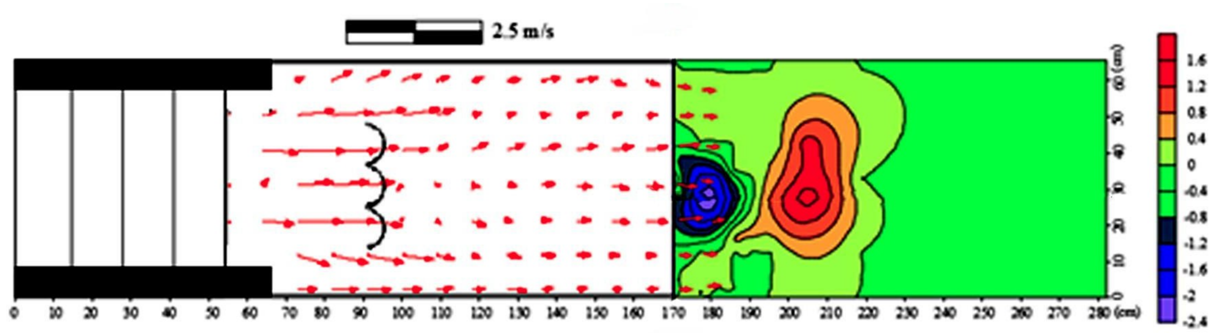

Fig. 6 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (xo = 0.34, Fo = 0.08)

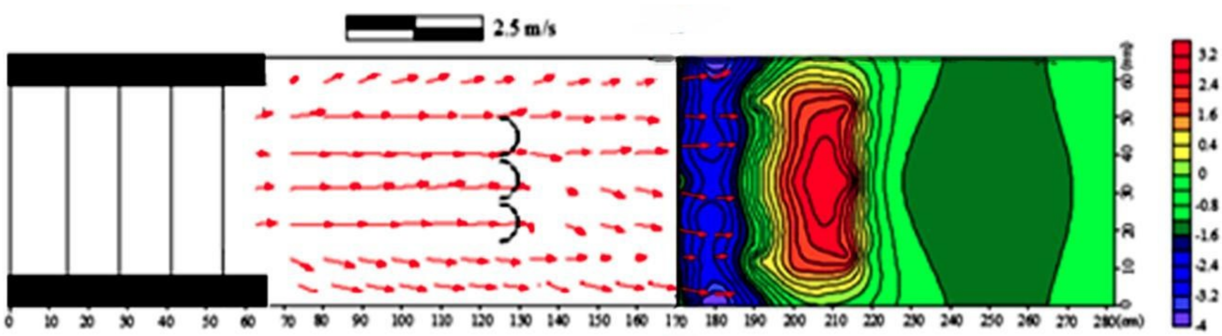

Fig. 7 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (xo = 0.67, Fo = 0.08)

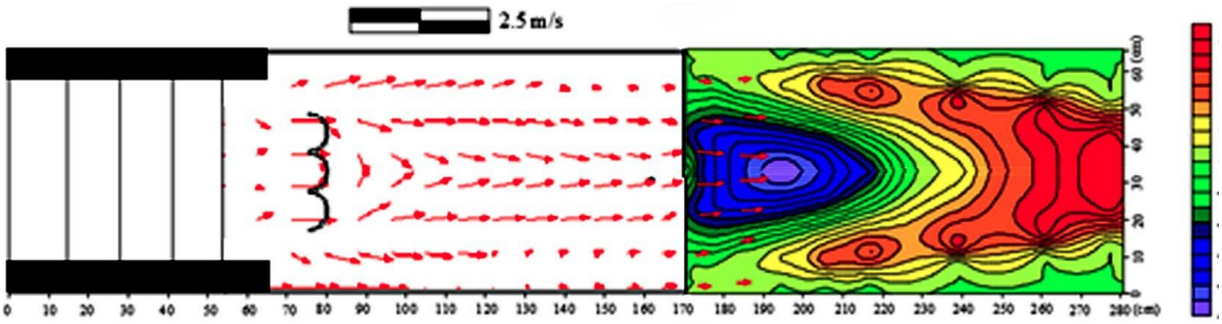

Fig. 9 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (ho=0.25, xo = 0.21, Fo = 0.08)

