



Use of non-linear prediction tools to assess rock mass permeability using various discontinuity parameters



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ABSTRACT

Because of complex discontinuity patterns, it is almost impossible to determine the permeability of rock masses if no proper testing methodology is used. As available in the literature, many empirical approaches to estimate the permeability of a rock mass have been proposed. There is no publication, however, that uses regression analyses and ANFIS (Adaptive Neuro-Fuzzy Inference System) modeling to determine the rock mass permeability. The purpose of the study is to develop various ANFIS and multiple regression models to estimate the rock mass permeability. To this end, a dataset including 453 cases with Lugeon test results and corresponding RQD (Rock Quality Designation), spacing of discontinuities and SCR (Surface Condition Rating) properties is employed. The data were obtained from granite, diorite, volcanic breccia, andesite and agglomerate rock masses from various dam sites and a coal mine in Turkey. Whole data were randomly divided into two parts for training and testing. Two different models were developed to estimate the rock mass permeability. The inputs of the first model are RQD and SCR (Model 1), and the inputs of the second model are discontinuity spacing and SCR (Model 2). Simple regression analyses indicate that there is no statistically meaningful relationship between the Lugeon values with discontinuity spacing and SCR. There is a statistically meaningful relationship, however, between the Lugeon values and RQD. Non-linear multiple regression analyses were implemented for two independent variables and a dependent variable because of the non-linear relationships between the inputs and the output. ANFIS was employed as a second non-linear tool to construct prediction models. According to the performance assessments of the developed models, both of the models and all of the sets are successful. ANFIS is a more successful tool than NLMR. These results show that the models developed are reliable enough and, if there is no direct test result, these models can be used in engineering projects.

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1. Introduction

In rock mechanics, empirical approaches to estimate various rock mass and intact rock properties have been proposed by various researchers (i.e., Gokceoglu et al., 2003; Kayabasi et al., 2003; Dincer et al., 2008; Diamantis et al., 2009; Cevik et al., 2011; Shen et al., 2012). Rock mass permeability (RMP) is an important parameter for engineering applications, such as constructing dams, tunnels and nuclear and liquid waste containment structures. Because of this property, estimating the RMP is important for engineering geologists and rock engineers as a relationship exists between the intrinsic permeability and hydraulic conductivity. The intrinsic permeability of a rock or soil is a measure of its ability to transmit fluid as the fluid moves through (Schwartz and Zhang, 2003), and the hydraulic conductivity is a parameter describing the ease with which the flow takes place through a porous medium. Hydraulic conductivity is introduced in Darcy's law

as a constant of proportionality relating the specific discharge to the hydraulic gradient (Eq. (1)).

The basic law regarding hydraulic conductivity was defined by Darcy (1856). The law states that the rate of flow (Q) per unit area of an aquifer is proportional to the gradient of the potential head (i) measured in the direction of flow:

$$V = K \times i \text{ (m/s)} \quad (1)$$

where, K (m/s) is hydraulic conductivity. For a particular aquifer or a part of an aquifer of area (A) (m^2) and flow rate, Q :

$$Q = V \times A = A \times K \times i \text{ (m}^3/\text{s)} \quad (2)$$

The equation of intrinsic permeability is as follows:

$$k = c \times d_{10}^2 \quad (3)$$

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Table 1
Permeability values for jointed rock masses.

Rock mass description	Permeability degree	Permeability constants (k) (m/s)
Very closely spaced joints	Highly permeable	$1-10^{-2}$
Closely to moderately spaced	Medium permeable	$10^{-2}-10^{-5}$
Widely to very widely spaced	Slightly permeable	$10^{-5}-10^{-9}$
Unjointed, massive	Impermeable	$<10^{-9}$

where k is the intrinsic permeability, c is a coefficient related to the shape of grains and d is the effective grain diameter.

The equation relating hydraulic conductivity and intrinsic permeability is as follows:

$$K = k \cdot (\gamma / \mu) \quad (4)$$

where K is the hydraulic conductivity, k is the intrinsic permeability, γ is the unit weight of water and μ is the dynamic viscosity of water.

Intact or massive rocks are almost impermeable, but jointed rock masses can be permeable, depending on their discontinuity properties. An increase in discontinuity systems results in the flow of water, such as a channel. According to Serafim (1968), if a rock mass is intersected by a system of parallel sided joints with an aperture (e) separated by a distance (d), the hydraulic conductivity could be defined as follows:

$$K = (e^3 \cdot \gamma_w) / 12d\mu \quad (5)$$

where γ_w is the unit weight of water and μ is the viscosity.

