International Journal of Mining Science and Technology 27 (2017) 415–421

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

New empirical model to evaluate groundwater flow into circular tunnel using multiple regression analysis

Farhadian Hadi [a], Katibeh Homayoon [b,*]

[a] Departmen of Mining Engineering, Faculty of Engineering, University of Birjand, Birjand, Iran
[b] Department of Mining and Metallurgical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran

ARTICLE INFO

Article history:
Available online 2 May 2017

Keywords:
Groundwater inflow
Analytical equation
Multiple regression analysis
Stepwise algorithm
Tunnel

ABSTRACT

There are various analytical, empirical and numerical methods to calculate groundwater inflow into tunnels excavated in rocky media. Analytical methods have been widely applied in prediction of groundwater inflow to tunnels due to their simplicity and practical base theory. Investigations show that the real amount of water infiltrating into jointed tunnels is much less than calculated amount using analytical methods and obtained results are very dependent on tunnel's geometry and environmental situations. In this study, using multiple regression analysis, a new empirical model for estimation of groundwater seepage into circular tunnels was introduced. Our data was acquired from field surveys and laboratory analysis of core samples. New regression variables were defined after perusing single and two variables relationship between groundwater seepage and other variables. Finally, an appropriate model for estimation of leakage was obtained using the stepwise algorithm. Statistics like R, R^2, R_p^2 and the histogram of residual values in the model represent a good reputation and fitness for this model to estimate the groundwater seepage into tunnels. The new experimental model was used for the test data and results were satisfactory. Therefore, multiple regression analysis is an effective and efficient way to estimate the groundwater seepage into tunnels.

1. Introduction

One of the most important problems in tunneling operation is groundwater seepage into tunnels. The most significant difficulties, resulted from water seepage into tunnels, include reduction of rock mass stability around the tunnel, imposition of extra pressure on temporary and permanent supporting systems, reduction of tunnel advance rate, and creating financial problems [1–3].

Due to impossibility of recognition and exact determination of all effective factors on groundwater flow into tunnels, especially during drilling operation in rocks, exact prediction of groundwater seepage into tunnels is difficult [4,5]. Hence, analytical solutions, because of their simplifications and practical theories, have many uses in calculation of groundwater infiltration into tunnels [6,7].

The most important researches about calculation of groundwater seepage rate into tunnels are studies of Muskat et al. [8–28]. Specific solutions have also been effectively used to account for different situations. Ribacchi et al., for example, introduced a solution for lining tunnel assuming a constant hydrostatic load along the tunnel border [29]. Considering Jacob and Lohman solution, Marechal and Perrochet used the solution to model transient ground water discharge into deep tunnels [30,31]. El-Tani used a Mobius transformation and Fourier series to present an equation for a semi-infinite isotropic and homogeneous aquifer drained by a circular tunnel [21]. Park et al. presented a closed-form analytical solution for the steady-state groundwater inflow into a drained circular tunnel with focus on different boundary conditions [25]. Also, El-Tani deliberated a solution for a semi-infinite aquifer drained by a circular tunnel in different heterogeneous aquifer settings using a modified Helmholtz equation [22]. Ming et al. introduced an equation for estimating the distribution of the hydraulic head and the pore pressure boundry condition at the tunnel perimeter in a fully saturated, homogenous, isotropic, and semi-infinite aquifer [32]. Yet, the analytical formulas are generally valid for homogeneous and isotropic aquifers and provide highly overestimated values of the tunnel water inflow, especially in discontinuous rock mass where the anisotropy is high [33–36].

In this study, the monitoring data and information of Amirkabir, Ghomroud and Nosoud water conveyance tunnels, where most

* Corresponding author at: Department of Mining and Metallurgical Engineering, Amirkabir University of Technology (Tehran Polytechnic), 424 Hafez Ave., P.O. Box 44113-15875, Tehran, Iran.

E-mail addresses: Farhadian@birjand.aut.ac.ir (H. Farhadian), Katibeh@aut.ac.ir (H. Katibeh).

http://dx.doi.org/10.1016/j.ijmst.2017.03.005
2095-2686/

parts of them drilled in discontinuous rock masses, used for introducing an empirical equation using multiple regression analyses. By examining the relation between the effective variables on groundwater flow into tunnels and considering each of the analytical equations' parameters for seepage into tunnel in various media (water table, permeability coefficient, radius of the tunnel, the amount of overburden) and regression analysis, a new empirical model is presented to calculate groundwater seepage into circular tunnels.

2. Analytical relations of groundwater seepage flow into tunnel and their validity limits

Groundwater inflow depends on a number of factors, such as the permeability of the rock mass, the groundwater table, the aperture of rock fractures, and the size of the excavation. Groundwater inflow equations are based on Darcy's Law and conservation of mass [37]. Analytical methods considering the parameters such as rock mass permeability, water table height above tunnel axis, and tunnel radius, is used for estimation of groundwater seepage rate into tunnels. Table 1 shows the analytical equations used to estimate seepage flow to tunnels. Fig. 1 shows the applied parameters in the equations presented in Table 1. The presented analytical equations are not valid under these conditions: the vertical seepage flow towards tunnel, bedding variation in rock around the tunnel, and inexact determination of the rock mass permeability [38].