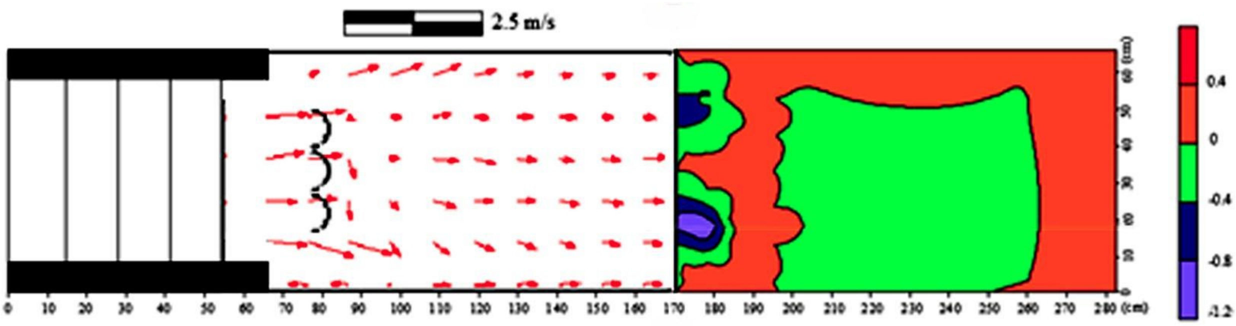

Fig. 10 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (ho=0.375, xo = 0.21, Fo = 0.08).

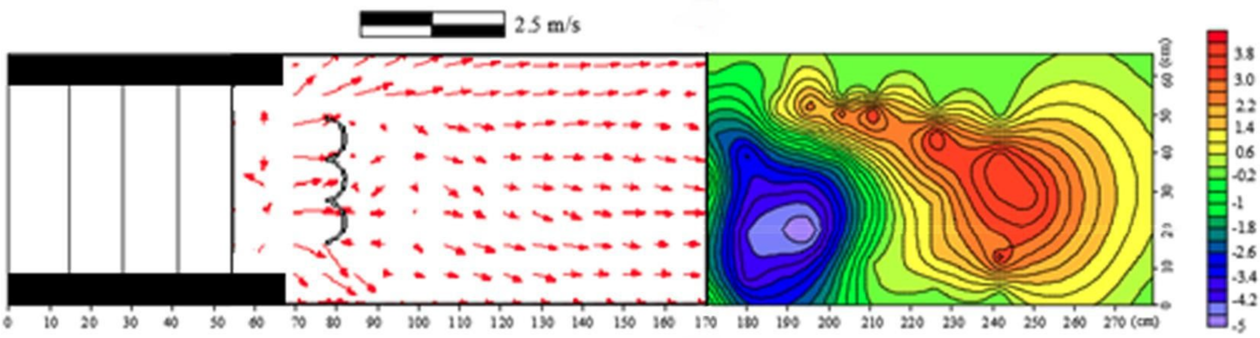

Fig. 11 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (ho=0.625, xo = 0.21, Fo = 0.08)

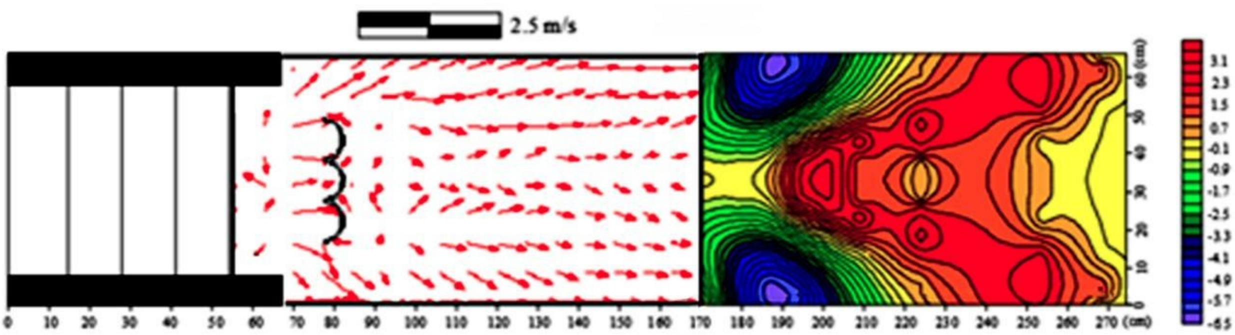

Fig. 12 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (ho=1.25, xo = 0.21, Fo = 0.08)

