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Combination of engineering geological data and numerical modeling results to classify the tunnel route based on the groundwater seepage

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Abstract. Groundwater control is a significant issue in most underground construction. An estimate of the inflow rate is required to size the pumping system, and treatment plant facilities for construction planning and cost assessment. An estimate of the excavation-induced drawdown of the initial groundwater level is required to evaluate potential environmental impacts. Analytical and empirical methods used in current engineering practice do not adequately account for the effect of the jointed-rock-mass anisotropy and heterogeneity. The impact of geo-structural anisotropy of fractured rocks on tunnel inflows is addressed and the limitations of analytical solutions assuming isotropic hydraulic conductivity are discussed. In this paper the unexcavated Zagros tunnel route has been classified from groundwater flow point of view based on the combination of observed water inflow and numerical modeling results. Results show that, in this hard rock tunnel, flow usually concentrates in some areas, and much of the tunnel is dry. So the remaining unexcavated Zagros tunnel route has been categorized into three categories including high Risk, moderately risk and low risk. Results show that around 60 m of tunnel (3%) length can conduit the large amount of water into tunnel and categorized into high risk zone and about 45% of tunnel route has moderately risk. The reason is that, in this tunnel, most of the water flows in rock fractures and fractures typically occur in a clustered pattern rather than in a regular or random pattern.

Keywords: tunnel; seepage hazard; classification; universal distinct element code

1. Introduction

Groundwater inflow into tunnel during the construction and operation phases can lead to numerous hazards. Water inflow and water pressure control are needed in the design, construction and exploitation of tunnels. Uncontrolled water behavior may cause mechanical instability, additional loads on the lining discomfort and adverse environmental impacts.

Reliable estimates of groundwater inflow are required for design and construction of underground excavations in rock masses. However, tunnel inflow is not always correctly assessed prior to construction. This is effectively due to simplifications and inaccurate estimation of hydraulic conductivity of rock masses. Investigations so far such as analytical and empirical solutions consider only the homogeneous geological conditions. Whereas, rock mass as a natural product, forms a complex geological structure with strongly heterogeneous permeability

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distribution, whose hydraulic behavior is affected by many factors. Indeed, the present approaches study the role of each of these factors individually, keeping the others constant. Therefore, they cannot adequately estimate the rate of tunnel inflow in rock mass. (Zarei *et al.* 2012).

Water inrush can be described exactly by the potential energies of water leaking from conduit. Based on the mechanism of water inrush in tunnel, it can be categorized into geological flaws and no geological flaw (Jurado 2012). Fig. 1 shows the typical cases of tunnel inflow during the construction in Iran.

The uncertainty of geology induces the uncertainty of evaluation index value. The evaluation indices generally rely on objective factors such as hydrogeology and geology factors. The values of evaluation index are always different from each other even in the same condition. Therefore, the value of evaluation index must account for the randomness (Li 2015, Yang 2015, and Yuan 2016).

Due to the uncertainly of geological conditions, prediction of groundwater inflow into tunnel is very difficult. (Heuer 1995, El Tani 2003). One of the most important stages in tunnel site investigations is related to the groundwater inflow into tunnel and its effects on the tunnel construction and operation. Many researchers have proceed to calculation of water inflow into tunnels such as Goodman *et al*. (1965), Heuer (1995), Lei *et al.* (1999), Karlsrud (2002), Raymer (2001) and El Tani (1999, 2003). Table 1 shows the summary of analytical equations to prediction groundwater inflow into tunnel.

(a) Alborz Tunnel, inflow 500 l/sec

(b) Alborz Tunnel, inflow 500 l/sec

(c) Semnan Tunnel, inflow 750 l/sec

(d) Ghomroud Tunnel, inflow 80 l/sec

Fig. 1 Typical case of tunnel inflow during the construction (Zarei *et al.* 2012)

Table 1 Summary of analytical equations to groundwater seepage flow into circular tunnels

References	Equation	
Goodman (1969)	$Q = 2\pi K \frac{h}{\ln(\frac{2z}{r})}$	(1)
Freeze and Cherry (1979)	$Q = \frac{2\pi K H_o}{\ln(\frac{2H_o}{r})}$	(2)
Heuer (1990)	$Q_L = \frac{2\pi K H_o}{\ln(\frac{2z}{r})} \times \frac{1}{8}$	(3)
Raymer (2002)	$Q = 2\pi K \frac{h}{\ln(\frac{2h}{r} - 1)}$	(4)
Lei (1999)	$Q = 2\pi K \frac{h}{\ln(\frac{h}{r} + \sqrt{(\frac{h}{r})^2 - 1})}$	(5)
El-Tani (2002)	$Q = 2\pi K \frac{1 - 3(\frac{r}{2h})^2}{[1 - (\frac{r}{2h})^2]\ln(\frac{2h}{r} - (\frac{r}{2h})^2}$	(6)
Katibeh (2010)	SGR Method	(7)

