A new method to estimate the permeability of rock mass around tunnels

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Abstract

Estimating the equivalent hydraulic conductivity (hereafter it will be called: equivalent permeability) of a rock mass is the first and most important step in computing the water flow into underground excavations. Existing analytical models used to estimate equivalent Permeability have several shortcomings that limit them for practical usage. A new model has been introduced to estimate rock mass equivalent permeability by considering rock fractures as a finite disc shape plane. This new model provided more reliable estimation of equivalent permeability compared to the other models for the rock mass around the ventilation drift in Stripa Mine in Sweden.

Introduction

Uncontrolled water inflow inside tunnels causes numerous problems during their construction and continuing operation. It may increase cost of projects by damaging support systems and may cause decrement on advance rate. Therefore, engineers need to have control inundation through predicting of water inflow by numerical modelling techniques (discontinuous and continuous methods) and analytical and empirical methods. Continuum numerical modelling and analytical methods are relatively easier to use and need fewer input data. Therefore, they are the most common techniques to estimate water inflow.

The equivalent permeability of rock mass is the most important input parameter for computing tunnel inundation based on continuum numerical modelling and analytical methods. In the most rocks, discontinuities including joint, bedding planes and foliations control the water flow and the permeability [1]. When water passes through such a medium the flow becomes heterogeneous. Because these discontinuities act as channels, flow through the rock mass is controlled by the location, orientation and characteristics of individual discontinuities or discontinuity sets [1].

A considerable amount of literature has been published on the equivalent permeability of jointed rocks. Long [2], Min *et al* [3], Wang & Kulatilake [4] have used discrete fracture network (DFN) to simulate the flow inside of the fractured network. This approach assumes that the geometric character of each fracture (position in space, length and width) is known exactly as well as the pattern of connection among fractures [5]. A combination of percolation theory and DFN was used by Hestir & Long [6] and de Dreuzy *et al* [7, 8]. Zimmerman & Bodvarsson [9] have replaced each fracture by a conductive element that its conductance depends on the hydraulic aperture of fracture. They used this virtual network to determine the permeability of two-dimensional fractured rock. Snow [10], Oda, [11, 12] and Zhou *et al* [13] introduced fully analytical methods based on the geometrical properties of jointed networks for determining the equivalent permeability tensor of rock mass. These methods are easy to use by engineers and provide a relatively acceptable estimation for rock mass permeability.

The first comprehensive analytical model to estimate the equivalent permeability of jointed rock mass was presented by Snow [10]. He argued that joints have an infinite size, i.e. the joints extend throughout the rock mass volume (objective volume). In the Snow model [10], the equivalent permeability tensor (k_{ij}) is given by:

$$\boldsymbol{k_{ij}} = \frac{g}{12\vartheta}\sum_{j=1}^{n}\frac{a_j^3}{s_j}\ (\boldsymbol{\delta_{ij}} - \boldsymbol{n_i n_j}) \tag{1}$$

Where g is the gravitational acceleration, ϑ is the kinematic viscosity, a_j and s_j are hydraulic aperture and spacing of *jth* joint set, δ_{ij} is the Kronecker delta and n_i and n_j are direction cosines of the unit vector normal to the fracture in the x, y and z direction, respectively. Since infinite joints were considered in this model, it is not possible to quantify the scale effect and inter-connectivity of fractures on the equivalent permeability of the rock mass.

As commonly known, the length of discontinuities inside of the objective volume of rock mass are not infinite therefore, Snow's model [10] overestimates the permeability of rock mass (its results can be considered as upper bound values for rock mass permeability). Several researchers have tried to overcome the shortcomings in the Snow method. Oda [11, 12] and Zhou *et al* [13] presented two approaches that are able to consider finite joints. For instance, to assess the influence of the scale effect on the equivalent permeability, the number of joints in each set of joints must be calculated first. Both methods must compute the number of joints in each set of joints using numerical methods (e.g. stochastic discrete fracture network), or alternatively, the density of each set of joints should be estimated by mapping the joints. Furthermore, Oda's approach does not consider the inter-connectivity of the joint network, while the method proposed by Zhou *et al* [13] requires numerical modeling to estimate the inter-connectivity coefficient.

Zoorabadi *et al.* [14, 15] proposed a new method for estimating the equivalent permeability of rock mass around a tunnel. In this report, the basic of the method is presented in more detailed. Furthermore, a sensitivity analysis was conducted by using this method to find the effect of geometrical properties of discontinuities on rock mass permeability in Stripa Mine in Sweden.

Equivalent permeability of rock mass around tunnel

When joints are assumed to be a finite plane, the number of joints inside the objective volume of the rock mass must be known in order to determine the equivalent permeability using analytical models. In new proposed model, concept of intersection probability of each facture with a circular cross section tunnel is used for estimating of number of joints inside objective volume. Here, the objective volume is considered to be a cylindrical volume that surrounds a tunnel, with a circular cross section (Figure 1).

