- RESEARCH PAPER -

International Journal of Mining and Geo-Engineering

IJMGE

IJMGE 55-1 (2021) 33-41

DOI: 10.22059/ijmge.2020.306044.594856

Estimating groundwater inflow into Dorud-Khorramabad railway tunnel using analytical and numerical methods

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Article History:

Received: 11 July 2020,
Revised: 27 October 2020,
Accepted: 20 November 2020.

ABSTRACT

The main objective of this study is to estimate the amount of groundwater inflow into Dorud-Khorramabad railway tunnel. To this end, in the first place, existing approaches of predicting groundwater inflow into tunnel was reviewed. According to the literature, up to now, a wide range of approaches have been proposed in order to predict the groundwater inflow into tunnel which can be classified into three distinct groups including, analytical solutions, empirical equations, and numerical modeling. Analytical solutions and empirical equations are mainly developed based on the given hypotheses and specific data sets, respectively, and should be applied in similar conditions. On the other hand, results obtained from numerical modeling are generally dependent on a wide range of parameters. Literature review revealed that one of the most effective parameters on the numerical modeling results is model extent, which controls not only final results but also numerical runtime. Hence, a sensitivity analysis is performed in order to investigate the effect of model extent on numerical results. The results demonstrated that increasing model extent decreases the groundwater inflow rate, and for a large model extent (greater than 1000), the amount of groundwater inflow tends to a constant value. In the second part, analytical solutions and finite element numerical modeling are applied for estimating the amount of groundwater inflow into Dorud–Khorramabad railway tunnel. The results indicate that the groundwater inflow into the tunnel, based on analytical methods, gives higher values than the numerical modeling. Assumptions and simplifications may justify this difference in analytical methods, accordingly, it can be inferred that if an appropriate model extent selected, the results of the numerical model based on the fact in the project can be more reliable.

Keywords : *Groundwater Inflow, Numerical Modeling, Analytical Solution, Railway Tunnel*

1. Introduction

Most tunneling activities encounter unwanted groundwater inflow into excavations which cause serious repercussions in both the construction and the operational phases. For instance, (1) putting the excavation face stability at risk possibly causing a collapse of the tunnel cavity, (2) damaging structures and installations on the surface due to subsidence, (3) losing workers' lives, (4) encountering suboptimal performance of rock drilling machines like TBM, and (5) producing environmental impacts such as springs and streams drying up [1-4]. Some tunneling projects in Iran like Alborz, Semnan, and Kuhrang, came up against the groundwater problems with the maximum groundwater inflow rate of 780, 750, and 1200 lit/s, respectively [5]. In order to prevent such problems, delays, and interruptions in tunneling procedure as well as financial losses, adequate drainage system should be considered. Therefore, reliable estimates of groundwater inflow to the tunnel are fundamentally required to design efficient drainage systems. In order to estimate the amount of groundwater inflow into a tunnel, several approaches such as analytical solutions, empirical equations, and numerical modeling, have been developed.

During the last couple of decades, several researchers tried to develop different analytical solutions to estimate the amount of groundwater inflow into tunnel for both steady-state and transient flow conditions [6-17]. Analytical solutions are generally developed based on some basic assumptions such as homogeneous and isotropic rock mass permeability, steady-state flow, circular tunnel cross-section, and constant hydraulic potential. Accordingly, it should be noted that the amount of groundwater inflow cannot always be predicted adequately by these solutions. This is effectively due to simplification and the aforementioned assumptions. In fact, rock mass contains complex geological structures with strongly heterogeneous permeability distribution, thus hydraulic behavior can be affected by many factors. On the other hand, based on the experience gained from past projects, a series of methods including design graphs, classifications, and empirical equations have been proposed in order to readily estimate the amount of groundwater inflow. These methods generally provide the qualitative and quantitative evaluation of the amount of groundwater inflow to the tunnel by considering geological and geotechnical parameters. Site Groundwater Rating (SGR), Tunnel Inflow Classification (TIC), and IMS are among the most well-known examples of empirical approaches [5, 18-24].

On the other end of the spectrum, with advances in computational performances, the application of numerical modeling has become widespread. Up to now, researchers have presented several numerical schemes for continuum and discontinuous media such as the finite difference method (FDM), the finite element method (FEM), the boundary element method (BEM), the discrete element method (DEM), the discontinuous deformation analysis (DDA), and the bounded

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particle model (BPM)[18-21]. These numerical methods are applicable for simulating heterogeneous and anisotropic conditions as well as interactions between groundwater and underground excavations [22, 25]. Such models will not only take complex geometrical situations into consideration, but will also, possibly, be able to estimate the spatial distribution of the hydraulic head field and tunnel inflow. In addition, it should be pointed out that these numerical methods acquire more data than other approaches [21, 22, 26].

Over the last past few decades, numerical modeling has been applied for identifying the amount of groundwater inflow in both surface and underground projects. In the following, some recent applications of numerical modeling in estimating groundwater inflow in such projects are reviewed.