3. Materials and methods

3.1. Multiple regression analysis

The multiple regression analysis is based on the relation between effective variables on groundwater inflow into tunnels. Many theoretical relations can also be expressed with regression models. However, a restriction on regression models is that they are only valid in the range from which data have been extracted. Therefore, to achieve a global experimental relationship, it is necessary to have a lot of various series of data [40,41].

The general purpose of multiple regression is to learn more about the relationship between several independent or predictor variables and a dependent or criterion variable. In general, multiple regression procedures will estimate a linear equation of the form.

$$Y = b_0 + b_1X_1 + b_2X_2 + \cdots + b_nX_n + \varepsilon \tag{1}$$

where ε is the error rate of model. The regression coefficients or 'b terms' represent the independent contributions of each independent variable to the prediction of the dependent variable. The regression line expresses the best prediction of the dependent variable (Y), given the independent variables (X). However, there is usually substantial variation of the observed points around the fitted regression line. The deviation of a particular point from the regression line (its predicted value) is called the residual value [42,43].

3.2. Fitness criteria

One of the points which should be considered about regression models is the assumptions that are taken into account errors. These assumptions are: (1) the mean of errors (ε) is equal to zero, (2) the error variances (σ^2) is constant, (3) errors are uncorrelated, and (4) errors are normally distributed. The last one is essential for testing the assumptions and obtaining the confidence limit. It should be noted that for assessing the fitness of the final inflow model, validity of the assumptions should be evaluated and analysis must be directed to testing of the model well-fitness. Extreme deviations from the assumptions can lead to unstable models. Normally, these deviations are not obvious with the standard tabloid statistics such as T or the F-statistics and R^2. These are general properties which do not guarantee a good final model [44].

3.3. Structure of groundwater seepage into tunnel

Although there are many effective factors on groundwater inflow, a subset of regression variables, which will be used in the model, should be specified. Finding a suitable subset of regression variables is called variable selection subject. Two key aspects of the

Table 1
Analytical equations for prediction of groundwater seepage into tunnels (H_0 = distance between tunnel center and water table; h = hydraulic head into the tunnel; z = overburden; r = tunnel radius; K = hydraulic conductivity; D = hydraulic load above load surface and Q = water inflow to tunnel).

Reference	Equation	Description
Polubarinova-Kochina [9]	$Q = \frac{2\pi K(d-\varnothing_0)}{\ln\left(\frac{2D}{r}\right)}$	For a horizontal tunnel in a fully saturated, semin-infinite homogeneous media, Polubarinova-Kochina derived an approximate expression for Q, the steady state inflow rate per unit length of the tunnel. D is the depth of the tunnel's centerline; is the hydraulic head at the tunnel perimeter and d is the water height above ground
Goodman [10]	$Q = 2\pi K\frac{h}{\ln\left(\frac{2h}{r}\right)}$	This equation has three basic defaults; radius flow, no significant changes in bedding, accurate application of media equivalent permeability
Heuer [13]	$Q = 2\pi K\frac{H_0}{\ln\left(\frac{2z}{r}\right)} \times \frac{1}{8}$	Heuer reduction coefficient $\left(\frac{1}{8}\right)$ and some changes in denominator applied in order to revise Goodman's equation
Lei [15]	$Q = 2\pi K\frac{h}{\ln\left(\frac{h}{r}+\sqrt{\left(\frac{h}{r}\right)^2-1}\right)}$	In this equation, Goodman method has been corrected with application of exact real conditions
El-Tani [20]	$Q = 2\pi K\frac{1-3\left(\frac{r}{2h}\right)^2}{\left[1-\left(\frac{r}{2h}\right)^2\right]\ln\left(\frac{2h}{r}\right)-\left(\frac{r}{2h}\right)^2}$	El-Tani has defined this equation as an optimum equation by considering above mentioned equations
Karlsrud [16]	$Q = 2\pi K\frac{h}{\ln\left(\frac{2h}{r}-1\right)}$	A combination of above mentioned equations, according to field observations, is edited for reducing error in deep and shallow tunnels (under water table)
Lombardi [19]	$Q = 2\pi K\frac{h}{ln\frac{2h}{r}\left(1+0.4\frac{r^2}{h}\right)}$	In this equation, Karlsrud method has been corrected with application of exact conditions
El-Tani [21]	$Q = 2\pi K\frac{\lambda^2-1}{\lambda^2+1}\frac{h}{ln\lambda}$	In this equation El-Tani has applied Mobius transformation method and fourier series and presented a new analytical solution for flow calculation, in which $\lambda = (h/r) - ((h^2/r^2) - 1)^{1/2}$
Park et al. [25]	$Q = \frac{2\pi KL(A+D)}{ln\left(\frac{(H-D)}{r}+\sqrt{\frac{(H-D)^2}{r^2}-1}\right)}$	In this equation: Water table is above the land surface. Hydrostatic load along the tunnel border depending on the stage is varying
Li et al. [39]	$Q = K(S + C.H)$	In this equation, S and C are coefficient related tot he tunnel's shape and depth