Tunnelling and Underground Space Technology 71 (2018) 505–517

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Groundwater Seepage Rate (GSR); a new method for prediction of groundwater inflow into jointed rock tunnels

Mahdi Rasouli Maleki*

Senior Advisor of Water & Power Resources Development Co. (IWPCO) and Head of Engineering Geology Department at Harazrah Consulting Engineers Group, Tehran, Iran

ARTICLE INFO

Keywords:
Groundwater Seepage Rate (GSR)
Groundwater inflow
Hydraulic conductivity
Fracture and joint sets
3D dimensional
Elastic behavior

ABSTRACT

The main purpose of this research is to introduce a new method for estimating the groundwater inflow rate into tunnels excavated in rock environments. The Groundwater Seepage Rate (GSR) is a novel analytical method that has the capability to assess the rock mass potential in conducting the groundwater into tunnels. Geological and hydraulic parameters and radius of the tunnel are the main parameters used in the GSR method. In this method, geological parameters are defined based on the characteristics of the joint sets including the strike, number, spacing and aperture of joints of each joint set. In addition, hydraulic head and hydraulic conductivity are other principle inputs of the proposed model. In GPR method, the rate of groundwater inflow has been evaluated in 3D dimensions and efforts were made to obtain acceptable values by creating rational correlations among input data. The taking account of joints condition in tunnel and the direct effect of tunnel radius, the separate study of the joint sets and the role of fracture systems in the groundwater conductivity into excavated openings are the main advantages of this model. According to the results of this study, GSR method can provide better estimations of the inflow volume for rock masses with elastic behavior in which fracture systems have been developed. Finally, in the end this paper for validation of GSR values, the results of this method were compared with the obtained results of empirical methods and observed groundwater inflow in various geological units of the Zagros tunnel in Iran. Additionally, the calculated value of groundwater inflow based on GSR method shows good compatibility with empirical methods.

1. Introduction

Groundwater inflows during construction pose one of the greatest risks to the successful completion of tunnel projects. Tunnels constructed below the water table are exposed to some level of risk associated with water inflows with magnitude of highly variable risk. Groundwater inflows may constitute a potential hazard as well as an important factor controlling the rate of advancement in driving a tunnel.

Indeed, some of the most disastrous experiences in tunneling have been the result of interception of large flows of water from highly fractured water-saturated rocks (Freeze and Cherry, 1979). As for the discontinuous rock masses, the water flow is strongly dependent upon the hydraulic characteristics of joint sets and rocks fracturing conditions (Gattinoni et al., 2009).

Since the presence of joint and fracture systems in rock masses around the tunnel is the main factor affecting the amount of groundwater conducted into tunnel, the use of engineering characteristics of joints and fractures can be a proper way of estimating the quantity of groundwater inflow into tunnels.

In this research, efforts were made to represent a new analytical method, known as Groundwater Seepage Rate (GSR) via using joint and fracture characteristics as well as the hydraulic parameters of the rock mass. In GSR model, the amount of water inflow is estimated by applying aperture surface area of joints of rock mass with respect to the tunnel surface area. Finally, compared with the results of empirical methods, the results of this method for different units of Zagros tunnel can be more credible.

2. A review of previous methods

So far many researchers all over the world have presented different equations for calculating the extent of groundwater discharge into underground openings. Most of these equations are based on one of the empirical, analytical or numerical methods.

The empirical method is a procedure adopted by Heuer (1995) and subsequently developed by Raymer (2001). This method is based on the experiences obtained from other tunnels, excavated in similar

---

* Corresponding author. Tel.: +98 914 400 3015; fax: +98 21 88768555.
E-mail address: Mahdi.Rasouli@yahoo.com.

http://dx.doi.org/10.1016/j.tust.2017.10.006
Received 25 December 2016; Received in revised form 17 September 2017; Accepted 18 October 2017
0886-7798/

hydrogeological conditions and on the basis of available hydrogeological information (in situ tests, chemical and physical measures, etc.) (Dematteis et al., 2007).

The analytical approach is based on the application of Dupuit's formula, with corrections to the geometry of aquifer layers, the intake area and permeability reduction associated with hydraulic head variations and the effective stress around deep tunnels.

Water inflow into tunnels can be modeled using numerical methods and the seepage into tunnels can be calculated according to various site conditions. These methods require comprehensive data regarding the site condition. Numerical methods are quite complex and their application is time consuming, however, the results are more precise in comparison to analytical methods, particularly when the tunnel is excavated in fractured rock mass and the impact of geo-structural anisotropy of fractured rocks on tunnel inflows needs to be addressed.

In both of the empirical and analytical methods, the equivalent hydraulic conductivity obtained from packer test is applied for predicting the amount of water inflow into tunnel.

Polubarinova-Kochina (1962), Goodman et al. (1965), Lohman (1972), Herth and Arndts (1973), Custodio (1983), Zhang and Franklin (1993), Heuer (1995), Knutsson et al. (1996), El Tani (1999), Raymer (2001), Karlsrud (2001), Ribacchi et al. (2002), Cesano et al. (2003), Perrochet and Dematteis (2007), Hwang and Lu (2007) and Park et al. (2008) have introduced different ways for estimating the groundwater flow into tunnels.