Arianfar et al. used finite element modeling in order to estimate the water flow rate of an open-pit mine. They predicted both flow rate and subsidence height in sloped open-pit mines [27]. Mikaeil and Doulati estimated the amount of groundwater inflow into a railway tunnel located in Iran. In addition, they conducted a comparison between results obtained from numerical modeling and results obtained from analytical solutions. Results showed that analytical solutions agree well with numerical results within a maximum error of 6% [28]. Bahrami et al. used an artificial neural network coupled with the genetic algorithm to predict the groundwater flow rate in an open-mine pit[29]. More recently, Majdi et al. performed a sensitivity analysis in order to investigate the effect of three parameters including water head, permeability, and radius of a tunnel on the amount of groundwater inflow into the tunnel [30].

In this paper, analytical solutions, empirical equations, and numerical methods were studied in order to estimate the groundwater inflow rate into tunnels. In predicting the amount of groundwater inflow to a tunnel using numerical methods, the results depend on the numerical model extent and the boundary conditions. Hence, a sensitivity analysis is performed to obtain the optimal model size. To this end, the effect of three parameters, including permeability coefficient, water head, and tunnel radius, on the amount of incoming water and the numerical model dimensions were examined. All in all, the amount groundwater inflow into the tunnel 'km 78+493' at tunnel of the Dorud-Khorramabad was obtained using seven different analytical solutions and a finite element code as a numerical method.

2. Site Investigation

The approximately 3.7 km long Dorud-Khorramabad Railway named 78+493 tunnel is presently under construction in Lorestan, Iran (**Fig. 1**). Lorestan is one of several mountainous provinces in western Iran and is located in the Zagros Mountains. In terms of tectonics, the Zagros Mountains are divided into two parts the high Zagros and folded Zagros. The under consideration tunnel lies in the high Zagros area. Climatically, Lorestan contains three parts: the mountainous regions, where this tunnel is located; the area surrounding Lorestan is characterized by cold winters and moderate summers; the central region, and the southern area come under the influence of warm air. Due to the average annual precipitation totaling 550-700 millimeters, Lorestan is the third most water-rich province in Iran [31].

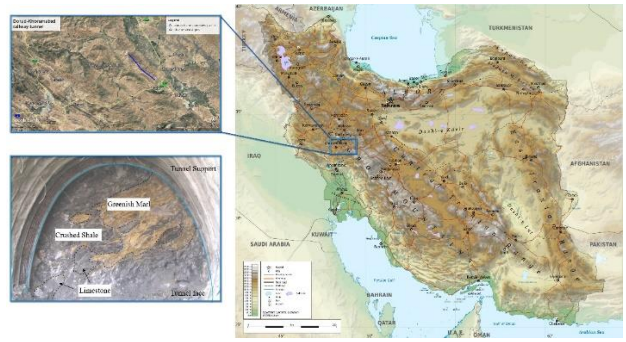

Fig. 1. Geographical Map of Iran and the location of Dorud-Khorramabad railway tunnel and a section of tunnel.

The tunnel passes through marl and shale formations in the entrance portal toward the consolidated conglomerate formation. The tunnel is covered by five stratigraphy units along its route including a Chaghalvand marly shale unit, a Miocene conglomerate unit (categorized by two parts: a consolidated conglomerate with strong cementation and a weak conglomerate with weak-cementation and limited thickness), the in-situ weathered Chaghalvandi marly soils, the in-situ weathered Miocene conglomerate soils, and the sticky and fine soil unit resembling clay, as may be observed in the exit portal. As per the Basic Geotechnical Description (BGD) method suggested by ISRM [32] the tunnel route can be divided into seven zones as follows:

T^a is the first section with an approximate length of 414 meters consisting of green to black Marly shale rocks and limestone blocks. Due to the variation in thickness of overburden in the first 50 m from the tunnel portal, it has been categorized into two sub-sections, T^{a1} and T^{a2}. In addition, T^{a1} and T^{a2} exist under dry to wet and wet conditions, respectively. Moreover, this zone is classified as crushed shale and limestone, I_3, f_4, S_4, A_4 as per the BGD method. T^b is mainly formed of Miocene conglomerate 505 meters long and an overburden thickness of around 169 to 239 meters. In this zone, the groundwater condition varies between wet to damp and may be classified as the conglomerate, I_1, I_2, f_1, S_3, A_2, based on the BGD method. T^c is approximately 550 meters long where conglomerate rock layers with an overburden thickness of 239-370 m are common. Also, this zone is between damp to dripping conditions and is classified as the Conglomerate, $I_{1,2}$, f_1, S_3, A_2 as per the BGD method. T^d zone with 900 meters long is comprised of the T^b zone iteration associated with the different overburden thickness around 208 to 307 meters due to the conglomerate formation fold. In addition, this zone exists under damp to dripping conditions and is classified as the conglomerate $I_{1,2}$, f_1, S_3, A_2 based on the BGD method. T^{e1} zone with an approximate length of 1115 m and an overburden thickness variation between 50 to 280 m will be extracted in the conglomerate formation, as well as a groundwater condition between damp to dripping, and is classified as the conglomerate, I_2, f_2, S_2, A_3 as per the BGD method. T^{e2} zone is 325-meter long where the maximum overburden thickness reaches about 50 meters and the same as the T^{e1} zone is under damp/dripping conditions and classified as the conglomerate, I_2, f_2, S_2, A_3.As can be seen in **Table 1**. The classified geological zones and their detailed geological features along the tunnel route are provided as well as seven measurement stations of the groundwater permeability values.

Table 1. The characteristics of geological units along the tunnel route with respect to permeability measurement stations.