Table 2 SGR rating of groundwater inflow into tunnel

SGR	Tunnel Rating	Class	Probable conditions for groundwater inflow into tunnel(L/S/min)
0-100	No Risk	I	0-0.04
100-300	Low Risk	II	0.04-0.1
300-500	Moderate Risk	III	0.1-0.16
500-700	Risky	IV	0.16-0.28
700-1000	High Risk	V	Q>0.28, inflow of groundwater and mud from crashed zone is probable
1000<	Critical	VI	Inflow of groundwater and mud is highly probable

The main purpose of this paper is to categorization of tunnel based on the amount of water inflow. There are a number of models to classification of rock mass. Until now, for rock engineering, the most generally used rock mass classification methods are including, the Rock Mass Rating (RMR; Bieniawski 1973, 1975, 1979, 1989), the Rock Structure Rating (Wickham *et al.* 1972) and the NGI Q system (Barton *et al.* 1974). However, for the groundwater site rating there is the just one method to classification of tunnel route. For the first time, Katibeh and Aalianvari (2009), using the experiments on ten tunnels in Iran, have proposed a new method for rating tunnel sites in the groundwater risk point of view, named "Site Groundwater Rating" (SGR). In this method, the tunnel site, according to the preliminary investigations of engineering geological and hydrogeological properties, is categorized into six rates as follow: no risk, low risk, moderate risk, risky, high risk, and critical. Considered parameters in this method are joint frequency, joint aperture, karstification, crashed zone, schistosity, and head of water above tunnel, soil permeability, and annual raining. Based on the SGR method, the tunnel site will be categorized in six, classes including: no danger, low danger, relatively dangerous, dangerous, highly dangerous and critical (Table 2).

But there are a lot of parameters that regulate inflows such as topographical, technical, and geological parameters that have not been considered in the SGR method. (Aalianvari *et al.* 2010). In this paper at first using the numerical method (FEM Software) the groundwater inflow into tunnel has been calculated and the results compare with the observed inflow. Based on the composition of numerical results and observed flow, the remaining unexcavated Zagros tunnel route has been categorized from seepage hazards point of view.

2. Zagros tunnel

Zagros tunnel with about 48.7 km length is being constructed in Kermanshah province of Iran. This tunnel consists of 4 parts being excavated separately. The execution of the last part of the tunnel is in progress by two TBMs from the Leileh River to KordiGhaseman river.

The remaining 3-km long part of the Nosoud tunnel located in Zemkan is characterized by complicated geological conditions. Both TBMs were run into extreme water inrush before approaching this part.

2.1 Geology

The geological structures of the western part of Iran are under the influence of the general trend of the Zagros Mountain Zemkan Anticline at el.730 m.a.sl is the lowest part of the route and the Zemkan River flows with an angle proportionate to the Range.

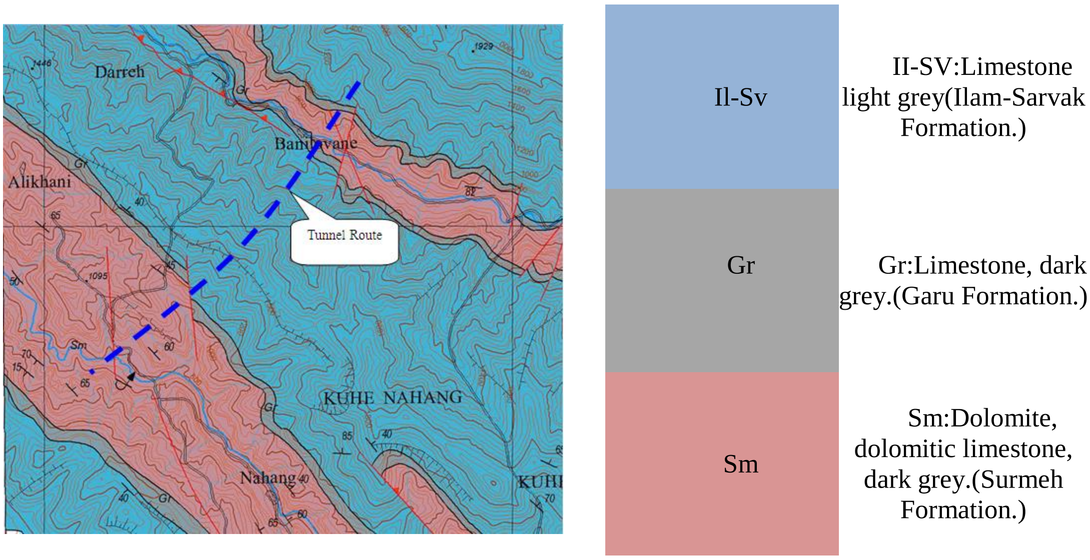

Fig. 2 Location of tunnel and geological map of tunnel route

This trend is in NW-SE direction observed along the folds cropping out (anticline, syncline). The axis of axis of Zemkan; therefore, the least overburden (113-m thick) lies in this section. There are syncline structures on both sides of Zemkan anticline whose most heights are about 1682 and 1384 m.a.sl in the north and south of Zemkan area respectively. The tunnel is at el.612 m.a.sl of Zemkan.

