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Projection of seepage and piezometric pressure in earth dams using soft computational models

Mohammad Najafzadeh

Assistant Professor, Department of Water Engineering, Faculty of Civil and Surveying Engineering, Graduate University of Advanced Technology, Kerman, Iran

ABSTRACT: Earth dams are always one of the main components of water conservation projects. Nowadays, accurate estimation of piezometric pressure and seepage discharge in earth dams using numerical models and artificial intelligence (AI) approaches is one of the fundamental steps in their design studies. In this research, soft computing models including gene-expression programming (GEP), M5 algorithm and group method of data handling (GMDH) have been used to predict the piezometric pressure in the core and the seepage discharge through the body of Shahid Kazemi Boukan Earth Dam. For this purpose, the information recorded in the last 94 months has been used. The results showed that all of the applied models have permissible level of accuracy in the prediction of seepage discharge and piezometric pressure. The best performance in the piezometric pressure estimation is related to the M5 algorithm with a coefficient of determination (R2) of 0.95 and root mean square error (RMSE) of 0.86. The GMDH by considering the two units (months) delay time and with R2= 0.92 and RMSE=1.541 modeled and predicted the seepage discharge, which was more accurate than other models. In general, increasing the time delay in the input information of models generally increases the performance of proposed models.

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1. INTRODUCTION

Earth dams are one of the oldest hydraulic structures that has been constructed to save water and sometimes also for flood diversion. The history of the design and construction of earth dams dates back several thousand years ago. Considering the possibility of building earth dams in arid and semi-arid areas, the use of these structures to control the surface waters of seasonal is of high importance [1, 2]. Nowadays, with the development of instrumentation, as well as much research on earth dams and their related issues, it is possible to construct dams with large reservoirs [3]. With respect to the natural sensitive of the earth dam in relation to the hydraulic failure, in addition to using advanced instrumentation, numerical methods are also used to predict hydraulic flow characteristics such as pore pressure, hydraulic gradient, and seepage discharge in the earth's dams. It should be noted that the design carried out using numerical modeling is examined and evaluated by observing new samples form body of dam during the construction stages [4]. By installing the instrumentation after construction, the safety and health of the dam are monitored continuously. Due to the heterogeneity of the materials used in the earth dam and also the complexity of the hydraulic flow in different parts, it is always necessary to continuously monitor the parameters such as settlement, pore pressure, hydraulic gradient and seepage [5]. It should be noted that the recorded data from the instrumentation provides with the most accurate information possible in relation to the health of the dam. Researchers evaluate the accuracy and performance of numerical models with these data. As mentioned, due to the complexity of the hydraulic of flow in the body and the foundation of the earth's dams, today, in addition to numerical models, artificial intelligence (AI) methods were used to estimate the hydraulic parameters of earth dams. It can be said that the development of AI models is based on data recorded by instrumentation devices.

In this regard, Tayfur et al [6] proposed an Artificial Neural Network (ANN) model to predict the flow in a soil dam in Poland and compared its results with finite element results (FEM). The water level in the upstream and downstream of the dam as input variables and water levels in the piezometers fitted to the dam were considered as the output of the ANN model. Both models were calibrated by the piezometers fitted to the Jizierzco Dam. The water levels predicted by the ANN model were satisfactory as compared to the actual measured piezometers. The results of their research showed that the ANN model, like the FEM method, has a permissible level of accuracy. Sharghi et al. [7] designed and predicted leakage in the Sattarkhan earthquake using different types of artificial intelligence models including multilayer neuron networks (MLPs), support vector machines (SVMs) and adaptive neuro-fuzzy inference system. They considered three strategies for developing models that included different combinations of inputs. They used the surface water in the

*Corresponding author's email: moha.najafzadeh@gmail.com

upstream and downstream of the dam to develop their model. Their research results showed that each of the models used has a precise accuracy in estimating leakage in the body of the Sattarkhan earthquake dam.

2. METHODOLOGY

- Case study

Boukan Dam was created on Zarrineh River (located at the North-West of Iran) to regulate and use the water and flood of that river and it was designed to irrigate the downstream lands located at the southeast of it. This Dam irrigate about 140,000 hectares of agricultural land. The height of the dam is about 50m and the length of the crest is 720m. The lake's volume of Boukan Dam is about 752 million cubic meters. Boukan dam is a reservoir dam that has been used for more than forty years. The location of this dam is shown in Figure 1. The seepage discharge after passing the core of dam, alluvial foundation and grout curtain is directed to the outlet using nine drain wells. The water from these wells is loaded into three collectors and finally poured into three small channels. Each collector summarized discharge of three wells.

