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Investigation of the Accuracy and Applicability of Genetic Programming for Estimating Scour Depth Downstream of a Spillway

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ABSTRACT

Scouring is an important issue in the safety of hydraulic structures such as downstream spillways, dams, downstream sluice gates, bridge foundations, and pipelines. The scouring phenomenon downstream of composite spillways is one of the important issues in the design and safety assessment of hydraulic structures. Spillways and sluice gates are hydraulic structures that can control water levels and measure flow rates. For this reason, extensive studies have been conducted on these two structures, but these structures also have disadvantages. By combining these two structures, a combined spillway-sluice gate structure can be proposed to overcome these disadvantages. The scouring problem downstream of these structures in erodible beds is an important issue. If not controlled, it may cause instability of the structure and ultimately its destruction. For this purpose, many laboratories have studied the effect of various variables on the scour depth of these structures. Various models such as neural networks (ANN), group data hierarchy (GMDH) and regression equations have predicted the scour depth in hydraulically sensitive structures. In this study, the accuracy and application of genetic programming (GP) in the downstream of the dam spillway were investigated. From the studies conducted, it was concluded that the GP model when used to estimate the scour depth downstream of the spillway has a coefficient of determination (R^2 = 0.977) and also when this GMDH model is trained with genetic programming, the result has a higher coefficient of determination.

Keywords: scour, GP model, spillway

INTRODUCTION:

Spills play a very vital and important role from various perspectives such as economic, environmental and flood control. Erosion and bed erosion downstream of spillways can have a direct impact on the stability of their structure (Tohid Habibi et al., 2024). Spillways and gates are among the hydraulic structures that have the ability to control water levels and measure flow rates, for this reason, extensive studies have been conducted on these two structures, but these structures also have disadvantages that by combining these two structures, a combined spillway-gate structure can be presented to eliminate their disadvantages. The problem of erosion downstream of these structures in erodible beds is an important issue that, if not controlled, may cause instability of the structure and ultimately its destruction (Behnam Namdian and Hossein Ebrahimnejad, 2025).The erosion of the bed on the banks of rivers, canals, downstream of the spillway, and downstream of the lower gate due to the passage of the flow is called scour. The difference in the depth of the eroded bed compared to the original bed is called scour depth. One of the important issues in water and hydraulics is estimating the scour depth. First, understanding this phenomenon and secondly, proper estimation and estimation of the scour rate is necessary and vital for arranging the effect in the design of bridges. (Abolfazl Rafat, 2014).One of the most important challenges in the design of spillways is ensuring their stability, which is mainly used in the foundation design of these structures using the equilibrium scour depth under constant flow, while concourse spillways are exposed to flood flows, and due to the limited duration of the peak flood discharge, the scour downstream of them does not reach equilibrium. Therefore, using the equilibrium scour depth can overestimate the required foundation depth. Accordingly, the instantaneous scour depth values can provide designers with useful information for accurate scour estimation (Mojtabi Mursali and Ali Babakhani, 1400). In this study, the scour downstream of the spillway was investigated using a genetic programming (GP) model.

RESEARCH BACKGROUND:

In 2025, Sasan Nejati and colleagues conducted a study entitled Comparative Analysis of Downstream Scour of a Triangular-Triangular Composite Spillway Using the Classical Method and the Support Vector Machine Artificial Intelligence Model. In this study, the performance of a classical empirical model and a support vector machine (SVM)-based artificial intelligence model in predicting three key scour parameters including maximum depth, maximum location, and total hole length was investigated. Physical experiments were conducted on a triangular-triangular composite spillway model under different hydraulic conditions, and the resulting data were used as the basis for evaluating the models. The results showed that although the classical model was able to reflect the overall trend of scour changes, its statistical error rate was in relatively high ranges (MARE between 13 and 20 percent).In contrast, the SVM model performed much more accurately and was able to reduce the relative error to less than 2%. Comparative analysis shows that the AI model with high generalizability is a reliable option for more accurate prediction of scour behavior in laboratory conditions. However, the combined use of the two approaches, especially in large and sensitive projects, can improve both prediction accuracy and computational efficiency (Sasan Nejati et al., 2025).