The outcrops in the study area are generally sedimentary rock whose age ranges between Triassic and Upper Cretaceous. The formations existing in the area under consideration include Triassic Unit, Surmeh, Garu and Gurpi formations from old to new respectively (Fig. 2).

Cretaceous unit (Garu formation) includes shale limestone and calcareous shale.

Jurassic unit (Surmeh Formation) in this area includes alternate layers of lime and dark shale lime, shale; in the middle parts of the area, it includes evaporative layers (gypsum).

Triassic unit is mostly composed of dolomitic limestone, cliff-maker limestone, and shale limestone units in the surficial sections.

3. Prediction of groundwater inflow into tunnel

There are several analytical expressions in literature to calculate groundwater discharges into tunnels, such as Goodman (1965), Lohman (1972), Zhang (1993), Heuer (1995), Lei (1999), Karlsrud (2001), Raymer (2001) and El Tani (2003). In addition to analytical methods which imply basis estimation of infiltration rate, regarding to the basic equations in seepage flow, using numeric methods such as finite element method, finite difference method, distinct element method, or finite volume method, it is possible to simulate groundwater seepage flow into tunnels and calculating seepage rates in different boundary conditions and material properties. In this paper, the groundwater inflow into Zagros tunnel has been calculated using both method analytical and numerical method (FEM software).

3.1 Input data

The variables in analytical equations have practical ranges for tunnels. These practical ranges give insight into which are more important and which are less. In summary, K is the most important term and hardest to estimate, H0 is less important and easy to estimate, and ln(2z/r) is importance and easy to estimate.

Rock mass permeability and head of water above tunnel are the main factors that affecting the water flow in rock media. Due to the excavation of considerable length of tunnel, the required data were chose after processing the observed flow.

3.1.1 Head of water above tunnel

In most situations, the maximum for the static head (H) is the elevation difference between the tunnel and highest water table around the tunnel. The minimum is the elevation of the lowest water table around the tunnel. These values can be estimated readily from topographic maps and piezometers.

During the tunnel construction, groundwater inflow into tunnel from different layers. Therefore the head of water above tunnel has been reduced. Figs. 3 and 4 show the variation of water above tunnel and groundwater inflow into tunnel with time.

Based on the exploratory bore holes results, geological investigations and data back analysis the groundwater level has been chosen for calculating around 640 m.a.s.l.

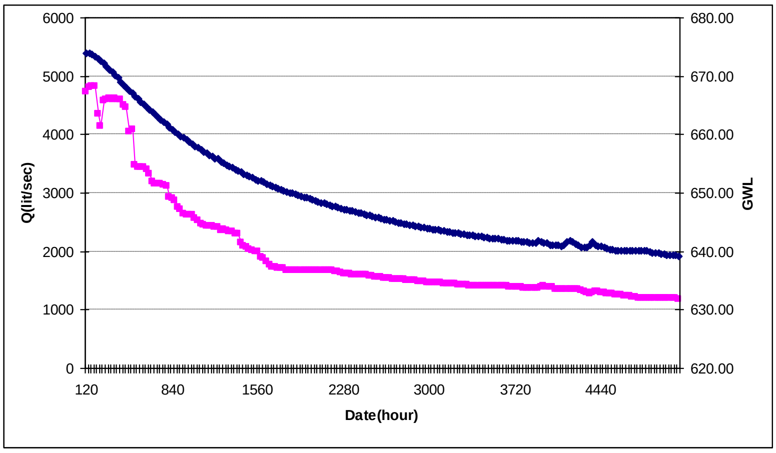

Fig. 3 Simultaneity variation of water inflow and groundwater elevation with time(blue line, groundwater level and pink line, amount of water inflow into tunnel)