- Group Method of Data Handling (GMDH)

GMDH, introduced by Ivakhnenko [8], is a self-organized AI method. The idea of developing GMDH was derived from Volterra's series. According to this idea, the relation between the input and output of each complex system can be approximated by an infinite series of polynomials. The algebraic form of Volterra series is presented in Equation (1).

$$y = w_0 + \sum_{i=1}^{n} w_i x_i + \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} x_i x_j + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} w_{ij} x_i x_j x_k + \ldots \quad (1)$$

Where, $, w_i, w_{ij}, \ldots$ are weights and $x_i \;\; x_j \;\; x_k, \ldots$ are inputs. In development of the first layer of GMDH network, pairs of inputs are introduced to neurons, individually. The number of neurons in the first layer is calculated as Equation (2).

$$\frac{n\left(n-1\right)}{2} \quad (2)$$

Where, n is input features. Ivakhnenko [8] stated that for modeling each complex system using GMDH network, a quadratic polynomial (Equation 3) of Volterra's series as governing equation (transfer function) on the neurons is enough.

$$y = \varphi\left(x_i, x_j\right) = w_0 + w_1 x_i + w_2 x_j + w_3 x_i x_j + w_4 x_i^2 + w_5 x_j^2 \quad (3)$$

- Genetic-Expression Programing

Genetic-expression programing (GEP) is a smart function fitting method the idea of which was based on genetic algorithm. The main point about GEP is the artificial evolution, which is a manifest characteristic of GEP. This means that GEP involved some artificial evolution such as genes, multigene, mutation and so on. GEP developed a new formula based on mathematical operators such as (+, −, /, and *) and functions such as (ex, x, sin, cos, tan, lg, sqrt, ln, power). GEP conducts this operation by randomly generating a population of computer programs (represented by tree structures) and then mutating and crossing over the best performing trees to create a new population. Unlike conventional regression operation, where the researcher defines the structure of empirical formula, GEP automatically creates the structure of developed formula called semi-empirical formula. Final developed formula that is resulted from summarization of multigene, consists of one or more genes that is called GEP tree. To improve the performance of fitness (e.g. to reduce a model's sum of squared errors on a dataset), the genes are obtained increasingly. The final formula maybe weighted linear or nonlinear. The optimal weights for the genes are automatically obtained using the ordinary least squares to regress the genes against output data [9].

- M5 tree model

The M5 model, proposed by the Quinlan [10], is based on the classification tree method. The M5 model uses for the mapping the relation between the independent variables to the dependent variable and unlike the decision tree model in addition to qualities' data uses for the quantitative data. The M5 model is similar to the Piece-wise linear functions method which is a combination of the linear regression and tree regression method. The M5 model widely uses in the most area of the science. A linear or nonlinear regression proposes an equation for the all the data which researchers attempt to mathematical modeling whereas the M5 tree model try to divided data into several categories which named leaf. Modeling the relationship between input and out pout data which categorized in each leafs by the linear regression is the main process which is conducted in the M5 tree method.

3. DISCUSSION AND RESULTS

In this section, the results of modeling and estimating of piezometric pressure and seepage discharge in the body of Shahid Kazemi Boukan earth dam using soft computing methods are presented. Checking these data shows that they have historical records. In other words, these data can be investigated in terms of the time series; therefore, two scenario can be used to model the piezometric pressure (water level versus the piezometers). The first scenario is the modeling of the correlation of this data regardless of their time series. In this scenario, the goal is to model the relationship between the surface water level in the reservoir and the surface water in the piezometers. Considering this scenario involves the state of equilibrium of the system being examined. After more than four decades of operation, it seems that the dam system (flow in the dam body) has reached a state of equilibrium. In this section, the most important piezometer (piezometer installed in the core of earth dam) is modeled and the accuracy of the applied AI models for this piezometer will be investigated. The second approach, which follows the first approach, is to consider the time series in modeling. In other words, in designing input patterns for the development of artificial intelligence models, their time series are also considered. In the modeling of relation between elevation of water in reservoir of dam and piezometric pressure Regardless of the their time series, the data shuffling technique can be used, but in the design of input patterns based on their time histories, that technique cannot be used. In this research, 70% of the data is used for training purposes and the rest is used for testing.

