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Modeling and Estimating the Uplift Force of Gravity Dams Using Finite Element and Artificial Neural Network Whale Optimization Algorithm Methods

Bahram Nourani[1], Farzin Salmasi[2,*] , Mohammad Ali Ghorbani[3]

[1] Ph.D Candidate, University of Tabriz / Department of Water Engineering
[2] Associate Professor, University of Tabriz / Department of Water Engineering
[3] Professor, University of Tabriz / Department of Water Engineering

ABSTRACT: The correct identification of the uplift force plays an important role in the stability analysis of gravity dams. Therefore, it is very important to estimate it accurately. For this purpose, a numerical model of the foundation of a gravity dam of the Guangzhao, China was made using finite element method. After simulation, the uplift force values were obtained in different positions of drainage. Require experience, the timing of calculations and the accurate determination of the boundary conditions in numerical models, have caused to the development of the tendency to use intelligent models. For this purpose, in addition to the Artificial Neural Network model (ANN) with three-layer that consists of 4 input neurons, 1 hidden layer (with 8 neurons), and 1 output neurons, a new hybrid model of Artificial Neural Network-Whale Optimization Algorithm (ANN-WOA), was developed. The ratio of the parameters of the distance of the drain row from upstream dam, the distance from the center to center of drains, the drain diameter and the water surface upstream of the reservoir dam respect to the width of the dam foundation as input and relative uplift force were considered as output. The values of R^2, RMSE and RE% for the ANN-WOA model, were 0.998, 0.021 and 3.3%, respectively, and for the ANN model were 0.995, 0.261 and 4.67% respectively, that indicate the higher accuracy of the ANN-WOA model in the estimation of the uplift force than the ANN. In addition, the density plot box and the violin plot indicate that the point density and the probability distribution estimated data with the ANN-WOA model is very similar to that the data obtained from the numerical simulation compared with the ANN model.

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1. INTRODUCTION

Seepage from the dams and the resulting increase in uplift force is considered as one of the most important factors in the destruction of dams. All dams and structures associated with water storage are subjected to water flowing from the foundation, sides and sometimes their bodies. Thus, the water in the reser oir of the dam, at any moment, tends to seepage from the seam and the gap at the junction of the dam and the pores in the soil. The water flows from below the dam and appears in the downstream. The force from the bottom upwards to the dam body, is sometimes referred to as uplift force. The uplift force sometimes is so high that it causes the o erturning of the dam. Therefore, it is necessary to make projections and logistics in design, in order to reduce the amount of this force in design of the dam. This may be done by installing a drainage gallery in the dam body. Inside the drainage gallery, drainage wells collect seepage water from the body of the dam, and especially from the dam foundation.

A theoretical solution based on seepage theory was presented by Chawla et al. (1990) to determine optimal location of the drainage gallery system with equally spaced drains of uniform diameter of gra ity dams. The optimal location of the drainage gallery was selected for state that uplift force is minimum [1]. Optimum location for ertical drains in gra ity dams was in estigated by Nourani et al. (2016). Results showed that the optimum location of the ertical drain in drainage gallery system is not fixed, therefore, for each dam, the optimal location of the ertical drain will be determined by considering the effecti e factors [2]. Salmasi et al. (2017) in estigated the reduction of uplift forces by longitudinal drains with underlined canals. The in estigation generates sufficient data for typical 2D canal cross-sections by numerically sol ing a wide range of configurations using a pro ision of drain pipes. The generated data comprise the correlation between uplift forces and the arious configuration parameters in terms of effects of position of the drain pipes, their size and hydraulic factors, such as the effect of phreatic surface [3].

In this study, to estimate the total uplift force in gra ity dams, a numerical model of the gra ity dam is introduced using finite element method. This numerical simulation includes drainage system under the dam foundation. The diameter of drains pipe, their location from the dam heel and the distance among drains center are ariables in this study. After numerical simulation, the relati e total uplift force alues is estimated using ANN model. Then a new hybrid model of