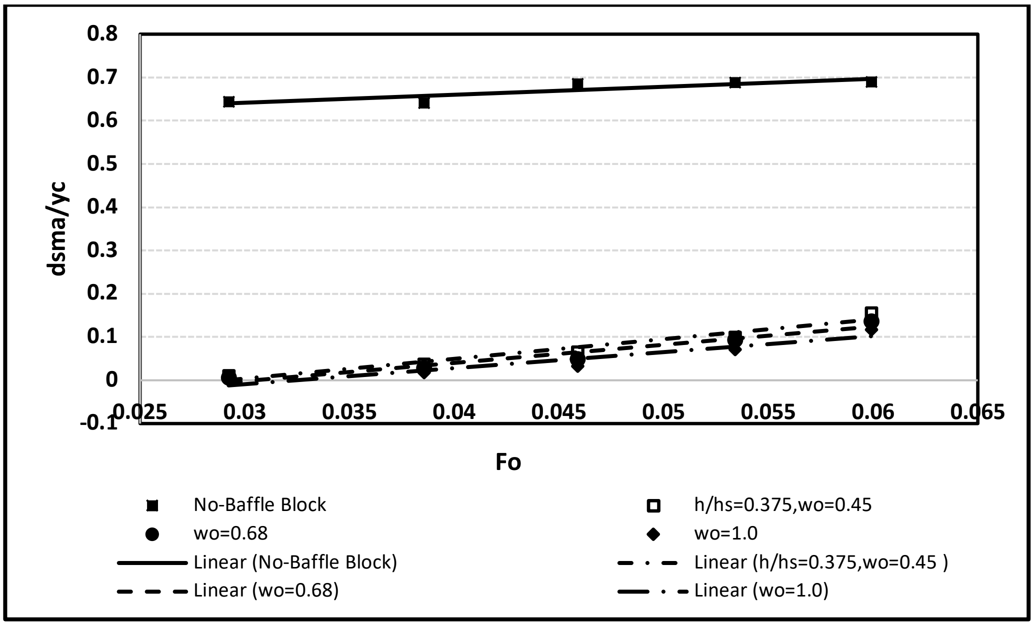

Fig. 13 Variation of Relative Scour Depth with Froude Number for Different SBB Widths (wo)

4. Development of Predictive Models

4.1 Regression-Based Approach

The relationship between the dependent variable and the independent variables can be expressed as:

$$\frac{ds}{yc} = f(xo, ho, wo, Fo) \quad \text{Eq.1}$$

A regression model was developed by testing several functional forms, including linear, polynomial, logarithmic, exponential, and power-law expressions, using 70% of the dataset selected randomly for calibration. Each formulation was evaluated based on statistical indicators such as , Mean Absolute Percentage Error (MAPE), and standard error. The best performance was obtained from a hybrid model combining linear and logarithmic components, which allowed the regression to capture both the direct proportionality of geometric parameters and the nonlinear attenuation associated with flow intensity. This structure also minimized multicollinearity and provided stable parameter estimates. The final regression equation is given by:

$$\frac{d_s}{y_c} = 0.50 + 13.5x_o + 0.82h_o - 0.25w_o + 207.5F_o$$

$$-18.30\ln(1 + x_o) - 211.2\ln(1 + F_o) \quad \text{Eq. 2}$$

Model evaluation metrics for the training and testing datasets are summarized as follows. For the training dataset (70% of the data), the regression model yielded a coefficient of determination (R^2) of 0.856, a mean absolute percentage error (MAPE) of 0.15, and a standard error of 0.09, demonstrating strong explanatory power and predictive accuracy. For the testing dataset (remaining 30% of the data), the model achieved a R^2 of 0.818, a MAPE of 0.17, and a standard error of 0.11, thereby it confirmed the robustness and generalizability of the proposed formulation.

