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Investigation of effective parameters in determining the optimal grouting pressure of cement slurry in dams with rock bed

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Abstract

One of the essential parameters in grouting operations for various purposes of foundation improvement is the optimal grouting pressure for the penetration of cement slurry. In this study, the role of effective parameters in determining the optimal grouting pressure was investigated based on grouting data and engineering geology data obtained in drilling and grouting workshops from 42 dam projects in Iran and the world. Then, Multiple Linear Regression (MLR) and Multiple Nonlinear Regression (MNLR) methods and soft computation methods such as Fuzzy System (FUZZY), Artificial Neural Network (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS) were used to estimate optimal grouting pressure from these parameters. The results show that the depth (D), geological strength index (GSI), and uniaxial compressive strength of rock mass (UCS_{RM}) have the highest correlation in the grouting pressure (GP), respectively. Among the statistical methods, the ANFIS method with a coefficient of determination (R^2 = 0.803) and the root mean square error (RMSE = 4.47) performs better than other models.
Additionally, the results show that R^2 and RMSE are improved in FUZZY, ANN, and ANFIS analysis methods compared to MLR and MNLR. In the fuzzy system, fuzzy rules are formulated using the worker's experience as well as the results of studies of others. These rules select the output using specific ranges of input values, so fuzzy systems models show more flexibility and give better results than the data used in the model.

Keywords: *Improvement, Grouting operation, Optimal grouting pressure, Regression analysis, Soft computing*

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Extended Abstract:

1. Introduction

Dam foundations, especially large dams, are critical to their stability. For several reasons, improvements can be made. They are undertaken in some situations to seal the foundation and prevent water leakage and in others to maintain stability and raise the foundation's carrying capacity or minimize deformation. The improvement objective might be to improve long-term stability by lowering erodibility or decreasing dissolution in certain situations. Nowadays, drilling and grouting technology, as one of the improvement methods, has developed in earth engineering. This field of geoscience is utilized in reducing the permeability and consolidation of supports and foundation of dams, mining activities, and drilling of tunnels and shafts (Mohammadi and Sadeghi, 2021). Groutability and slurry penetration depth are among the most critical issues that are considered in grouting operations. Various parameters such as in-situ stress, pore water pressure, joint geometric and geomechanical characteristics, slurry properties (viscosity and yield stress), and technical factors such as grouting pressure and flow rate are affected the groutability and slurry penetration depth in a jointed rock mass (Mortazavi and Maadikhah, 2016). Considering the material of rock mass, determining the grouting effective pressure is of great importance. The grouting pressure should always be less than the fracture pressure of the rock mass. However, it should be more than the minimum effective pressure that can insert the grouting slurry into the fine joints (Ewert, 1985).
Despite the significance of the pressure need for the grouting process, there is still no agreed-upon method among specialists for estimating the ideal pressure in actual practice or in published publications and reference materials. The assessment of pressure is entirely experimental and carried out by contractors in the workshops because there is now no precise criterion and relationship to estimate the appropriate pressure. In both cases, choosing an unsuitable pressure—low or high—has led to numerous issues with construction projects.

2. Materials and methods

This study has attempted to present statistical methods, models, and applicable relationships to compute the ideal grouting pressure in foundations with rock bed using grouting data and engineering geological data from 42 dam construction projects in Iran and other countries.
The collected information was evaluated and validated. In order to determine the optimal grouting pressure, the primary parameters were finally refined from 13 to just 8 final and useful parameters as follows:

- Depth (D), m
- Tensile Strength (TS), MPa
- Uniaxial Compressive Strength (UCS), MPa
- Modulus Of Deformation (MOD), MPa
- Geological Strength Index (GSI), -
- Discontinuity Spacing (S), cm
- Rock Quality Designation (RQD), %
- Water Pressure Test (Lugeon Permeability Test) (WPT), Lu

The following research and analyses have also been carried out using statistical techniques and soft computing:
1- GraphPad Prism 9 software is used for the linear multiple regression analysis (LMR)
2- Using the XLSTAT program, perform a nonlinear multiple regression analysis (NLMR)

3- Soft computing technique using the Matlab software's fuzzy system
4- Soft computing technique using an artificial neural network (ANN) and Matlab software
5- Adaptive neuro-fuzzy inference system (ANFIS), a soft computing technique, is used in combination with Matlab
In order to examine their function in defining the optimal grouting pressure of cement slurry, a total of 525 final data for all 8 parameters have been studied using regression analysis methods and soft computing techniques.