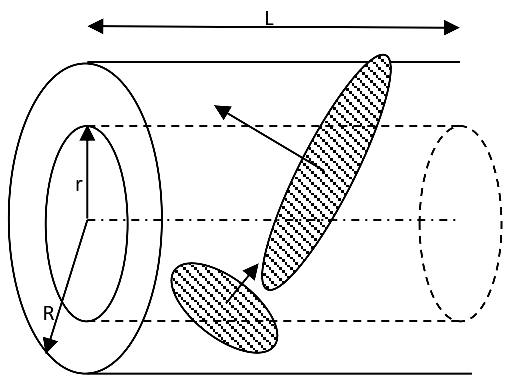

Figure 1. Interested objective volume of rock mass around the tunnel

Formulation of proposed method has been established based on the following assumptions [14]:

1- All discontinuities have planar shape.
2- Discontinuities are assumed to be presented as circular discs.
3- The centers of discontinuities are distributed in space randomly and independently.
4- The size of discontinuities is independent of spatial location.

The global coordinate system is supposed that to have x-axis points toward east, y-axis points north, and z-axis in upward direction. The probability P_{ij} that is a circular cross section tunnel with radius, trend, and plunge r, β_t and α_t, respectively will intersect a discontinuity (*i*th discontinuity for *j*th set) of diameter D_{ij} and with dip direction β_{ij} *and* dip α_{ij}, can be estimated as follows [16, 17]:

$$P_{ij} = \begin{cases} For\ (D_{ij} < 2r\cos\theta_{ij}) \\ \frac{2rL_p}{\pi R^2} \\ For\ (2r\cos\theta_{ij} \le D_{ij} < 2r) \\ \frac{0.25\pi {D_{ij}}^2 \cos\theta_{ij} + rL_p + \pi r^2 - J_1 - J_2 + J_3 + J_4}{\pi R^2} \\ For\ (D_{ij} \ge 2r) \\ \frac{0.25\pi {D_{ij}}^2 \cos\theta_{ij} + rL_p + \pi r^2}{\pi R^2} \end{cases} \tag{2a}$$

Where R is the radius of the objective volume of the rock mass around the tunnel (Figure. 1), θ_{ij} is the acute angle between the axis of the tunnel and normal vector of *i*th discontinuity of *j*th set. L_P, J_i and x are constants determined by:

$$L_p = \frac{\pi D_{ij}\sqrt{1+\cos\theta_{ij}}}{\sqrt{2}} \tag{2b}$$

$$J_1 = r^2 \cos^{-1}\left[\frac{{D_{ij}}^2/4 - r^2(1+\cos^2\theta_{ij})}{r^2(1-\cos^2\theta_{ij})}\right] \tag{2c}$$

$$J_2 = \frac{{D_{ij}}^2\cos\theta_{ij}}{4}\cos^{-1}\left[\frac{{D_{ij}}^2 + \cos^2\theta_{ij}({D_{ij}}^2 - 8r^2)}{{D_{ij}}^2(1-\cos^2\theta_{ij})}\right] \tag{2d}$$

$$J_3 = rD_{ij}\int_{\pi/2-x}^{\pi/2}\sqrt{\sin^2\theta_{ij} + \cos^4\theta_{ij}}\,d\theta \tag{2e}$$

$$J_4 = D_{ij} r \cos^2\theta_{ij}\int_{\pi/2-x}^{\pi/2}\frac{d\theta}{(\sin^2\theta_{ij} + \cos^4\theta_{ij})^{3/2}} \tag{2f}$$

$$x = \frac{1}{2}\cos^{-1}\left[\frac{{D_{ij}}^2 + ({D_{ij}}^2 - 8r^2)\cos^2\theta_{ij}}{{D_{ij}}^2(1-\cos^2\theta_{ij})}\right] \tag{2g}$$

Consequently, the average number of discontinuities of *j*th set in the objective volume of rock mass around the tunnel can be estimated as [17, 18]:

$$m_j = \frac{N_j}{P_{ij}} \tag{3}$$

In above equation, N_j is the number of discontinuities for *j*th set observed from mapping in the tunnel. For the specific length of tunnel L, equation (3) is simplified as follows:

$$m_j = \frac{1}{P_{ij}}\frac{L\cos\theta_j}{S_j} \tag{4}$$

Where S_j indicates the average real spacing of discontinuities in *jth* set. Finally, total number of discontinuities of *j*th set in the objective volume of rock mass around tunnel is obtained by:

$$
\boldsymbol{m_j} = \begin{cases} \boldsymbol{For\ (D_j < 2r\cos\theta_j)} & \dfrac{\sqrt{2}\, V_R \cos\theta_j}{\pi s_j (2\, r\, D_j \sqrt{1+\cos\theta_j})} \\ \boldsymbol{For\ (2r\cos\theta_j \le D_j < 2r)} & \dfrac{V_R \cos\theta_j}{s_j (0.25\, \pi\, D_j^2 \cos\theta_j + r\dfrac{\pi D_j \sqrt{1+\cos\theta_j}}{\sqrt{2}} + \pi r^2 - J_1 - J_2 + J_3 + J_3)} \\ \boldsymbol{For\ (D_j \ge 2r)} & \dfrac{V_R\ \cos\theta_j}{S_j \left(0.25\pi {D_j}^2 \cos\theta_{ij} + r\dfrac{\pi D_j \sqrt{1+\cos\theta_j}}{\sqrt{2}} + \pi r^2\right)} \end{cases} \tag{5}
$$

Where V_R is the total volume of rock mass around the tunnel and the volume of excavated rock mass. For any other discontinuity sets seen on the wall of the tunnel, the discontinuity number can also be estimated as above.