4.2 Genetic Programming Approach

Genetic Programming (GP) is an evolutionary optimization method inspired by biological selection, where candidate solutions are iteratively refined to maximize a fitness function (Holland, 1975; Koza, 1992; Johari et al., 2006). Unlike fixed algorithms, GP adapts its structure dynamically through operations such as crossover and mutation. Programs are constructed from terminals (variables) and functions, including arithmetic operations and advanced mathematical functions (e.g., exp, sin, log, sqrt). In this study, GP uses a two-point string crossover, where random segments are exchanged between parents, and mutation, where operators or operands are replaced with alternative symbols from the same set, to maintain population diversity (Bramier and Banzhaf, 2001). The GP model was formulated by defining the terminal set, functional set, fitness function, control parameters, and termination criterion (Koza, 1992). The first three components establish the algorithm's search domain, whereas the latter two regulate the efficiency and quality of the evolutionary process. The terminal set comprises four fundamental groups of *ds/yc*, representing the nondimensional hydraulic relationships derived from the key variables governing scour depth (*xo*, *ho*, *wo*, and *Fo*) (Eq. 1). During the evolutionary process, crossover and mutation probabilities were set at 90% and 0.15, with a population size of 1000 individuals over 50 generations. The resulting GP model attained a maximum depth of 15 and a length of 138 nodes, reflecting considerable structural complexity. Similar to the regression model, approximately 75% of the data was used for training, with the remaining portion reserved for testing and validation. The GP-generated prediction formula is presented as follows:

$$\frac{ds}{yc} = \left(\frac{N}{D}\right) 0.167 + 0.663 \qquad \text{Eq.3}$$

In which;

$$N = 15.9 + 1.92xo + 2.96wo - 2.08ho - E_1 - \left\{-1.63xo\left[\frac{(0.33 - 1.33ho)(-0.45Fo)}{(0.88xo + 19.15) + 28.33}\right] - 51.40 + 0.659Fo.xo\right\}$$

$$E_1 = exp[45.3(0.33 - 1.33ho)(-5.72 - 1.161ho)(0.50ho - 0.99wo)]$$

$$D = \exp(-2.74) - \left\{-1.02xo + \frac{E_2}{\dfrac{0.96xo}{10.55 - (-1.09xo.ho - 235)\dfrac{0.50ho - 0.99wo}{-5.73 - 1.16ho}}} - (-22.30ho + 131.65)\right\}$$

$$E_2 = exp\left[\frac{(0.33 - 1.33ho)(-5.72 - 1.161ho)(2.08ho - 235.5)(0.50ho - 0.99wo)}{-5.39}\right]$$

The performance of the proposed GP formulas was assessed using standard statistical indicators. The coefficient of determination (R^2) reached 92% for the training data and 88.5% for the testing data. The standard error was 0.07 for training and 0.084 for testing, while the mean absolute prediction error was 0.098 and 0.12, respectively. Figs 14 and 15 compare the measured ds/yc values with the predictions from both the regression and GP models for the training and testing datasets. As demonstrated, the GP model consistently outperforms the regression model, achieving a higher R^2 (88.5% vs. 81.8%) and lower error values. The regression model, based on a hybrid formulation combining linear and logarithmic terms, was therefore less accurate than the GP approach