Zone	Rock Type	Description	Maximum overburden (m)	Length (m)	Km From To	K measurements stations	K (*10^{-7} m/s)
T^{a1}	Marly shale with crushed limestone blocks	Crushing/ limestone blocks existence	50	184	76+606 - 76+690	76+670	3
T^{a2}	Marly shale with crushed limestone block	Crushing/ limestone blocks existence	169	230	76+690 - 77+020	76+800	6
T^b	Consolidated conglomerate	Consolidated/ large block/ limestone cementation/ clay matrix	239	505	77+020 - 77+525	77+225	8

T^c	Consolidated conglomerate	Consolidated/ large block/ limestone cementation/ clay matrix	307	475	77+525 - 78+000	77+850	9
T^d	Consolidated conglomerate	Consolidated/ large block/ limestone cementation/ clay matrix	307	900	78+000 - 78+900	78+750	14
T^{e1}	Consolidated conglomerate	Consolidated/ large block/ limestone cementation/ clay matrix	208	1115	78+900 - 80+015	79+765	13
T^{e2}	Fairly consolidated conglomerate	Fairly weak/ large block/ limestone cementation/ clay matrix	50	325	80+015 - 80+340	80+240	10

3. Methodology

3.1. Analytical solutions

Prediction of the groundwater inflow to the tunnel is one of the most challenging issues in designing and excavating tunnels. Since the 1960s, many researchers have tried to present their solutions to estimate the groundwater inflow into tunnels [6-17]. The first approach is analytical solutions, which are developed based on hypotheses and simplifications such as the circular tunnel cross-section, the steady-state flow, the homogeneous structure, the uniform permeability of the rock mass, and constant water head. Therefore, these methods might overestimate or underestimate the amount of groundwater inflow into the tunnel due to the geological complexities and the aforementioned assumptions. Farhadian et al. [33] and Kong [34] have proved that where (1) the water flows around the tunnel are not radial, (2) the rock mass contains variant bedding around the perimeter of the tunnel, and (3) the estimated permeability coefficient of the rock mass is imprecise, analytical evaluation of the groundwater inflow into the tunnel will not be reliable. **Table 2** illustrates the analytical solution given by several researchers. Also, the cited variables in these formulas are shown in **Fig. 2**.

An empirical approach is the second way to investigate the groundwater inflow rate into tunnels. Up to now, many researchers have presented various empirical methods to account for estimating the groundwater inflow into tunnels. Like Q, GSI, and RMR classification systems which are used as empirical methods to determine the characterization of rock masses and to provide tunnel maintenance, different empirical methods are suggested for the evaluation of groundwater inflow potential in tunneling such as IMS, SGR, and TIC that are based on preliminary hydrogeological and engineering geological investigations.

Table 2. The analytical equations for estimation the groundwater inflow into the tunnel.

No	Equations	Proposed by
(1)	$Q = 2\pi K \dfrac{h}{\ln(\frac{2h}{r})}$	Goodman (1965) [6]
(2)	$Q = 2\pi K \dfrac{h}{\ln(\frac{h}{r} + \sqrt{\frac{b^2}{r^2} - 1})}$	Lei (1999) [7]
(3)	$Q = 2\pi K \dfrac{\left[1 - 3\left(\frac{h}{2r}\right)^2\right]}{\left[1 - \left(\frac{h}{2r}\right)^2\right] \ln\left[\left(\frac{2h}{r}\right) - \left(\frac{h}{2r}\right)\right]}$	El Tani (1999) [10]
(4)	$Q = 2\pi K \dfrac{h}{\ln(\frac{2z}{r})} \times \dfrac{1}{8}$	Raymer (2001) [17]
(5)	$Q = 2\pi K \dfrac{h}{\ln\left(\frac{2h}{r} - 1\right)}$	Karlsrud (2001) [16]
(6)	$Q = 2\pi K \dfrac{h}{\left[1 + 0.4\left(\frac{r}{h}\right)^2\right] \ln\left(\frac{2h}{r}\right)}$	Lombardi (2002) [35]
(7)	$Q = 2\pi K \dfrac{\lambda^2 - 1}{\lambda^2 + 1} \times \dfrac{h}{\ln \lambda}$ $\lambda = \left(\frac{h}{r}\right) - \left[\left(\frac{r}{h}\right)^2 - 1\right]^{0.5}$; $if\ h = r \Rightarrow Q = 2\pi K r$	El Tani (2003) [8]

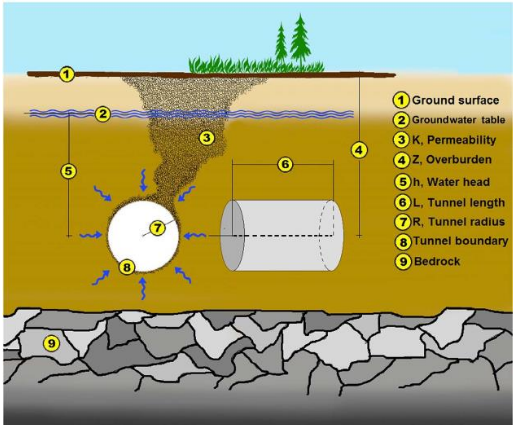

Fig. 2. Circular tunnel in a semi-infinite rock mass with a horizontal groundwater table [21].