For joint sets or bedding planes parallel with the axis of the tunnel (θ_j=90), the above equations cannot be used to estimate their total number inside the objective volume. For these discontinuities, the ratio of the excluded volume of two fracture planes to the total volume of rock mass around the tunnel is used as a rough estimation of joint number:

$$
\boldsymbol{m_j = \frac{2L(R^2 - r^2)}{S_j D_j^2}} \tag{6}
$$

The inter-connectivity represents the hydraulic contribution of each joint in a system or network of rock joints. Thus, a fracture with more intersections with other fractures has a greater effect on the apparent flow velocity for the overall joint network. According to Zhang *et al* [19], inter-connectivity of joint networks depends on the length, density and orientation of the joints. Rouleau and Gale [20] introduced an empirical inter-connectivity index, I_{ij}, to quantify the inter-connectivity between two discontinuity sets as:

$$
\boldsymbol{I_{ij} = \frac{l_i}{s_j} \sin\gamma_{ij}} \tag{7}
$$

Where l_i is the mean trace length of joint set *i*, s_i is the mean spacing of joint set *j* and γ_{ij} is the average angle between fractures of joint set *i* and joint set *j*. It is obvious that I_{ij} is generally different from I_{ji}. The total inter-connectivity index for a discontinuity set is defined as:

$$
\boldsymbol{I_i = \sum_{j=1}^{n} I_{ij}\ (i \neq j)} \tag{8}
$$

Where *n* is the number of discontinuity sets. A joint set with a higher inter-connectivity index has a higher contribution on hydraulic properties of joined rock mass. In this study, inter-connectivity coefficient for each set of joints in a network is proposed (C_i), by normalizing its inter-connectivity index with a maximum inter-connectivity index in the whole network.

$$\boldsymbol{C_i = I_i / I_{max} \qquad 0 < C_i \leq 1} \tag{9}$$

As much as C_i of a joint set approaches 0, its contribution on the hydraulic behavior of jointed rock mass will be lower. Using this concept for inter-connectivity provides an ability to determine the most effective joint set on permeability of rock mass.

The jointed rock mass is assumed to be a homogeneous, anisotropic porous medium. Based on the Darcy's Law, the apparent seepage velocity $\overline{v_i}$ is related to the gradient J_i through a linking coefficient k_{ij} called the permeability tensor, as follows [21]:

$$\boldsymbol{\overline{v} = -k_{ij} J_i} \tag{10}$$

In most rocks, except those which have intrinsic porosity, fluid flow is controlled principally by the discontinuities; hence the apparent flow velocity $\bar{v}$ can be defined as follows (modified after Oda, [11]):

$$\boldsymbol{\overline{v} = \frac{1}{V} \int_{V^{(f)}} v_i^{(f)} C_i \, dV^{(f)}} \tag{11}$$

Where V is the objective volume of the surrounding rock mass, and $V^{(f)}$ is the total volume of fractures inside the objective volume around the tunnel. The total number of rock joints inside the objective volume is determined by equations (5) and (6), then equation (11) can be written as:

$$\boldsymbol{\overline{v} = \frac{1}{V_R - V_r} \sum_{j=1}^{n} \sum_{i=1}^{m_j} v_{ij}^{(f)} C_j V_{ij}^{(f)} = \frac{1}{V_R - V_r} \sum_{j=1}^{n} m_j v_j^{(f)} C_j V_j^{(f)}} \tag{12}$$

Where V_r is the volume of excavated rock mass.

Rock joint is assumed as a circular disc with diameter D_{ij} and a hydraulic aperture a_{ij}; its void volume of joints is equal to $(\pi/4) D_{ij}^2 a_{ij}$. From the Navier-Stokes equations for slow laminar single phase flow of an incompressible Newtonian fluid, the following equation was gained for the average velocity per unit width of a parallel plate conduit [21].

$$\boldsymbol{v_i{}^{(f)} = -\frac{g}{\vartheta} \frac{a_i{}^2}{12} J_i^{(f)}} \tag{13}$$

Where J_i is a projection of the field gradient on the *ith* fracture.

If the intersection of two or more smooth planar conduits are not sealed by dislocation or enlarged by solution, the amount of head lost at intersection will be negligible under laminar flow conditions [10]. Therefore, the field gradient J_i is uniform over the whole flow region [11] and the head gradient which applied on each fracture can be calculated by following equation [11, 13].

$$\boldsymbol{J_i^{(f)} = (\delta_{ij} - n_i n_j) J_i = \begin{bmatrix} 1-n_1^2 & -n_1 n_2 & -n_1 n_3 \\ -n_2 n_1 & 1-n_2^2 & -n_2 n_3 \\ -n_3 n_1 & -n_3 n_2 & 1-n_3^2 \end{bmatrix} \{J_i\}} \tag{14}$$

Introducing equation (14) into equation (13) results in:

$$\boldsymbol{v_i^{(f)} = -\frac{g}{\vartheta}\frac{a_i^2}{12}\,(\delta_{ij} - n_i n_j) J_i} \tag{15}$$

By replacing equations (15) in equation (12), the apparent seepage velocity $\overline{v_i}$ is obtained as:

$$\boldsymbol{\overline{v} = -\frac{\pi g}{48\,\vartheta(V_R - V_r)} \sum_{j=1}^{n} m_j C_j\, D_j^2 a_j^3 (\delta_{ij} - n_i n_j) J_j} \tag{16}$$

Form equations (10) and (16), a new formulation for estimating the equivalent permeability of rock mass k_{ij} is determined as:

$$\boldsymbol{k_{ij} = \frac{\pi g}{48\,\vartheta\,(V_R - V_r)} \sum_{j=1}^{n} m_j C_j\, D_j^2 a_j^3 (\delta_{ij} - n_i n_j)} \tag{17}$$

In this new equation, the equivalent permeability tensor of jointed rock mass around a tunnel depends on the length of the joint, the hydraulic aperture, the orientation and the inter-connectivity of the joints, and the average spacing of each set of joints.