In 2024, Sina Parvaz et al. conducted a study entitled Laboratory Study of Scour Morphology Downstream of a Stepped Spillway with a Middle Passage. In the present study, the effect of a middle passage with different geometries on changes in scour characteristics downstream of a 1:1 slope stepped spillway was investigated experimentally.Analysis of the results showed that although the installation of the middle passage leads to an increase of between 12 and 25 percent in the range of minimum and maximum discharges, due to the change in the hydrodynamic flow pattern in the scour pit downstream of the stepped spillway, it shifts the position of the maximum scour depth from the foot of the stepped spillway to the middle part of the scour pit and also reduces scour in the vicinity of the walls (Sina Parvaz et al., 2024).

In 2025, Sasan Nejati et al. conducted a study entitled Investigating the Effect of Predicting Maximum Scour Depth on the Stability of Compound Sharp-Edge Spillways by Analyzing the Trend of Scour Profiles. In this study, the scour phenomenon downstream of a compound sharp-edge spillway under variable flood flow conditions was investigated.Composite spillways, combining different geometries, allow for increased discharge capacity at high discharges and proper performance at low discharges, and are considered effective options in managing fluctuating flows. However, flow instability downstream can lead to increased bed erosion and threaten the stability of the structure against floods. In this study, using a physical model in a laboratory flume, the effect of geometric and hydraulic parameters on the formation of scour holes was investigated and its profiles were drawn at four different discharges. The results showed that at low discharges, the trend of increasing scour depth was small, and at high discharges, the depth and length of the hole increased significantly. Therefore, by designing the foundation depth in the area below the maximum scour depth, the stability of the structure against strong and erosive flows can be ensured (Sasan Nejati et al., 2025).

Leila Babakhah and colleagues conducted a study in 2025 entitled Laboratory Investigation of Local Scour Downstream of Piano Key Spillway Type B in Sand and Sand Bed Materials. In the present study, for the first time, local scour downstream of a trapezoidal piano key spillway type B was investigated. The spillway was installed at a distance of 5.50 meters from the beginning of the channel and has a height of 0.20 meters and three cycles (three outlet keys, two inlet keys and two half inlet keys). Three different downstream depths and three different flow rates were also used. With increasing particle landing number and flow rate and decreasing the downstream depth, the maximum scour depth increases. The dimensionless parameter range of particle landing number in the present study varies between 1 and 2. Also, two bed materials, sand and sand, were used. With increasing the diameter of the bed materials, the maximum scour depth will decrease.The scour index in gravel bed materials is much lower than the scour index in sand materials, which means that the risk of spillway overturning is much lower in gravel bed materials (Leila Babakhah et al., 2025).

In 2018, Moein Fallah and colleagues conducted a study titled Predicting the Depth of Scour in the Downstream of a Cup-Shaped Spillway Using a Powerful Learning Machine Model and a Multi-Layer Validation Method. In this study, the depth of scour in the downstream of cup spillways was simulated using a powerful learning machine model. A powerful learning machine is a type of single-layer feedforward neural network that selects computational nodes randomly and determines the output weights analytically. In addition, Monte Carlo simulations are used to measure the capability of powerful learning machine models. Monte Carlo simulation is a broad classification of computational algorithms that use random sampling to calculate numerical results. A multi-layer validation method is also used to examine the capability of numerical models.In the multi-layer validation method, the main sample is randomly divided into k subsamples of equal size. The advantage of this method is the random repetition of subsamples in the testing and training process for all observations, and each observation is used exactly once for validation. In this study, the value of k was considered equal to 5. Then, the parameters affecting the scour depth were identified and six robust machine learning models were defined. By performing a sensitivity analysis, the most effective parameter, which included the dimensionless discharge parameter, was introduced. Also, by analyzing the results of different models, the superior model was introduced. This model predicted scour values with acceptable accuracy and was a function of all input parameters. For example, the values of the coefficient of determination and the dispersion index were obtained as 0.993 and 0.071, respectively (Moin Fallah et al., 2018).

Chenur Abdi Choublou et al. conducted a study titled Laboratory and Numerical Investigation of Downstream Scour of Trapezoidal Piano Key Spillways Type A and B in 2024. The aim of this paper is to investigate the downstream local scour of two types of trapezoidal piano key spillways under different hydraulic conditions using both numerical and experimental methods. Three-dimensional numerical simulation was implemented using the CFD package. In order to investigate the effect of spillway type on downstream scour of trapezoidal piano key spillway, numerical simulation was performed and changes in bed topography were investigated. The results showed that the average scour and sedimentation in trapezoidal spillway type A was about 7.4 and 18.7 percent less than type B, respectively. Also, the location of the maximum scour depth and the maximum sediment level downstream of type B spillway occurred about 56 and 28 percent further from the spillway toe than type A spillway, respectively.The effect of the type of spillway on the area and volume of the scour hole is more evident at lower depths of the foothills (Chenur Abdi Choublou et al., 2024).