3.2. Numerical Modeling

Numerical modeling is the third category for estimating groundwater inflow into a tunnel. In engineering practices, various numerical methods have been developed [18-20]. In general, to make a numerical model of groundwater inflow requires considering a conceptual model for the qualitative description of the main inflow system characteristics at first. Next, based on the main features of the system, the appropriate approach will be chosen for applying in numerical modeling. Up to the present, different approaches have been developed for numerical simulation of groundwater inflow to the tunnel. A review of available sources shows there are three main approaches for numerical analysis of the groundwater inflow to underground space including[36, 37]:

1) The continuum model called Equivalent Porous Medium (EPM) which is used to simulate the rock mass and the fracture networks with high density.
2) The discrete fracture network model (DFN) which is applied to show the large-scale fractures in the rock.
3) The hybrid model containing elements of both the aforementioned models.

The results of related articles have demonstrated that EPM models are more efficient and faster in calculations in comparison with the other models with regard to simulation of the groundwater inflow [38, 39]. Therefore, in this study, the EPM approach is utilized in order to predict the groundwater inflow into tunnels.

Numerical models have been applied to different conditions of groundwater analysis in tunneling projects. The most important of which the analysis of steady-state and transient regimes around both unlined and lined tunnels are and which takes into account complex geotechnical and hydrogeological conditions [22, 25]. Another advantage of numerical groundwater models is that they can account for a tunnel lining which may have different hydraulic properties. Since the lined tunnel is not spatially discrete, it has the capability to change the transfer rate of groundwater inflow at the tunnel perimeter as well as the resistance in contrast to the seepage of groundwater inflow to the tunnel. Therefore, the type of tunnels and their corresponding lining can affect the groundwater inflow and groundwater drainage in aquifers. For this purpose, Butscher [22] has suggested three categories for the tunnels based on the lining:

1) Unlined tunnel;
2) Tunnel with a lining and drainage layer
3) Tunnel with a lining without a drainage layer.

In type 1, the hydraulic head at the tunnel perimeter correlates with the elevation. This means that the hydraulic head is not uniform, in the other words, it is higher in the tunnel crown than at the invert. Also, the boundary condition (BC) considered through the assumption of the effective atmospheric pressure (zero water pressure) inside the tunnel and at the tunnel perimeter. Type 2 represents a tunnel where the tunnel opening is surrounded by a lining and a drainage layer behind the lining. The hydraulic head at the tunnel perimeter (within the drainage layer) is uniform. In this type, the uniform boundary condition is selected by assuming that the drainage layer provides no resistance to flow. These assumptions are justified if the hydraulic conductivity within the drainage layer is very high compared to the hydraulic conductivity of the lining and the aquifer. In type 3, tunnels contain a lined without a drainage layer where the hydraulic head at the tunnel perimeter corresponds to the elevation (zero water pressure inside the tunnel). Accordingly, the boundary condition of an elevation head is adjusted as in type (1). This study is aimed at estimating the groundwater inflow rate to the tunnel by considering type (1) for modeling following from the statements above.

In this paper, a finite element code is considered for use in the estimating the steady-state groundwater inflow into Dorud-Khorramabad railway tunnel. The numerical code used here simulates both saturated and unsaturated conditions in either confined or unconfined aquifers and examines the hydraulic conductivity and volumetric water content as a function of pore water pressure [40]. The finite element code handles different geological and geotechnical challenges [27, 41-48].

The governing partial differential equation for two dimensional saturated/unsaturated flow of groundwater may be obtained by coupling the continuity equation with Darcy's law:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)=C\frac{\partial}{\partial x}(h)+Q \qquad (8)$$

Where Q is the discharge per unit volume, K_x and K_y are the hydraulic conductivities in the x and y directions respectively; h is the hydraulic head, t is the time, and C is the slope of water storage curve. The hydraulic head is in relation to the volumetric water content (θ) using Eq. (9) [46]:

$$\frac{\partial \theta}{\partial t}=C\frac{\partial h}{\partial t} \qquad (9)$$

In order to solve the two-dimensional flow equation, the Galerkin approach was applied. Further details can be found in [28]. Finally, based on the considered assumptions, the Boussinesq equation (Eq. (10)) is applied to solve groundwater inflow to the tunnel as follows:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S_y}{T}\frac{\partial h}{\partial t}+Q \qquad (10)$$

Where S_y is the specific yield and T is the transmissibility.

4. Application of the Analytical Solutions and the Numerical Modeling

In the km 78+493 tunnel of the Dorud-Khorramabad railway, groundwater inflow into the tunnel was calculated with respect to the sections of permeability measuring is defined in **Table 2** and the presented equations in **Table 3**. As mentioned previously, analytical formulas were presented specifically with the assumption of the circular cross-section for tunnels. Whereas, the tunnel cross-section is like the horseshoe (**Fig. 3**), the equivalent radius of the tunnel needs to be calculated. In this paper, for determining the groundwater inflow based on analytical relationships, the equivalent radius was obtained 4.5 meters. Consequently, the results of groundwater inflow for seven cross-sections are provided in **Table 3**.