When there are not any joint set parallel with tunnel axis and the lengths of all the fractures included in the objective volume are larger than the diameter of the tunnel, equation (17) will change as:

$$\boldsymbol{k_{ij} = \frac{gR^2}{48\,\vartheta\,(R^2 - r^2)} \sum_{j=1}^{n} \frac{D_j^2 a_j^3\ \cos\theta_j}{S_j\left(0.25{D_j}^2\cos\theta_j + r\frac{D_j\sqrt{1+\cos\theta_j}}{\sqrt{2}} + r^2\right)}\ C_j\ (\delta_{ij} - n_i n_j)} \tag{18}$$

In above equation, if the diameter of the tunnel was reduced to zero (it means the length of fractures can be considered infinite), equation (18) changes to the Snow model (considering $C_j=1$ for all joint sets; same inter-connectivity for all fractures). This result demonstrates that the new model has a correct base and assumption.

In this study the author has developed a new code, using Visual C++ programming language, to compute the equivalent permeability tensors for the new proposed model and Snow's method. This code can consider up to 10 joint sets inside rock mass (Appendix).

Verification of the proposed model

For verification of the new proposed model for estimating the equivalent permeability of jointed rocks, a data set obtained from Stripa Mine is used. Strip mine is located in central Sweden and an extensive research on groundwater flow through jointed rock was conducted at this site to study the possibility of disposing high-level nuclear waste. Rougleau and Gale [20] reported the complete data of joints system characterisation (Figure 2 and Table 1), which collected from the ventilation drift. The ventilation drift has a rectangular shape with dimensions of 5 m× 5 m× 33 m (equivalent to a circular cross section with a radius of 2.8 m), the orientation (trend/plunge) is 350/0, and is located at the depth 338 m in the mine.

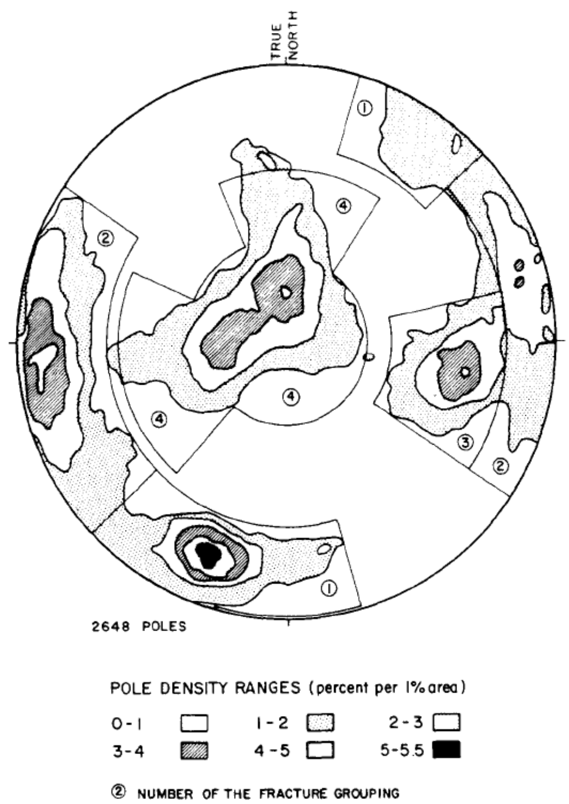

Figure 2. Pole diagram for all joint planes measured on the ventilation drift [20].

Table 1. Geometric characterisation of rock joints [1, 20, 23]

Joint Set	Dip	Dip/Dir	Spacing	Length	Hydraulic aperture [μm]
Set 1	76	23	0.93	2.19	8.3
Set 2	85	83	0.36	1.11	8.3
Set 3	53	278	0.79	1.61	8.3
Set 4	12	155	0.51	1.38	8.3

Considering these input data and assuming water with 20^0 C temperature (for the kinematic viscosity of water), the permeability of rock mass around the ventilation drift of the Stripa Mine was estimated by the new proposed model and Snow's model [10] as shown in Table 2. The results from Oda's model [11] are also reported in this table.

Table 2. Equivalent permeability of rock mass around the ventilation drift

	K_{11} [cm/s]	K_{22} [cm/s]	K_{33} [cm/s]	Mean [cm/s]
Snow	2.87×10^{-7}	2.15×10^{-7}	1.52×10^{-7}	2.18×10^{-7}
Oda (1987)	6.36×10^{-8}	4.96×10^{-8}	3.37×10^{-8}	4.9×10^{-8}
Proposed Model (R=12 m, r=2.8m)	9.5×10^{-9}	4.68×10^{-9}	5.1×10^{-10}	3.58×10^{-9}

Despite the fact that in other references such as Wei *et al* [23] and Lee & Farmer [1] the hydraulic aperture of rock joints in the Stripa Mine was reported to be 8.3 µm but Oda *et al* [12] used 5.43 µm for the hydraulic aperture of joints. Since the equivalent permeability of the rock mass has a direct relationship with the hydraulic aperture, if 8.3 µm was applied as the hydraulic aperture of joints in the Oda model, its results will be higher than the data reported by Oda [11].