METHODOLOGY:

Downstream scour of spillway:

The discharge of flood water beyond the dam reservoir is done through spillways, which are usually located in the dam body. There are different types of spillways, the most commonly used being the spillway, Figure 1. (Azmatullah et al., 2008).

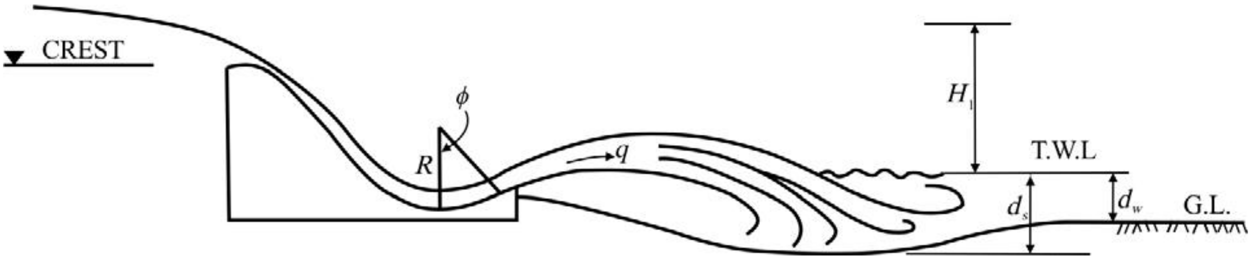

Figure (1): spilway scour

The coalition in such spillways is in the form of a jet plane. In this way, the water leaves the edge of the spillway and is thrown into the air and then plunges downstream. The flow downstream of the spillway has a very high speed, to prevent the experimental effects of this flow, energy-dissipating structures are used (Touzandeh Jani, 2011). Three of the most common structures for dissipating flow energy are stilling basins, in which the flow energy is dissipated using a hydraulic jump. A rolling cup in which excess energy is dissipated by creating a rotating flow and rolling the water. A jet stream in which in these structures, in order to dissipate the flow energy, water is thrown downstream of the dam by performing a ski jump in the form of a jet to reduce the erosive effects of the flow on the dam and important structures around the dam.Momeni and Salian et al. (Reza Momeni and Salian, 2006) investigated scouring caused by rectangular jets downstream of , shaped projectiles and introduced current intensity as the most effective parameter in the scouring phenomenon, and the depth of the downstream has an inverse effect on the scouring depth. Ranjbar et al. (Rangbar et al., 2006) investigated the temporal changes in the scouring hole downstream of free-falling jets and showed that the dimensions of the scouring hole increased with time, while the rate of increase in the dimensions of the hole decreased. Lashkara and al. (2008) used neural networks to predict the scouring rate downstream of projectile cups. Bahrami and Barani (2011) investigated the trend of air concentration changes in the flows passing over the chute as a numerical model.There are various hydraulic, morphological and geotechnical governing factors on scour depth (d_s) namely discharge intensity (q), fall height (H_1), bucket radius (R), edge angle (φ), rock type, rock uniformity (rock uniformity), time and mode of spillway operation. Figure 1. Throughout the study period, many empirical formulas based on laboratory results and observations have been developed to estimate scour depth downstream of spillways. Below are some good formulas for predicting scour depth of spillways (Azmatullah et al., 2005).

Veronese formula (provided by USBR):

$$d_s = 1.90q^{0.54}H^{0.225} \tag{1}$$

***Wu's formula*:**

$$\frac{d_s}{H_1} = 2.11\left(\frac{q}{qH_1^3}\right)^{0.51} \tag{2}$$

Martin's formula:

$$d_s = 1.5q^{0.6}H_1^{0.1} \tag{3}$$

GP model in downstream scour of spillway:

The GP program (GPLAB) was used in MATLAB software in relation to boundary undervalve in the study of downstream scour of spillway. Using previous experiments, the grouping of variables gave good results. The input parameter was the Froude number (q⁄ 〚(gH_1^3)〛 ^0.5) and the output parameter was the relative scour depth (d_s⁄H_1). Five operators were used to find the optimal formulation: addition, subtraction, multiplication, division and power. A large number of generations were required to find the formula with the least error. The first maximum of the tree and the branch length were divided (Azmatullah et al., 2005).