Afterwards, a finite element code was utilized in order to estimate groundwater inflow in the mentioned stations. According to the Butscher's [22] classification, selecting boundary conditions is significant and effective in estimating the amount of groundwater inflow into tunnels. There are several studies related to this point [22, 26, 49]. Another effective parameter on the validity and the accuracy of the numerical analysis of groundwater inflow is the numerical model dimensions. Researchers have tried to find an easy solution to deciding upon the optimum model domain based on the geometrical and the hydrogeological characteristics.

Table 3. The results of groundwater inflow as per the analytical equations in seven zones (liter per hour).

Zone	K ($*10^{-7}$ m/s)	head (m)	Goodman	Lei	El Tani (1999)	Raymer	Karlsrud	Lombardi	El Tani (2003)
T^{a1}	3	11.2	47.33	48.63	3.97	3.06	55.02	44.46	44.54
T^{a2}	6	15.4	108.61	109.87	6.82	6.05	118.32	105.02	105.07
T^{b}	8	21.6	172.73	173.57	7.86	10.47	181.56	169.78	169.76
T^{c}	9	28.2	226.94	227.52	7.96	14.59	234.66	224.65	224.60
T^{d}	14	34.15	397.41	398.05	11.55	27.48	407.62	394.67	394.58
T^{e1}	13	16.45	243.02	245.40	14.35	13.35	262.43	235.96	236.04
T^{e2}	10	5.69	138.65	180.65	19.16	5.19	303.01	110.91	110.55

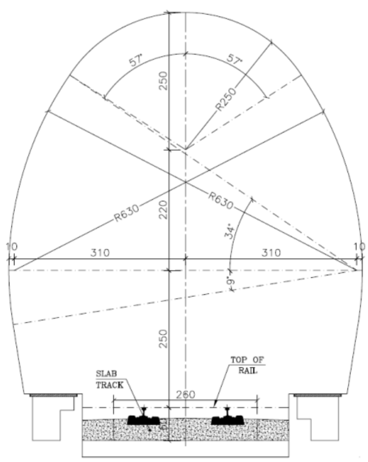

Fig. 3. The geometry and dimensions of the horseshoe cross-section for the km 78+493 tunnel.

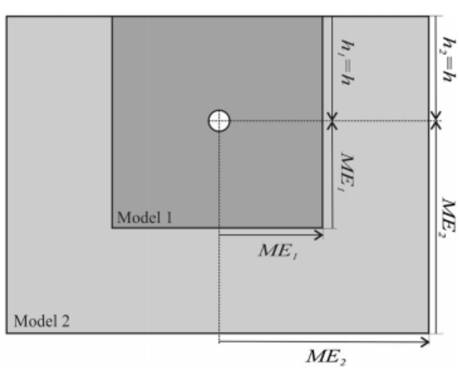

Fig. 4. Depth of model h and extend of model domain ME for two models with different ME, Subscripts refer to model 1 and model 2 [22].

The efficiency of these methods has been evaluated by discussing the different nature of the approaches set out above as well as their different levels of error. For this purpose, we present a hypothetical case with the specific characteristics (e.g., radius = 5 m, water head = 20 m, permeability coefficient = 1e-6 m/s). We first create models with different dimensions (from ME=20 m to ME=5000 m) to investigate the effect of model dimensions on the amount of groundwater inflow. The related results of these effects are plotted in **Fig. 6**. As can be seen, the total groundwater inflow decreases by increasing ME and when there is extremely large amount of ME (ME > 1000), the total groundwater inflow becomes about 97 lit/h. According to the Butscher's suggestion, if the minimum model dimensions are 20 times the tunnel radius (in this case 20*5 m = 100 m), the inflow rate will be equal to 120 (lit/h). Hence, the corresponding error is 25%, which is far greater than the 10% error Butscher noted. In the latter approach, when the tunnel radius relative to the water head is 0.2 (in this case r/h = 5/20 = 0.25 m), the optimum model dimensions with a 5% error will be roughly 9 times the water head. Accordingly, the model size and groundwater inflow will be equal to 180 m and 111 lit/h, respectively. This means the error value rises to 13%, which is, however, far greater than the assumed error of 5% posited by Nikvarhassani et al.

Among them, two important papers given by Butscher [22] and Nikvarhassani et al. are worthy of mention [26]. Butscher [22], examined the impact of optimal dimensions on the groundwater inflow into the tunnel by comparing the analytical solutions with the numerical modeling. Butscher's approach is set out in **Fig. 4.** As can be readily seen, the tunnel is at the depth of "h" and model dimensions are equivalent to ME from the center to downward and lateral boundaries. Butscher concluded that when an error less than 10% is acceptable, the model domain must be at least 20 times the tunnel radius.

In a similar case, Nikvarhassani et al. [26] incorporated the effect of the hydraulic head in calculating optimal model dimensions. They indicated that a decrease of groundwater inflow into the tunnel corresponds to an increase of the model size relative to the water head (ME/h). However, the amount of groundwater inflow reaches the constant number from one specific amount of increasing ME/h. To this end, a 5% relative difference, which is acceptable for practical purposes, has been considered correct in obtaining accurate results. The numerical analysis outcomes for different ratios of the water head relative to the tunnel radius are shown in **Fig. 5**.