A large scale permeability test was conducted around the ventilation drift by Wilson *et al* [24]. They reported 9.8×10^{-9} cm/s as equivalent permeability for that rock mass. According to the above results, the proposed model gives a better estimation of the equivalent permeability compared to the results of the large scale permeability tests.

Sensitivity analysis on input data

There is an inherent uncertainty on the geometrical properties of rock joints. This uncertainty affects the reliability of the estimated equivalent permeability of rock mass. Sensitivity analysis is a useful tool to investigate the influence of uncertainty on the estimated values. The inter-connectivity coefficient which used in the new model provides an ability to determine the most effective joint set on permeability of rock mass. For Stripa Mine, the joint set number 1 has maximum contribution of the hydraulic behavior of rock mass around the Ventilation drift (based on equation 9). The sensitivity analysis of the average equivalent permeability of surrounding rock mass in Stripa Mine's ventilation drift with variation of length, spacing and dip of joint set number 1 (most effective joint set) are shown in Figures 3 to 5.

These results depict that the rock mass equivalent permeability increases with increasing of joint length (Figure 3). In fact inter-connectivity of joint network increases with the increase of joint length and provides more flow path inside joint network.

In contrast to the joint length, increase of joint spacing reduced the equivalent permeability of rock mass (Figure 4). The rate of this reduction is decreased significantly after a certain value of joint spacing. In Stripa Mine, the increase of joint spacing more than 0.7 m has a negligible effect on the reduction of rock mass permeability.