*Corresponding author's email: Salmasi@Tabrizu.ac.ir

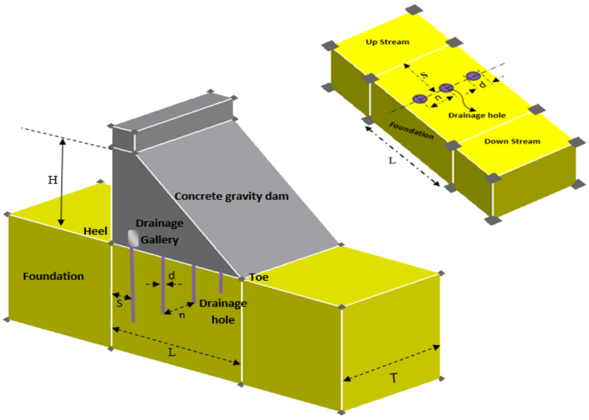

Fig. 1. Illustration the drain holes row of drainage gallery system in the gra ity dam

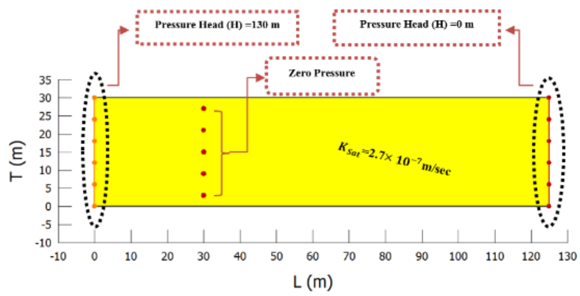

Fig. 2. Plan iew foundation of dam with 5 drains, with specified boundary conditions (*s*=30 m, *d*=0. 15 m, *n*=6 m, *H*=130 m)

Artificial Neural Network-Whale Optimization Algorithm (ANN-WOA), is de eloped and the accuracy of these intelligence models will be compared. Application of the ANN-WOA model in prediction of the uplift force in gra ity dams was not found in the literature re iew.

2. METHODOLOGY

2.1 Go erning Equations

The general equation of flow in porous media is the Darcy's equation, which this equation combines with the continuity equation of flow and con ert to Richard's equation, which is a partial differential equation describing seepage performance. The general go erning differential equation for two-dimensional (2D) seepage can be expressed as:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right)+Q=\frac{\partial \theta}{\partial t} \tag{1}$$

where h the total head, Q is the applied boundary flux (m/s), θ is the olumetric water content (m^3/m^3), k_x is the hydraulic conducti ity in the x-direction (m/s), k_y is the hydraulic conducti ity in the y-direction (m/s) and t is time. The abo e equation (Eq.1) in steady state condition changes as follows:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right)+Q=0 \tag{2}$$

In conditions that the porous media is homogeneous and isotropic (k_x=k_y) and input and output flow is zero (Q=0) the equation 2 is simplified in the form of equation 3, which is known as the Laplace's equation.

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=0 \Rightarrow \nabla^2 h=0 \tag{3}$$

The SEEP/W software (a part of Geo-Studio software) uses the finite element method (FEM) to sol e the go erning (Laplace) seepage equation regarding specified boundary conditions [4].

2.2 Numerical Simulation / Finite Element Method (FEM)

In this study, a gra ity dam with the dimensions shown in Fig.1 is considered. It should be noted that in this study, the width of the floor of the dam (L) and the length of the dam (T) to the order of 125 and 30 meters is considered.

The uplift force in gra ity dams is dependent of the function of the ertical drains of the drainage gallery. The effecti e factors are the diameter drain (d), the distance from the center to center the drains (n), the distance drain row from heel of dam (s), and water surface in upstream of the reser oir (H). In addition of simulation the foundation of gra ity dam in state of without drainage gallery, 12 other models including ertical drains are located inside the drainage gallery in different diameters (d) of 0.05, 0.10 and 0.15 meters, each of which in 4 modes with distance (n) of 3, 4, 5 and 6 meters. Also, the effect of the distance drain row from heel of dam (s) has been considered. For this purpose, the distance of drains row from upstream of dam in 12 different positions are 0, 5, 10, 15, 20, 25, 30, 40, 60, 80, 100 and 125 meters. The aforementioned conditions ha e been used for two states of water surface upstream of the reser oir dam (H= 168 and 130 m). Thus that the effect of water surface le el of the reser oir also is in estigated. Fig.1indicates a schematic iew of the location of the drains in the drainage gallery and the parameters in this study. Depending on the conditions of the present study, the plan iew of SEEP/W software is used to simulate dam foundation along with the ertical drainages. Fig. 2 shows the plan iew foundation of dam in software media in state of that s, d, n and H is equals 30, 0. 15, 6 and 130 meters respecti ely.