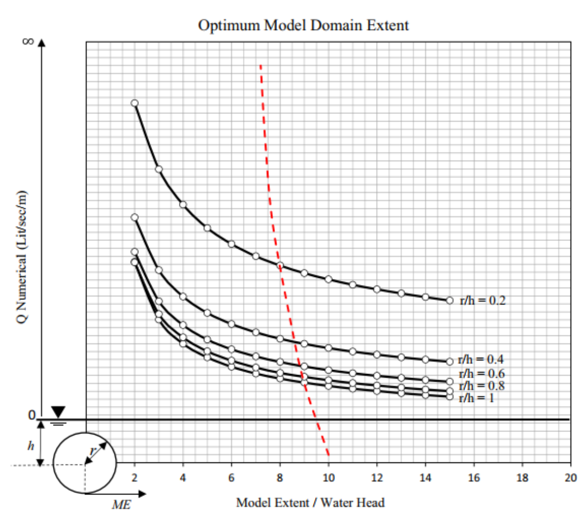

Fig. 5. A model is to determine the model domain extent. The chart shows the inflow rate (Q) versus ME/h (ME model extent, h head) with different r/h ratios. The red dashed line intersection with curves show the optimum model dimensions, which must be considered in producing the geological sections[26].

According to the significant influence of the model extent on the estimation of groundwater inflow into the tunnel, a sensitivity analysis was performed for the determination of the effective parameters on the optimum model dimension. In this section, the three effective parameters taken into account include the permeability coefficient, the tunnel radius, and the water head, on the groundwater inflow and model extent. The first parameter is the permeability coefficient which we change the amount from 0.5e-6 to 5e-6 m/s and the results represent that the groundwater inflow into the tunnel linearly increases by an increase of the permeability coefficient value (**Fig. 7**). However, as we see in **Fig. 8**, the numerical model dimensions are not affected by the permeability coefficient.

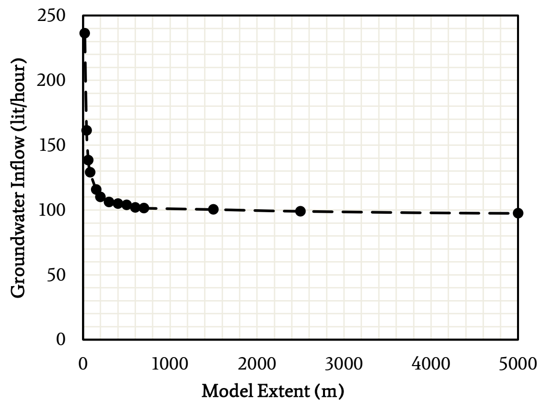

Fig. 6. The impact of model dimensions on the groundwater inflow rate.

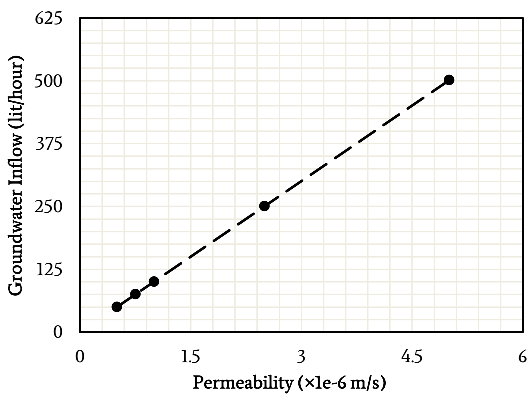

Fig. 7. The impact of the permeability coefficient on the groundwater inflow rate into the tunnel.

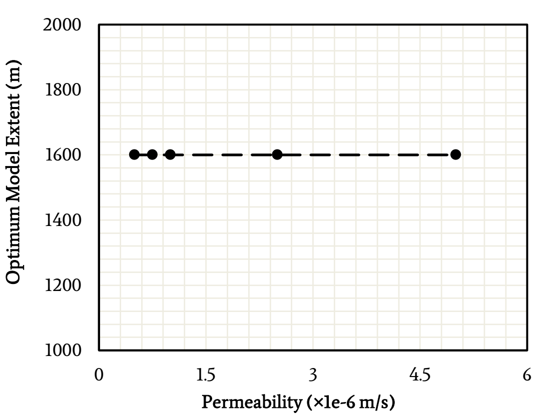

Fig. 8. The impact of the permeability coefficient on the numerical optimum model extent.

In the second step, we examine the effect of the hydraulic head on a groundwater inflow rate and optimal model extent. The different amounts of water head (10, 20, 25, 30, 35 m) are tested with the same characteristics (hypothetical tunnel). As shown in **Fig. 9**, the groundwater inflow raises by an increase of the water head. As well as a linear increase in the optimum model extent (taking into account an error 5%) is in tandem with a corresponding increase of the water head (**Fig. 10**).

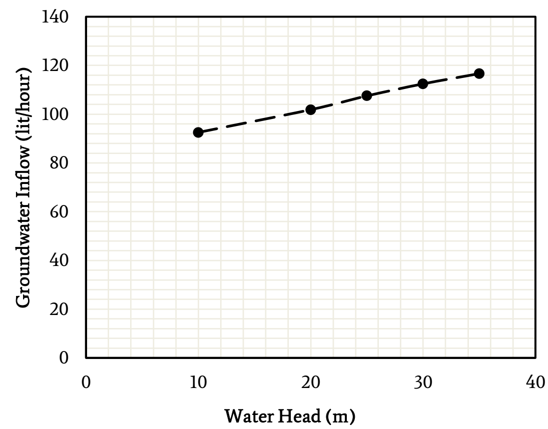

Fig. 9. The impact of water head values on the trend in groundwater inflow changes.