- Modeling and estimating piezometric pressure

In this section, the results of modeling and estimating of piezometric pressure in Shahid Kazemi Boukan dam using soft computing models including GMDH, GEP model, and M5 algorithm are presented. In order to achieve an optimal GEP tree model, the regulatory parameters such as functions, mutation rate, initial population of mutation ratio and number of generations should be determined by trial and error process. The model for the GEP model is presented in Equation (3). As is clear, this equation has three genomes. In this equation (Hw) the water level elevation in the reservoir of the dam and HP is the piezometric pressure. The genetic programming model has an error equal to (R^2 = 0.97 and RMSE = 0.735) in the training phase and (R^2 = 0.97 and RMSE = 0.740) in the testing phase. The M5 algorithm is classified as a tree algorithm, and is recommended for linear phenomena models (phenomena with linear behavior). According to regional water reports of West Azarbaijan, the relationship between the surface water level and the piezometric pressure at the core of the dam is almost linear. Therefore, it seems reasonable to use this method for the above problem. This developed model has only one branch and the derived linear function has been able to present the mathematical model of this phenomenon. Analysis of the statistical indices indicated that, in the training phase, the relationship between the water surface level inside the reservoir and the piezometric pressure in the core had the proper precision of the dam. The comparison of the developed mathematical model using this algorithm with previous models shows that the computation volume of this method is slightly smaller than that of GEP. This is worth noting that the volume of computations in the application of this method is less than the genetic programming model. To develop the GMDH, the first approach (modeling the relationship between the reservoir water surface and the piezometric pressure) used for the development of previous models is not effective because at least two input parameters are necessary for the development of this model. The performance of this model in different stages of development (training and experiment) shows that this model has the appropriate accuracy for modeling and predicting piezometric pressure in the core of Shahid Kazemi Boukan earth dam. Comparison of the performance of this model with the previous models shows that the computing volume of this model is less than Genetic programming model. A comparison of the performance of this model with the M5 algorithm also shows that both models have permissible level of accuracy. However, the GMDH for nonlinear models is also used.

- Modeling and estimating Seepage discharge

The development of artificial intelligence models to estimate and mathematical modeling the seepage discharge is based on the data recorded from this phenomenon. The same approach used for modeling and estimating the pressure at the bottom of the dam will also be used in this section. In order to estimate the seepage discharge in the dam body, using artificial intelligence models used in this study, the water level elevation in the reservoir of the dam as input and seepage discharge were considered as the output of the models. In other words, in this section, the relationship between the water elevation and the seepage discharge is modeled. For the development of this model, only the water level (Hw) elevation in the reservoir and its time delays have been used. For modeling and estimating the seepage discharge using GEP, three scenarios were considered. In the first scenario, the goal of modeling (mathematical formula) is the relationship between the surface water level in the reservoir and the seepage discharge. In this scenario, the delay is not considered. In the second scenario, in the design of the pattern of input data for models, a time delay unit (one month) was used for the surface water level in the reservoir, and in the third scenario, to examine the effect of increasing the time delay on the modeling accuracy, in addition to the first time delay (one month), the second delay time (two months) was added to the input information. The developmental model for the first scenario with the R^2 of 0.85 and RMSE of 1.859 at the training stage and R^2 of 0.85 and RMSE of 1.395 at the testing stage has been able to model and estimate the seepage discharge. Adding a time delay unit in the genetic programming model increased the accuracy of the model with statistical indices R^2 = 0.87 and RMSE = 1.668 in the training stage in comparison with previous scenario in that the accuracy level has increased (R^2 = 092 and RMSE = 1.428). By increasing the second delay, the accuracy of the modeling at the training stage was obtained as R^2 = 0.85 and RMSE = 1.239 and in the test stage statistical parameters were R^2 = 0.92 and RMSE = 1.406 which did not increase significantly compared to the previous scenario.

CONCLUSIONS

In this study the pure pressure and seepage discharge of Bukan earth dam were modeled and predicted via soft computing methods including Genetic Programing, group method of data handling and M5 algorithms. Results of modeling and prediction of seepage discharge and piezometric pressure using utylized soft computing methods showed that all of them have suitable performance, however, the M5 algorithm with R^2=0.95 and RMSE=0.87 for pure pressure prediction and R^2=0.87 and RMSE=1.59 for seepage prediction has best performance. Results of modeling and prediction of pure pressure and seepage discharge shows that using times series information (one month as time delays) significantly improves the modeling accuracy.

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