Goodman's formula is probably the most commonly applied approximation for quick estimation of water inflow rates. It also serves as the basis of the empirical method calculations proposed by Heuer (1995). It should be noted that relations obtained for prediction of tunnel water discharge rates by Goodman et al. (1965), Chisyaki (1984) and El Tani (2003) are developed according to analytical solutions for steady-state final values, and those adopted by Perrochet (2005a, 2005b), Perrochet and Dematteis (2007) are for transient inflows. Moreover, Jang et al. (1996) carried out a groundwater flow analysis based on 2D fracture network.

3. Groundwater Seepage Rate (GSR)

The main prerequisite for estimating the water inflow rate into the tunnels excavated in rock masses with many joints is adequate knowledge upon joint and fracture systems of tunnel excavation perimeter. Since the rate of amount of entrance water from a discontinuity always depends on the aperture surface area, it can be concluded that by determining the total aperture surface area of joints surrounding the tunnel, a rather precise estimation of water inflow rate into the tunnel can be obtained.

GSR model is a method based on the following data: geology, hydrology and the tunnel radius. The main purpose for introducing this analytical model is to provide a somewhat accurate estimation of the water inflow rate into tunnels being excavated in rocks based on joint and fracture characteristics of the excavation area. One of the advantages of this method is taking account of each joint system with its own geometrical features including the height, width and length through the calculation process.

In this proposed model, it is assumed that a tunnel with circular cross section is excavated in an isotropic media with even permeability coefficient. The main input parameters used in this model are the geological and hydraulic parameters as well as the radius of the tunnel (Table 1). Among the geological parameters, aperture and spacing of joints are of crucial importance, since they have direct relationships with the amount of water.

Unlike other models, in GSR model, the cross section from which water passes into the tunnel is assumed equivalent to the aperture surface area of joint sets available in the rock mass. Accordingly, for determining the cross section of joints in tunnel circumference, firstly by determining the number of joints (N_J), aperture surface area (A_J) in each joint set and the total aperture area of joints (A_{total}) around the tunnel is calculated. Then the rate of water inflow into the tunnel can be estimated in a form of analytical relationships via simple correlation between these data and hydraulic parameters.

Table 1
The effective parameters in assessment inflow water into tunnel based Groundwater Seepage Rate (GSR).

1. Geological parameters	2. Hydraulic parameters	3. Tunnel properties
● Strike of joints, α	● Hydraulic heads, H	● Radius of tunnel, r
● Number of joints, N_J	● Hydraulic conductivity, k	
● Spacing of joints, S_J		
● Aperture of joints, A_J		

The groundwater head (h) and hydraulic conductivity (k) of rock masses surrounding the tunnel play an important role for determining the water inflow rate. Due to the variability of these parameters along the tunnel route, it is necessary to divide the tunnel path into separate zones with similar structural and hydraulic characteristics for more accurate evaluations. In order to distinguish each zone from others, one should bear in mind specific criteria such as lithological changes, permeability variations with respect to lugeon value in boreholes, hydraulic head of groundwater changes and so on.

In GSR, the water inflow rate into the tunnel can be calculated in three different scenarios:

1. Groundwater inflow into the whole zones of the tunnel.
2. Groundwater inflow into each zone of the tunnel.
3. Groundwater inflow into drilling effective length of the tunnel.

3.1. *Geological parameters*

As stated earlier, the main purpose of applying geological parameters is to involve their vital effect through the water inflow evaluation procedure. Indeed, this important factor has not been adequately considered in other models. The analysis and assessment results using the GSR model can subsequently be compared with the actual conditions of the excavated zone.

Based on GSR model, the angle between the joint strike and tunnel axis (α), number (N_J), spacing (S_J) and aperture (A_J) of joints in each joint set are the main geological parameters involved in estimation of water inflow into tunnels. To sum up, the main purpose of involving geological parameters in GSR model is to determine the aperture surface area of total joints with respect to the surrounding area of tunnel (i.e. to determine the parameter of reduction (n) of joints and fractures around the tunnel). Fig. 1 shows the orientation, spacing and number of joint sets with respect to tunnel axis.

3.1.1. *Angle between joint strike and tunnel axis (α)*

The intersection of each joint with the tunnel path could form circular, elliptical or rectangular shapes in the cross section of a tunnel. The angle between joint strike and tunnel axis is used for determining: 1) the number of joints of tunnel and 2) the radius of the circular or elliptical shape or large length of rectangular shape.

3.1.2. *Number of joints (N_J)*

The development of joints around the tunnel results in a porous media with high permeability. Therefore, it could be mentioned that this geological parameter is an important factor which facilitates the groundwater inflow into the tunnel. As a result, this parameter has been applied in GSR model due to its significant role for accurate estimation of water inflow.

3.1.3. *Spacing of joints (S_J)*

A lower joint spacing means a greater number of joints, a lower rock mass quality and a higher permeability in the tunnel surface. The joint