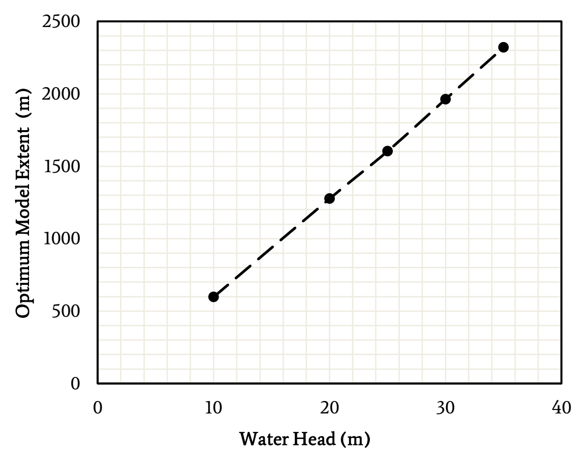

Fig. 10. The effect of water head on the optimal model extent.

The third parameter that has an effect on the numerical model dimensions is the tunnel radius. Generally, the results indicate that the groundwater inflow to the tunnel rises by increasing the tunnel radius (**Fig. 11**). However, assuming the 5% error, there is no discernable trend line between the tunnel radius and the optimum model dimensions (**Fig. 12**).

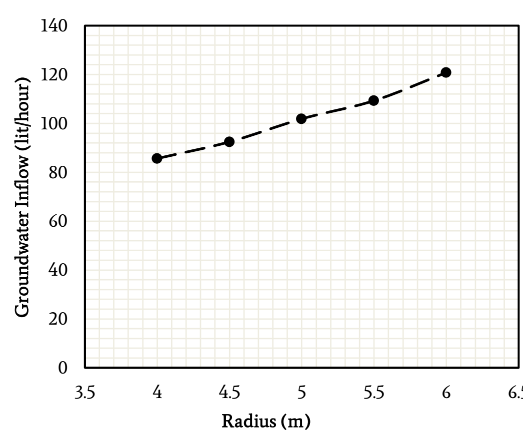

Fig. 11. The impact of tunnel radius on the groundwater inflow rate

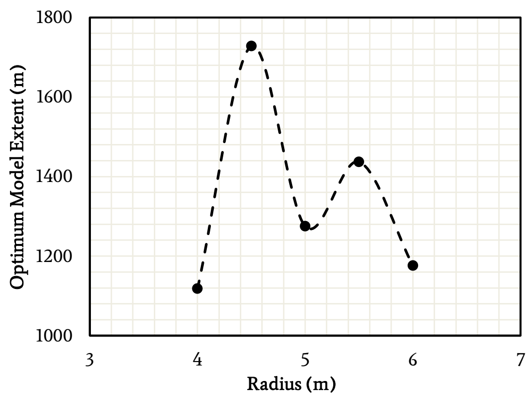

Fig. 12. The impact of tunnel radius on the optimal model extent.

Consequently, based on the results derived from the calculation in this section which are then compared to the present approaches, we recommend that engineers, especially in industry, who attempt to estimate the groundwater inflow into the tunnel, instead of using dimensions provided by researchers, utilize an alternative method based on multiple simulations with different numerical model dimensions in order to obtain an optimal baseline for their projects. The reason for this notion is the existing assumptions and simplifications such as fixed head, circular tunnel, isotropic permeability; or lack of attention to the framework layering in a variety of approaches e.g., Butscher [22] and Nikvarhassani et al. [26].

Afterwards, the amount of groundwater inflow into the mentioned tunnel was estimated in the given sections. The geometry and dimensions of the horseshoe cross-section are shown in **Fig. 3**. We used a four-meter wall and an arched section 4.70 meters high to plot the considered cross-section. Also, for plotting the arched part we used two bows with a radius of 6.30 and 2.50 meters, respectively. As a result, the amount of groundwater inflow to the tunnel within seven geological zones of the km 78+493 tunnel and using the numerical modeling is given in **Table 4**. In addition, the pore pressure contour and the amount of groundwater inflow for T^b zone are shown in **Fig. 13**.

Table 4. The Results of groundwater inflow rate (Q_{FEM} liter per hour) into the tunnel 78+493 using the numerical modeling in seven geological units.

Zone	K (*10^{-7} m/s)	h (m)	Q_{FEM}
T^{a1}	3	11.2	27.31
T^{a2}	6	15.4	55.05
T^b	8	21.6	76.21
T^c	9	28.2	95.48
T^d	14	34.15	163.55
T^{e1}	13	16.45	119.73
T^{e2}	10	5.69	89.76

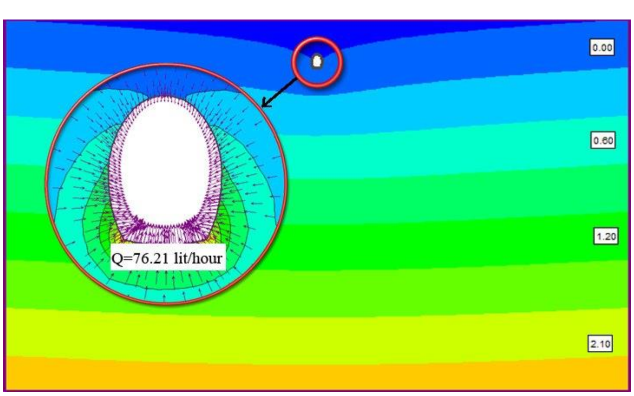

Fig. 13. Pore pressure contours in T^b zone of tunnel.