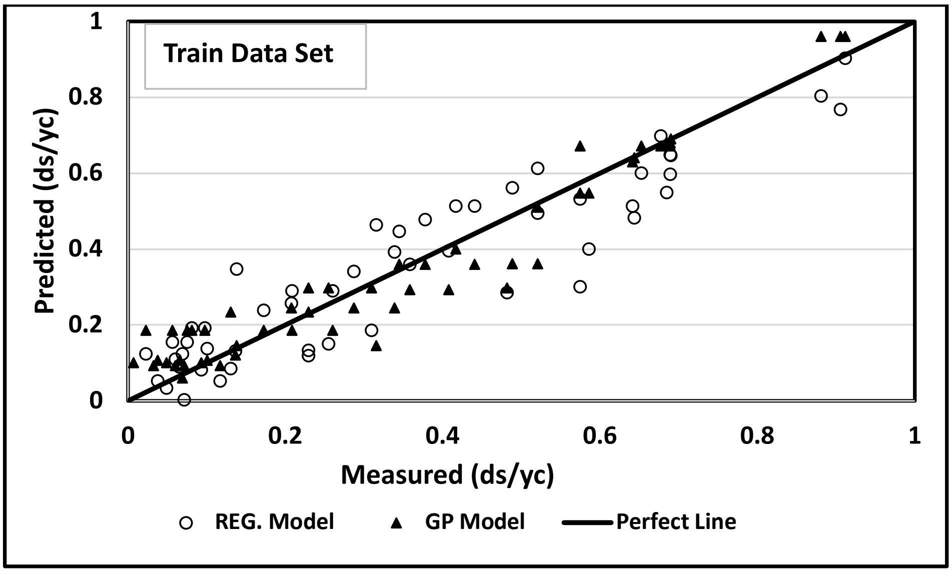

Fig. 14 Measured vs. predicted ds/yc for regression and GP models (train dataset)

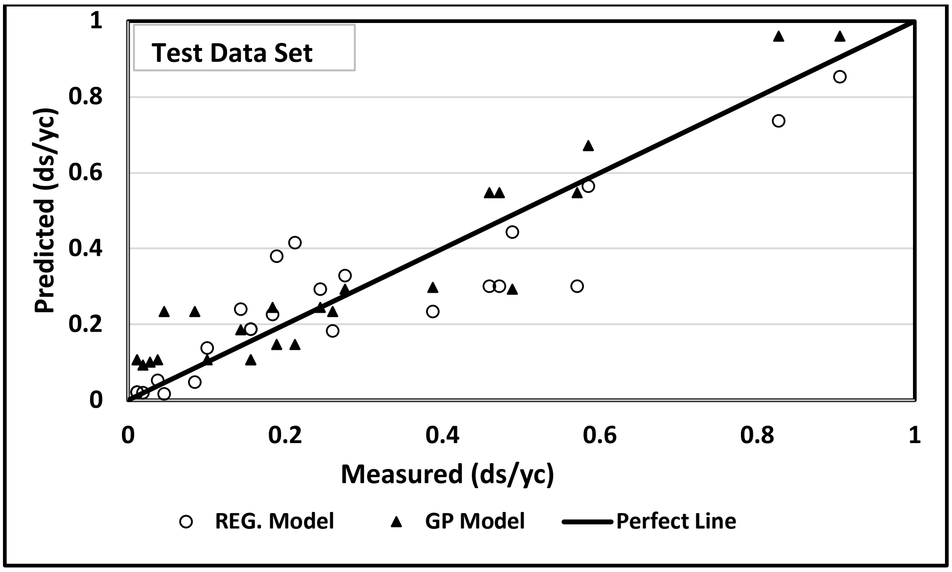

Fig.15 Measured vs. predicted ds/yc for regression and GP models (test dataset)

5. Conclusion

Mitigating local scour downstream of stepped spillways is essential to maintain structural stability and long-term performance. The experimental findings demonstrate that semicircular baffle blocks (SBBs) can reduce scour depth by up to 90% when positioned in the first third of the stilling basin (xo = 0.21) with an optimal height ratio ($ho \approx 0.375$). The block height was identified as the most influential parameter, while the block width had a little effect once the optimal configuration was established. On the modeling side, the hybrid regression approach provided a practical predictive tool, but the genetic programming (GP) model achieved superior accuracy and generalization. Collectively, these results highlight the effectiveness of SBBs as a cost-efficient countermeasure and underscore the value of GP-based predictive models in supporting sustainable hydraulic design.

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