3. Results and Discussions

3.1. Estimation of grouting pressure with linear multiple regression model (LMR)

This model illustrates the degree to which one independent variable depends on a number of other dependent variables. The grouting pressure (GP) is the dependent variable in the developed model. The variables D and GSI have a considerable difference from zero and a significant influence on the model and the dependent variable, GP, according to the results. The TS and UCS variables are significantly associated with each other and with one another. Model No. 2 was produced after these variables were removed. A decent model has fewer variables overall, but a high R2. In order to further analyze data using non-linear regression and soft computing techniques, model number 2 with 4 variables is preferred to model number 1 with 8 variables.

3.2. Estimation of grouting pressure with nonlinear multiple regression model (NLMR)

Model number 2 was selected in the previous section 3.1 to extract and construct nonlinear relationships using XLSTAT software since it performed best in a linear multiple regression analysis. After creating a number of nonlinear models with various relationships, equation number 1 generated the most effective results:

$$Y = pr_1 + pr_2 x_1 + pr_3 x_1 \hat{} 2 + \cdots \qquad \text{(Equation 1)}$$

Finally, according to the results of Table 2, equation No. 2 is presented for GP estimation by the NLMR method:

$$GP = 4.01 + 0.477(D) - 0.015(UCS) - 0.215(GSI) + 0.0951(S) - 0.003(D^2) + 0.0007(UCS^2) + 0.002(GSI^2) - 0.0003(S^2) \qquad \text{(Equation 2)}$$

3.3. Estimation of grouting pressure with the fuzzy system (FUZZY)

Fuzzy logic holds that no statement is either true or false, but rather has a "degree of truthfulness" associated with it. In this study, the Sugeno-type fuzzy inference system was employed to calculate GP.

3.4. Estimation of grouting pressure with artificial neural network (ANN)

ANNs are mathematical models that feature connected processing nodes (neurons) organized according to a predetermined topology (layers). The neurons often function in parallel layers. The input layer, one or more hidden layers, and the output layer make up a typical network topology.

3.5. Estimation of grouting pressure with adaptive neuro-fuzzy inference system (ANFIS)

Applying various learning strategies established in neural networks to a fuzzy inference system is known as "neuro-fuzzy modelling" (FIS).

To update the membership function and the associated parameter that approaches desired data sets, the ANFIS uses the neural training process (Wu et al. 2009; Maiti and Tiwari 2014). Sugno's fuzzy inference method is used in this study to build fuzzy-neural systems.

4. Comparing the performance of models

To assess the effectiveness of relationships and models, it is vital to look at performance and compare prediction power. The following indicators have been employed in this study to achieve this goal:

1- Coefficient of determination (R^2)

2- Root mean square error (RMSE)

$R^2 = 1$ and RMSE = 0 indicate a good model (Erzin and Cetin, 2012). According to the findings, R^2 has increased and RMSE has dropped in all models created using soft computing techniques compared to models created using linear and non-linear regression techniques. The model created using a fuzzy-neural system is slightly more effective than the other two methods in soft computing techniques.

5. Conclusion

The research results are summarized as follows:

- The findings revealed that the depth parameter (D), geological strength index (GSI), and uniaxial compressive strength (UCS_{RM}), in that order, play the largest roles in defining the ideal injection pressure in each of the developed models (GP).
- The model created by the fuzzy-neural system technique has the best R2 and the lowest RMSE and performs better than all the other models. This is true of all regression methods and soft computing methods.
- Although the results of the fuzzy-neural system were less favourable, the fuzzy system's use of fuzzy rules, which were developed using user feedback and the findings of other studies, resulted in input data that was associated with errors that could be managed and had less of an impact on the model's output.
- In each dam, there exist differences in the effectiveness and proper functioning of various models that were developed using various methodologies. The level of practical experience of the individuals who created the model, particularly in the fuzzy method, as well as the quality of the obtained data, especially with regard to all the parameters used in the model, the geological characteristics of the study areas that have an indirect impact on grouting operations, and other factors all play a role in this difference.

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