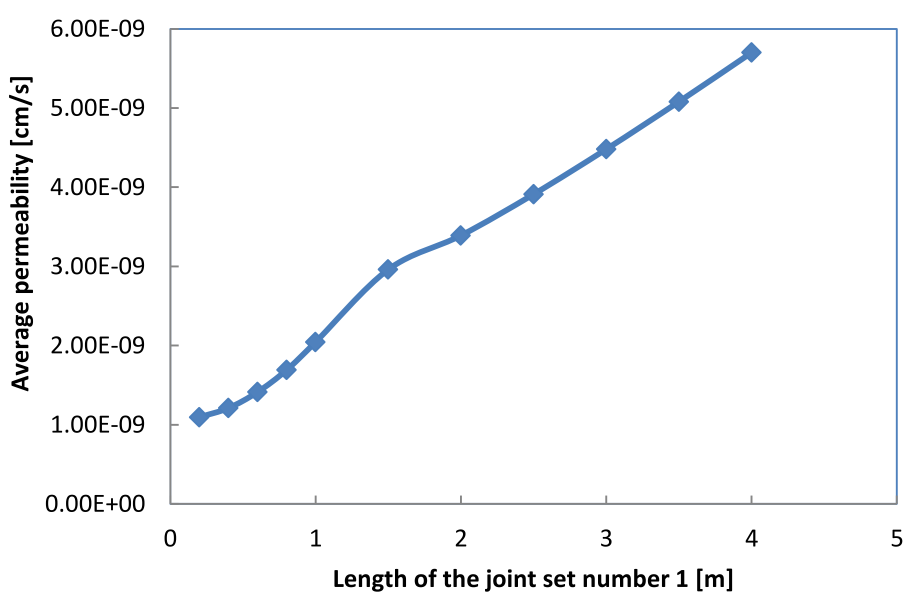

Fig.3. Variation of average permeability with increase of joint length

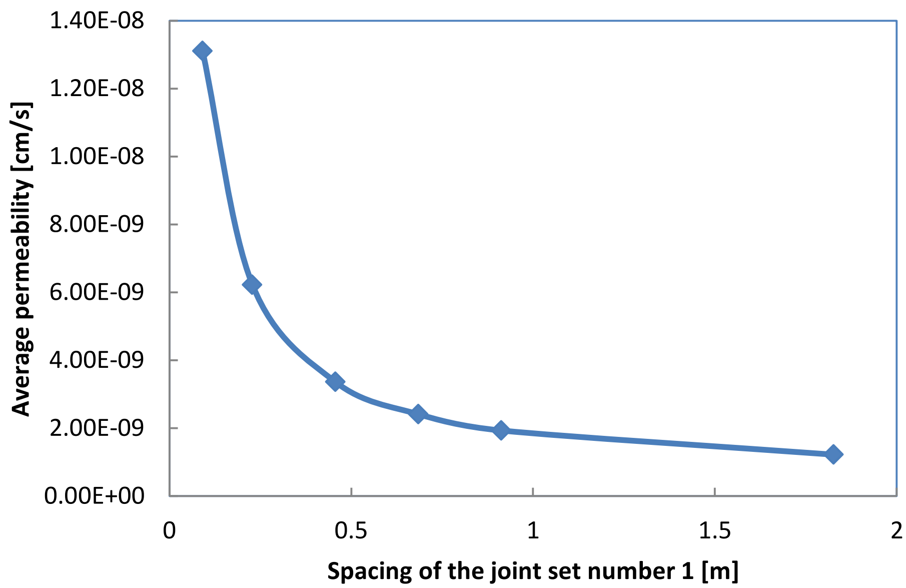

Fig.4. Variation of average permeability with increase of joint spacing

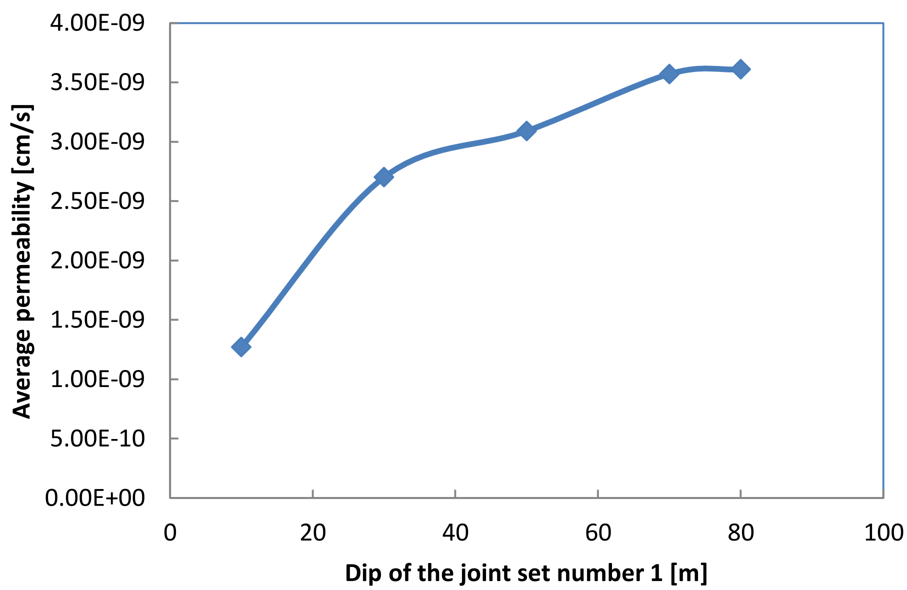

Fig.5. Variation of average permeability with increase of joint dip

The sensitive analysis of rock mass equivalent permeability respect to fracture's dip angle demonstrates that rock mass with vertical or sub-vertical fractures has higher permeability.

According to equation (2a), the intersection angle of rock joints and tunnel axis affects the probability of intersection so; total number of rock joints inside the objective volume and the equivalent permeability are a function of tunnel orientation. Therefore, the new proposed method offer a tool to assess the anisotropy ratio of rock mass based on discrepancy of average equivalent permeability in different orientations. The results in Figure 6 depict that the rock mass around the ventilation drift of Stripa Mine has an anisotropy ratio (maximum to minimum value) 1.62.

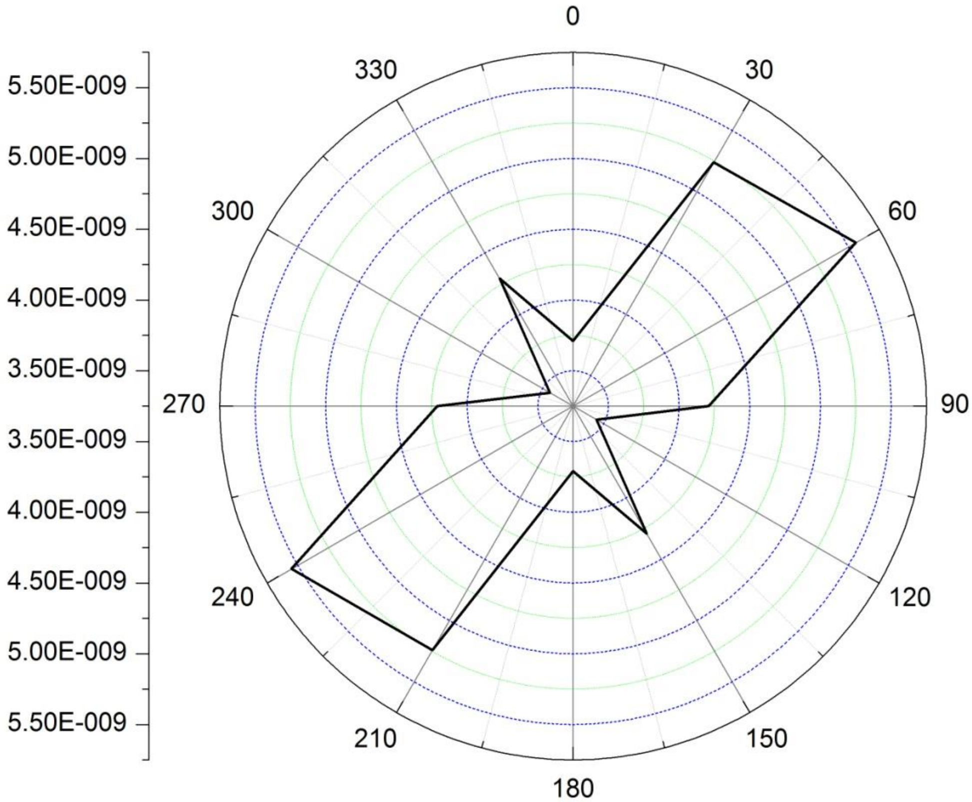

Fig. 5 Variation of average permeability respect to the tunnel trend

Conclusions

Since using discontinuous numerical modeling for estimating water inflow into every specific project is so time consuming, and it requires a large geotechnical study to prepare the input data, continuum modeling and analytical models are more convenient for site engineers. These methods need the equivalent permeability of a rock mass as most important input data.