For numerical simulation, the boundary conditions at the upstream and downstream of the gra ity dam are equal to the water surface le el at the reser oir and tail water in the form of a pressure heads. In this study the upstream water le el ariation is 168 and 130 meter, while the water le el in downstream is set to zero. For setting the boundary condition, Pressure head in upstream is 168 and130 meters. Also the boundary conditions at the ertical drains, was considered as zero pressure. Since all the analyses are for a steady state condition, olumetric water content not required. The foundation of dam material was considered homogeneous and isotropic within a saturated permeability of K_{sat}=2.7E-07 meters per second (m/s) (Fig. 2).

2.3 ANN and ANN-WOA Modelling

In this research, two models of ANN and ANN-WOA are used to estimate the relati e total uplift force (U_d/U_o) using

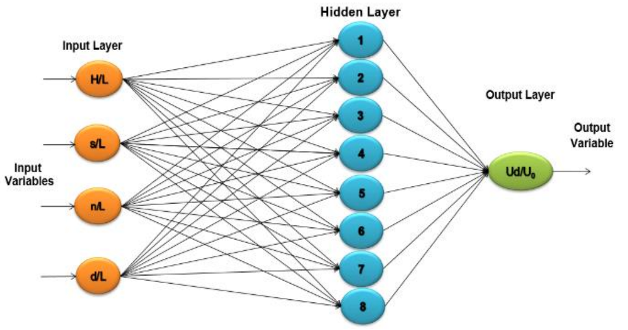

Fig. 3. Arrangement of the used artificial neural network in this study

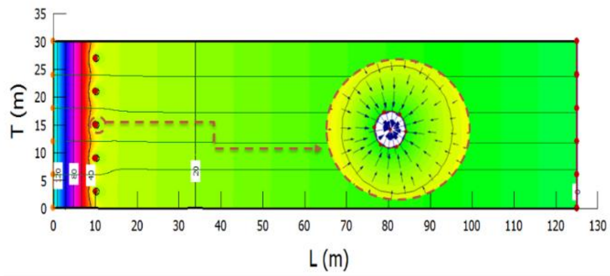

Fig. 4. Potential contour lines, flow lines and elocity ectors at foundation of the gra ity dam with ertical drain (s=10 m, d=0.015 m, n=6 m, H=130 m)

Table 1. alues of the parameters used in the WOA method

Parameters	*L*	*P*	Population size	Maximum iteration	Hidden layer
Range in this study	0.37	0.65	30	50	8

4-Input ariables *H/L, d/L, n/L* and *s/L*. The generated data are a ailable after the se eral numerical simulations using finite element method. In both models (ANN and ANN-WOA), the non-dimensional parameters *H/L, d/L, n/L* and *s/L* are as the input ariables and the non-dimensional parameter U_d/U_o (relati e total uplift force) is used as output ariable. Each set of data consists of 288 dataset. In both models, 70% of the dataset (200 data) is used for the training and 30% of the dataset (88 data) is used for the testing phase. It should be noted that a code was written in the Wolfram Mathematica software so that the dataset are randomly selected for each two training and testing period for se eral times. Then the desired model was selected based on the best alues for determination coefficient (R^2) and the root mean square error (RMSE). After 50 repetitions of the abo e-mentioned random selection criteria in the Wolfram Mathematica software, the best conditions for R2 and RMSE were selected (R^2 = 0.995 and RMSE = 0.0223). Fig. 3 shows a three-layered structure used in this study that consists of (i) input layer, (ii) hidden layer, and (iii) output layer. The independent ariables in input layer are: *s/L, n/L, d/*L and *H/*L. The dependent ariable used as output is U_d/U_o. The optimum network architecture was defined as 4-8-1 that include 4 neurons for input, 1 hidden layer with 8 neurons and 1 output neuron. In addition, the sigmoid tangent function for the input layer and the linear function for the output layer was selected using the Lewenberg Marquard Algorithm (LMA) with repeating 200. In this study, for the WOA method the alues of *P* and *L* were 0.65 and 0.37, respecti ely and also population size and maximum iteration were 30 and 50, respecti ely. Optimum number of neurons in hidden layer was 8 (Table 1).

3. RESULTS AND DISCUSSION

After numerical simulation using FEM, the pore water pressure is calculated in each point in the porous medium of soil in dam foundation. Fig. 4 shows the potential contours, flow lines and elocity ectors in state of that *s, d, n* and *H* is equals 10, 0. 10, 6 and 130 meters, respecti ely

The comparison of the obser ed and estimated data of U_d/U_o, by ANN and ANN-WOA models in testing period are shown in Figs. 5 and 6 in the form of scatter plots. It can be seen from the linear line fit equations and R^2 alues in scatter plots that the ANN-WOA estimates are closer to the obser ed alues than the ANN model. Thus ANN-WOA performs much better than the ANN model and therefore has a ery high accuracy in estimating of the parameter U_d/U_o.