Development of the GP model:

GP is a branch of the Genetic Algorithm (GA) is a method for learning very well computer programs by learning artificial intelligence. A population value consists of known random members of chromosomes and the compatibility of each chromosome with a ratio for a target value is investigated.The principle of natural selection has been used to select and reproduce healthier offspring. GP generates long equal or unequal computer programs that include variables and several mathematical operators (functions) as solutions. The function set of the system can be the object of computational operations (-, *, /) and functions such as exponential, trigonometric, logarithmic functions. Each function implicitly includes a transition for a variable that helps to use the output of multiple programs in GP, while in tree-based GP these effects are included (Bramir et al., 2001). The GP used in this study uses two root intersection points. A random position and a random length are selected in both parents and vice versa. If one of the children's outcomes exceeds the maximum length, the intersection is abandoned and started again by swapping an equal part (Bramir et al., 2001).An operator or an operator of a structure is changed by mutation into another symbol on the same set.

GP compatibility may be calculated using the following formula:

$$f = \sum_{j=1}^{N}(|X_j - Y_j|) \quad (4)$$

where X_j = the value of the output by a chromosome for compatibility case J and Y_j = the value ex compatibility case J.

In GP, the maximum size is usually limited to avoid unbounded program overgrowth (Brameyer et al., 2001). This configuration is tested for the purpose of the GP model to find coefficients.

To date, the application of GP in hydraulic engineering has been limited. Davidson (1999), and Babois and Keijzer (2000), respectively, determined empirical relations for friction (erosion) in turbulent pipe flow and additional resistance to flow due to vegetation flexibility. Keijzer and Babois applied the derivation of empirical equations to real-world hydraulic data (Babois and Keijzer, 2000). Giustoli (2004). determined the shear resistance coefficients in corrugated metal pipes. Gizhisor (2004) explored a better relationship between the temporal pattern of the flow stream and sediment movement using numerical model results and field data.Azmatullah predicted the scour at the bridge base in 2010 (Azmatullah et al., 2010).

The GP model was extended using the same input variables as an ANN-RBF model. Five of the ten parameters of equation 1, namely fluid density, buoyant sediment density, fluid dynamic viscosity, gravitational acceleration, and energy line slope, are constant in all experiments. Therefore, the first combination includes four of the ten parameters of equation 1 as inputs and the scour depth equation as the model output. The second combination includes six dimensionless parameters of the two normal scour depth equations as input and output patterns, respectively (Azmatullah et al., 2005)

Statistical error parameters:

The statistical error parameters of the coefficient of determination (R^2), mean absolute percentage error (MAPE), and root mean square error (RMSE) were used to evaluate the testing and training phases.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(O_i - t_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O_i})^2} \quad (5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - t_i)^2}{N}} \quad (6)$$

$$MAPE = \frac{\sum_{i=1}^{N}|O_i - t_i|}{N} \quad (7)$$

$$\delta = \frac{\sum|(o_i - t_i)|}{\sum o_i} \times 100 \quad (8)$$

Where t_i determines the target value of the scour depth, while O_i and (O_i)¯

are the observed values and the average of the observed values of the scour depth, respectively.

Table 1 presents the statistical errors for the GP model in estimating the scour depth of three hydraulic structures (pipeline, bridge footing, spillway) in the test phase

Table (1): GP model for three structures: spillway, bridge footing, and pipeline

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Structures	R^2	RMSE	MAE	δ
pipeline	0.741	0.0957	1.426	10.45
bridge pair	0.819	0.048	-13.666	26.262
spillway	0.977	0.861	-	0.177

CONCLUSION

The scour problem is an important issue in water engineering and hydraulic structures. In recent years, many studies have been conducted in this field and good results have been obtained. In this study, the accuracy and applicability of the GP model, which was developed by Azmatullah on three structures: spillway, bridge pier, and pipeline, were investigated and compared with each other. According to the studies conducted, it was found that the genetic programming model in the test stage for the lateral spillway has a higher coefficient of determination(R^2=0.977) , which means that there is a better correlation between the data. While this model has a lower coefficient of determination (R^2=0.741) in predicting the scour depth under the pipeline. In terms of the root mean square error (RMSE), the GP model has a lower error in predicting the scour depth of the bridge pier. In the bridge pier, the GP model has the lowest mean square error. When the GMDH model is trained with genetic programming, the result has a higher coefficient of determination.

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