Existing analytical models used to estimate equivalent permeability have several shortcomings that limit them for practical usage. In the new proposed model, a finite length of joint is considered, and the number of joints in each set of joints inside the objective volume can easily be estimated. The newly proposed model used to estimate the equivalent permeability of rock mass used in a case study (Stripa Mine) provided a better estimation of equivalent permeability compared to the other models.

Sensitivity analysis on input data is a procedure to assess the effects of inherent uncertainty in the input data (geometrical properties of rock joints) on rock mass permeability. This analysis indicates the average permeability of rock mass increases by increment of length and dip of joints. However, the incrimination of joint spacing declines the average permeability. The calculated average permeability in different orientation demonstrates that the rock mass around the ventilation drift of Stipa Mine has anisotropy ratio 1.62.

Acknowledgements

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References:

[1] Lee CH, Farmer I. Fluid flow in discontinuous rocks. Chapman & Hall publication; 1993.

[2] Long JCS. Investigation of equivalent porous medium permeability in networks of discontinuous fractures. PhD thesis, University of California, Berkeley; 1983.

[3] Min KB, Jing L, Stephansson O. Determining the equivalent permeability tensor for fractured rock masses using a stochastic REV approach: Method and application to the field data from Sellafield, UK. Hydrogeology Journal. 2004; 12: 497-210.

[4] Wang MY, Kulatilake PHSW. Understanding of hydraulic properties from configurations of stochastically distributed fracture networks. Hydrological Progresses. 2008; 22: 1125–1135.

[5] Chen YF, Zhou Ch, Sheng Y.. Formulation of strain-dependent hydraulic conductivity for a fractured rock mass. International Journal of Rock Mechanics & Mining Sciences. 2007; 44: 981-996.

[6] Hestir K. & Long JCS. Analytical expressions for the permeability of random two-dimensional Poisson fracture networks based on regular lattice percolation and equivalent media theories. J. Geophys. Res. 1990; 95: 565-581.

[7] de Dreuzy JR., Davy P. & Bour O.: Hydraulic properties of two-dimensional random fracture networks following a power law length distribution 1. Effective connectivity. Water Resour. Res. 2001a; 37: 2065-2078.

[8] de Dreuzy JR., Davy P. & Bour O.: Hydraulic properties of two-dimensional random fracture networks following a power law length distribution 2. Permeability of networks based on lognormal distribution of apertures. Water Resour. Res. 2001b; 37: 2079-2095.

[9] Zimmerman RW. & Bodvarsson GS.: Effective transmissivity of two-dimensional fracture networks. Int. J. Rock Mech. Min. Sci. 1996; 33(4): 433-488.

[10] Snow DT. Anisotropic permeability of fractured media. Water Resources research. ., 1969; 5: 1273-1289.

[11] Oda M. Permeability tensor for discontinuous rock masses. Geotechnique. 1985; 35: 483-495.

[12] Oda M, Hatsuyama Y. Numerical experiments on permeability tensor and its application to jointed granite at Stripa mine, Sweden. Journal of geophysical research, 1987; 92: 8037-8048.

[13] Zhou CB, Sharma RS, Chen YF, Rong J. Flow–stress coupled permeability tensor for fractured rock masses. International Journal for Numerical and Analytical Methods in Geomechanics. 2008; 32: 1289–1309.

[14] Zoorabadi M, Indraratna B, Nemcik J. A new equation for the equivalent hydraulic conductivity of the rock mass around a tunnel. International Journal of Rock Mechanics & Mining Sciences. 2012a; 54: 125-125.

[15] Zoorabadi M, Saydam S, Timms W, Hebblewhite B. Sensitivity analysis of effective parameters on the permeability of rock mass around a tunnel. 7th Asian Rock Mechanics Symposium, Seoul, South Korea. 2012b; 944-949.

[16] Mauldon M, Mauldon JG. Fracture sampling on a cylinder: From scanlines to boreholes and tunnels. Rock mechanics and rock engineering. 1997; 30: 129-144.

[17] Zhang L, Einstein H. Estimating the intensity of rock discontinuities. Int. J. Rock Mech, Min Sci & Geomech, Abstr. 2000; 37: 819-837.

[18] Andersson J, Shapiro AM, Bear J. A stochastic model of a fractured rock conditioned by measured information. Water resources research. 1984; 20: 79-88.

[19] Zhang X, Harkness RM, Last NC. Evaluation of connectivity characteristics of naturally jointed rock masses. Engineering geology. 1992; 33: 11-30.

[20] Rouleau A, Gale JE. Statistical characterization of the fracture system in the Stripa Granite, Sweden. Int. J. Rock Mech, Min Sci & Geomech, Abstr. 1985; 22: 353-367.