The flow of water through fractures was studied by Huitt (1956), Snow (1968), Louis (1969), Sharp (1970), and Maini (1971). Subsequently, determining the equivalent hydraulic conductivity of parallel, smooth, clean jointed platforms was studied (Davis, 1969). According to these studies, the hydraulic conductivity is provided by the following equation:

$$K = (e^3 \cdot g) / 12dv \quad (6)$$

where g is the gravitational acceleration (981 cm/s^2) and v is the kinematic viscosity coefficient (equal to $0.101 \text{ cm}^2/\text{s}$ at 20° for pure water). This equation represents the highest equivalent hydraulic conductivity for fracture systems (Hoek and Bray, 2004). Louis (1969) suggested using Eq. (7) for the laminar flow and parallel bedding of joint sets for capillary flow. If the flow is laminar and the joint system is saturated, the hydraulic conductivity of a rock mass can be determined using Eq. (7). The lowest equivalent hydraulic conductivity occurs for infilled discontinuities and it is given as follows:

$$K = (e/b) \cdot K_f + K_r \quad (7)$$

where, e is the aperture of a joint, b is the spacing of a joint, K_f is the hydraulic conductivity constant for the infilling material and K_r is the hydraulic conductivity of the intact rock material.

Lugeon (1933) developed a method, named the Lugeon test, which determines the transmissivity of a rock mass. The test is based on pressurizing water in an open borehole in a rock mass and recording the loss of water during a time interval. One Lugeon (L) is equal to 1 l of water

per minute injected into 1 m of borehole under a 10 atmospheres pressure. If the test results in less than 1 Lugeon, the rock mass is impermeable, 1–5 Lugeons means the rock mass is slightly permeable, 5–25 Lugeons means the rock mass is permeable and >25 Lugeons means the rock mass is highly permeable. A Lugeon is accepted as 10^{-7} m/s (Lugeon, 1933). The Lugeon test is a widespread test used to determine a rock mass permeability, especially at dam sites and for grouting projects.

Terzaghi and Peck (1967) and ISRM (1981) proposed a classification of rock mass permeability based on the spacing of discontinuities (Table 1).

Lee and Farmer (1990) suggested a simple method to estimate the fracture porosity and permeability using empirical relations between the fracture aperture, the Joint Roughness Coefficient (JRC) and the Joint Compressive Strength (JCS). A valid approximation of fracture porosity and permeability from conducting aperture (e_c), JRC and JCS can be made for an idealized structure.

Barton (2002) correlated the rock mass rating (Q) system with P-wave velocity, the static modulus of deformation, support pressure, tunnel deformation, Lugeon-value and cohesive and frictional strength of rock masses, undisturbed or affected from excavation processes. The researcher suggested that the normalized rock mass rating (Q_c) is inversely related to the Lugeon value (Eq. (8)):

$$L \approx 1/Q_c \quad (8)$$

Foyo et al. (2005) suggested that the Secondary Permeability Index (SPI), which is based on water flow through fissures, zones the dam foundation according to different quality classes. This index determines the rock mass quality using discontinuities discussed in the test section.

Ghaffari et al. (2009) emphasized the importance of uncertainty and vague information in geomechanical analyses. They developed soft granule construction and proposed a Self-Organizing Neuro-Fuzzy Inference System (SONFIS) and a Self-Organizing Rough Set Theory (SORST) as useful tools for data analyses. The permeability analyses were applied to the Shivashan dam site. The comparison of the NFIS (Neuro-Fuzzy Inference System) and the RST (Rough Set Theory) revealed that the NFIS was more able to detect areas with high Lugeon values, while the RST was able to locate low Lugeon zones. In the study, two common areas show similar outputs. The suggested method is a new development for an Intelligent Rock Engineering System (INRES).

Additionally, some researchers used soft computing methods to estimate reservoir parameters. Lim (2003) employed artificial neural networks to predict the reservoir permeability. Ouenes (2000) used fuzzy and neural networks to predict the fracture indicator for reservoir characterization.

Rock mass permeability (RMP) can be determined by considering discontinuity conditions, such as persistence, aperture, roughness, infilling and weathering conditions and the spacing of discontinuities and RQD (Rock Quality Designation). The study presented herein was performed for rock masses that have RMR (Rock Mass Rating) values between 21 and 83 ranging from slightly jointed to heavily jointed, respectively.

The surface condition rating (SCR) of a core run with corresponding Lugeon values can be used to determine the RMP. The SCR is one of the main components of GSI suggested by Hoek and Brown (1997). The

Table 2
The ratings for roughness, weathering and infilling (Sonmez and Ulusay, 1999).

Roughness rating	Very rough	Rough	Slightly rough	Smooth	Slickensided
	6	5	3	1	0
Weathering rating	None	Slightly weathered	Moderately weathered	Highly weathered	Decomposed
	6	5	3	1	0
Infilling rating	None	Hard (<5 mm)	Hard (>5 mm)	Soft (<5 mm)	Soft (>5 mm)
	6	4	2	2	0

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