5. Results and Discussion

Problems pertaining to groundwater inflow into tunnel during construction and operational phases are challenging to engineers, workers, and management teams, as they may threaten the entire project from the viewpoint of both worker safety and economical considerations. Precise estimation of the amount of groundwater inflow into tunnels is vital in better understanding problems that may be faced not only during construction but also when tunnels are in operation. Therefore, designing appropriate drainage systems is imperative. During the last couple of decades, numerous methods relying on the analytical solutions, the empirical equations, or the numerical modeling have been proposed in order to predict the groundwater inflow into tunnels. In this paper, we attempted to estimate the amount of groundwater inflow into Dorud-Khorramabad railway tunnel. To do this, the tunnel route was divided into seven units based on the engineering geological investigations. Afterwards, the groundwater inflow into the tunnel was estimated using the analytical solutions and the numerical modeling.

We applied analytical solutions by taking into account seven different formulas (Eqs. 1-7). The results showed that the amount of groundwater inflow into the tunnel using the Karlsrud and Raymer solution have the maximum and minimum values, respectively, and other solutions lie between these two values. It should be noted that in some cases like T^{e2} the maximum value may be 50 times greater than the minimum value. This difference may be related to the derivation process as well as the assumptions considered in each solution.

On the other hand, the numerical modeling was utilized as a common way for estimating the groundwater inflow into tunnels. A literature review revealed that the results of numerical modeling depend dramatically on model extend which not only controls final results but also affects the numerical runtime. In this regard, we examined two different methods of determination of model extend proposed by Butscher [22] and Nikvarhassani et al. [26]. In these methods, model boundary was defined as a function of tunnel radius and water head, taking into account an acceptable error of 10% and 5 %, respectively. Our examination was conducted by studying a hypothetical case (radius= 5 m, water head= 20 m, permeability coefficient= 1e-6 m/s). The results showed that the errors resulting from these methods are more than the assumed errors posited by Bustcher and Nikvarhassani et al. Moreover, results represent that increasing the model extent corresponds to decreasing the groundwater inflow and for an extremely large amount of model extent the amount of groundwater inflow moves toward a constant value. However, based on the two aforementioned methods, this constant number yields a higher value for Butscher [22] and Nikvarhassani et al. [26] and with errors of 13% and 25%, respectively.

In the next step, in order to investigate the effect of different parameters including the permeability coefficient, the water head, and the tunnel radius on the amount of groundwater inflow and model extent, we performed a sensitivity analysis. The results showed that the groundwater inflow linearly increases by an increase of the permeability coefficient value (**Fig. 6**) while the optimal model extent (assuming an error of 5%,) is not affected by the permeability coefficient (**Fig. 7**). In addition, both groundwater inflow and optimal model extent have a linear relationship with the water head (**Fig. 8** and **Fig. 9** respectively). A similar relation was observed between the groundwater inflow and the tunnel radius. As shown in **Fig. 10**, the groundwater inflow rate to the tunnel rises by increasing the tunnel radius. On the other hand, there is no trend to be determined between tunnel radius and model extent.

According to the results we ended up with, we suggest that to estimate the groundwater inflow rate in a specific tunnel, especially in the industry, instead of using the one-sided approaches proposed by various researchers, it is preferable to use multiple simulations with different dimensions in the numerical modeling in order to achieve an optimal baseline for specific projects.

6. Conclusion

In this study, the analytical solutions and the numerical modeling are utilized for estimating the steady-state groundwater inflow into the km 78+493 of the Dorud-Khorramabad railway tunnel. We estimated the groundwater inflow using analytical methods by taking into account presented solutions including Goodman (1965), Lei (1999), El Tani (1999), Raymer (2001), Karlsrud (2001), Lombardi (2002), and El Tani (2003). On the other hand, the numerical modeling was performed using FEM software based on the geotechnical and geological surveys. With regard to the numerical models, we considered rock masses as behaving in the same way as an Equivalent Porous Medium (EPM). The literature review revealed that model extent has the highest impact on the results of numerical modeling. Therefore, choosing the optimum model extent is crucial. Moreover, a sensitivity analysis was performed to determine the effect of three parameters including the permeability coefficient, the water head, and the tunnel radius on the model extent. Numerical results showed that increasing the permeability coefficient has no effect on the model extent, as well as increasing the water head causes increasing the model extent linearly, whereas, no trend was observed between tunnel radius and model extent.

Finally, based on the mentioned explanation above and by selecting the optimal model extent in the numerical model that we acquired from numerous modeling processes, we estimated the amount of groundwater coming into the km 78+493 tunnel of the Dorud-Khorramabad railway. The results provided from seven zones show that the predicted groundwater inflow rate by the numerical method is closer to the result obtained from the Lombardi analytical relationship. According to the numerical results, the maximum and minimum values of the groundwater inflow rate will be at T^d and T^{al} with 163.55 and 27.31 lit/hour, respectively.

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