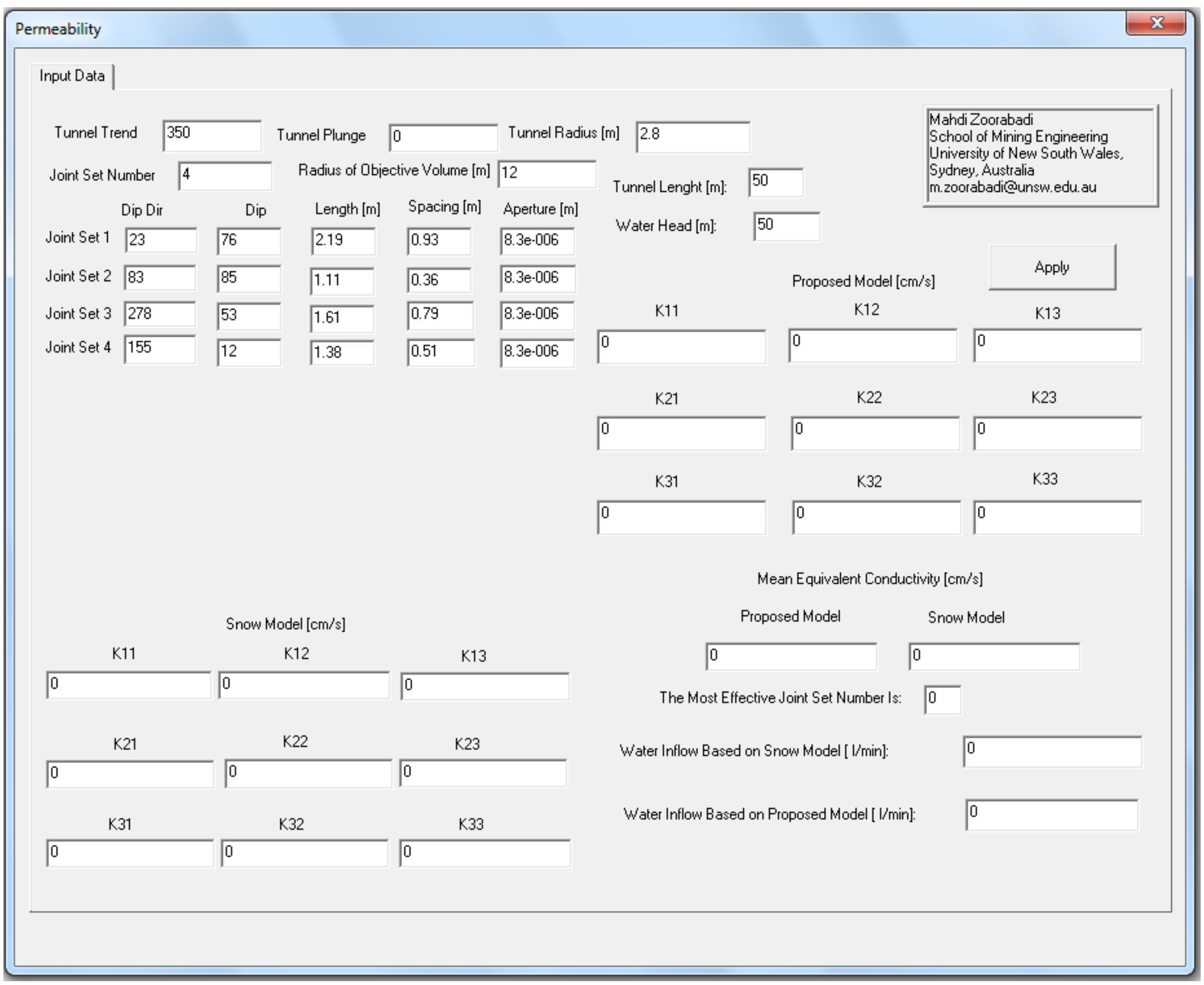
[21] Mao B, Elsworth D. Coupled processes in subsurface deformation, flow, and transport. ASCE Press; 2000.

[22] Zimmerman RW, Kumar S, Bodvarsson GS, Lubrication theory analysis of the permeability of rough-walled fractures. Int. J. Rock Mech, Min Sci & Geomech, Abstr, 1991; 28: 325-331.

[23] Wei AQ, Egger P, Descoeudres F. Permeability prediction for jointed rock mass. Int. J. Rock Mech, Min Sci & Geomech, Abstr. 1995; 32: 251-261.

[24] Wilson CR., Witherspoon PA, Long JCS, Galbraith RM, Dubois AO, McPherson MJ. Large scale hydraulic conductivity measurements in fractured granite. Int. J. Rock Mech, Min Sci & Geomech, Abstr. 1983; 20: 269-276.

Appendix


Permeability
Input Data
Tunnel Trend 350
Tunnel Plunge 0
Tunnel Radius [m] 2.8
Joint Set Number 4
Radius of Objective Volume [m] 12
Tunnel Lenght [m]: 50
Water Head [m]: 50
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Dip Dir
Dip
Length [m]
Spacing [m]
Aperture [m]
Joint Set 1 23 76 2.19 0.93 8.3e-006
Joint Set 2 83 85 1.11 0.36 8.3e-006
Joint Set 3 278 53 1.61 0.79 8.3e-006
Joint Set 4 155 12 1.38 0.51 8.3e-006
Apply
Proposed Model [cm/s]
K11 0
K12 0
K13 0
K21 0
K22 0
K23 0
K31 0
K32 0
K33 0
Mean Equivalent Conductivity [cm/s]
Proposed Model 0
Snow Model 0
The Most Effective Joint Set Number Is: 0
Water Inflow Based on Snow Model [l/min]: 0
Water Inflow Based on Proposed Model [l/min]: 0
Snow Model [cm/s]
K11 0
K12 0
K13 0
K21 0
K22 0
K23 0
K31 0
K32 0
K33 0

The established code for new proposed model