In this study, a model was de eloped for estimating the relati e total uplift force, U_d/U_o in gra ity dams using ANN and ANN-WOA. Statistical alues consist of (R^2, RMSE and RE%) of the training and testing dataset period for ANN and ANN-WOA methods are gi en in Table 2. Statistical criteria testing dataset show that ANN-WOA has better results than ANN. Therefore, the ANN-WOA model pro ides ery similar results to the results finite element method in estimating of U_d/U_o.

Results of the numerical simulations in the present study ha e been alidated by comparison Chawla et al. (1990)'s analytical method for the same conditions. In Table 3, the results of Chawla et al. (1990), numerical model using SEEP/W software, ANN model and ANN-WOA model for conditions of *d/L* = 0.0004; *n/L*= 0.048 and *H/L* = 1.344 for two states of *s/L* = 0.24 and 0.32 ha e been shown.

4. CONCLUSION

In this research, the two models of ANN and ANN-WOA ha e been used to estimate the total uplift force in gra ity dams. The relati e total uplift force (U_d/U_o) under the gra ity dam in contact with foundation was generated using numerical model

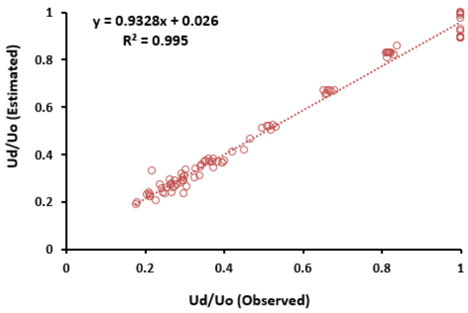

Fig. 5. Scatter plot of the obser ed and estimated data for testing period using ANN model

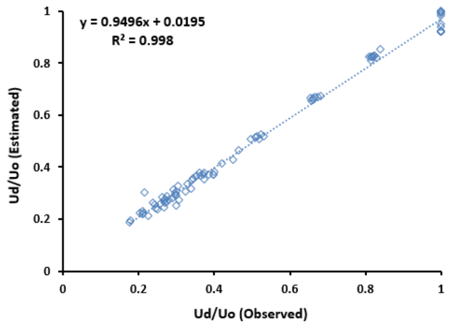

Fig. 6. Scatter plot of the obser ed and estimated data for testing period using ANN-WOA model

Table 2. Statistical alues of training and testing period for ANN-WOA and ANN models

	Test data			Train data		
	R^2	RMSE	RE%	R^2	RMSE	**RE%**
ANN	0.955	0.0223	4.67	0.994	0.0236	**3.4**
ANN-WOA	0.998	0.021	3.50	0.991	0.0177	**2.6**

Table 3. Comparison of ANN-WOA, ANN, SEEP/W and Chawla et al. (1990) results for testing phase

	(s/L=0.024)	(s/L=0.032)
Method	U_d/U_0	U_d/U_0
Chawla et al. (1990)	0.350	0.391
SEEP/W	0.369	0.420
ANN-WOA	0.371	0.414
ANN	0.372	0.411

SEEP/W. Then, the estimated alues of U_d/U_o were compared with the two models named ANN-WOA and ANN. These comparisons are based on three e aluation criteria, i.e., R^2, RMSE and RE%. It should be noted that the ANN model was performed using a code in the Wolfram Mathematica software with random sample selections. Total number of the data was 288 and 30% (88 data) was selected as testing phase and 70% (200 data) was selected as training phase. After repeated multiple random choices from all a ailable data, the data for the conditions with the highest R^2 and lowest RMSE for the estimated process was used in the ANN model. The results of this study showed that both intelligent models ha e reasonable accuracy in estimating of the relati e total uplift force (U_d/U_o). The alues of R^2, RMSE and RE% for ANN-WOA model were 0.998, 021 and 3.3% respecti ely. These alues for ANN were 0.995, 0.022, and 4.67% respecti ely. Both of the ANN-WOA and ANN models were successful in prediction of U_d/U_o. The data density diagrams and the iolin diagram were also obtained and was obser ed that the dispersion and probability distribution of the ANN-WOA model is resembled with the results of the numerical simulation.

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