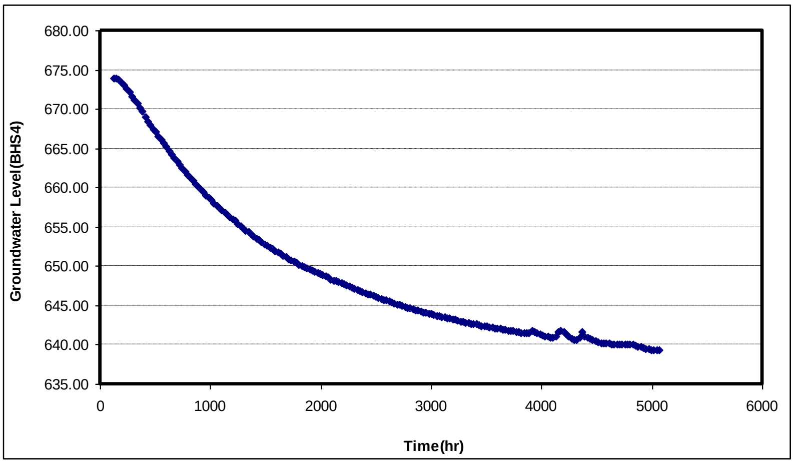

Fig. 4 Variation of groundwater with time(hr)

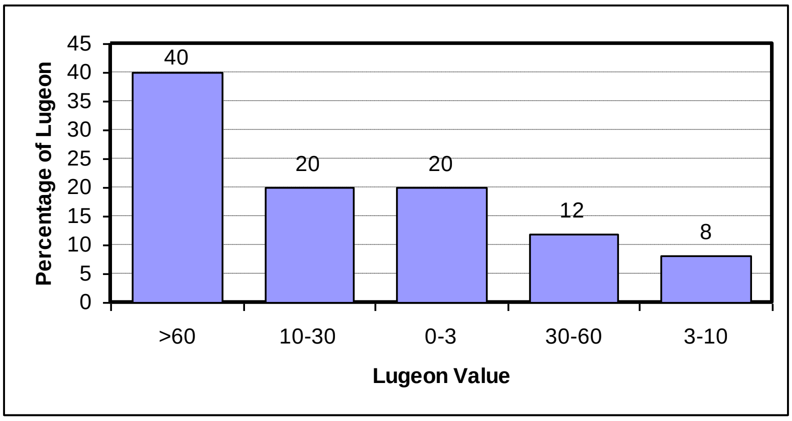

Fig. 5 Distributions of water pressure test results (lugeon) for exploratory bore holes

3.1.2 Rock mass permeability

In fractured rock, permeability ranges over many orders of magnitude within a given rock mass.

This variability is difficult to predict.

Massive rocks in tunnels alignment include one or more joint sets and tunnels cut them. Amount of water inflow into tunnels depends on joint frequency and joint aperture, so the permeability of rocks is depends on these parameters. Zagros tunnel cut the different layer with the various permeability. Due to the amount of joint sets (at least 3 joint set with bedding) the assumption of homogeneity of rock is correct. Distributions of water pressure test results (lugeon) test for different layer are show in Fig. 5.

Results show that the rocks in Zagros tunnel alignment have a high permeability. So to estimation of water inflow into tunnel, the permeability foe each layer has been defined.

3.2 Results of estimations

In analytical methods with taking into account parameters such as equivalent permeability of rock mass, water table height and tunnel radius, the rate of seepage into tunnel is estimated. Some conditions and assumptions should be considered to apply these Eq. (9).

- 2-D flow and circular tunnel section.
- Homogenous and isotropic permeability
- Tunnel section is located under water table (in saturated zone).

Table 3 Results of prediction water inflow into tunnel

Estimated Water Inflow (lit/sec)	Equivalent Length (m)	Chainage (km)
30	80	3400-3480
40	170	3480-3650
370	280	3650-3930
200	270	3930-4200
250	200	4200-4400
80	70	4400-4470
750	30	4470-4500
400	450	4500-4950
500	30	4950-4980
480	70	4980-5050
70	100	5050-5150
70	90	5150-5240
500	30	5240-5270
120	130	5270-5400
170	250	5400-5650
180	250	5650-5900
500	30	5900-5930
170	170	5930-6100

3.3 Results of analytical equations

Basically, water flow into tunnel is reported in the form of flow rate or more precisely, groundwater inflow volume per time per unit length of the tunnel. Due to slight geological variations of rocks around exploratory boreholes and in the distance between two adjacent holes, the effective length around each hole is defined in which water table and permeability coefficient is assumed equal to the data of the hole. Seepage rate into tunnel in the mentioned length is determined from multiple of length to discharge rate. The results of analytical equations are shown in Table 3.

Table 4 DEM modeling results

Estimated Water Inflow (lit/sec)	Equivalent Length (m)	Chainage (km)
28	80	3400-3480
50	170	3480-3650
350	280	3650-3930
280	270	3930-4200
245	200	4200-4400
110	70	4400-4470
700	30	4470-4500
300	450	4500-4950
610	30	4950-4980
530	70	4980-5050
100	100	5050-5150
120	90	5150-5240
520	30	5240-5270
140	130	5270-5400
168	250	5400-5650
210	250	5650-5900
480	30	5900-5930
200	170	5930-6100

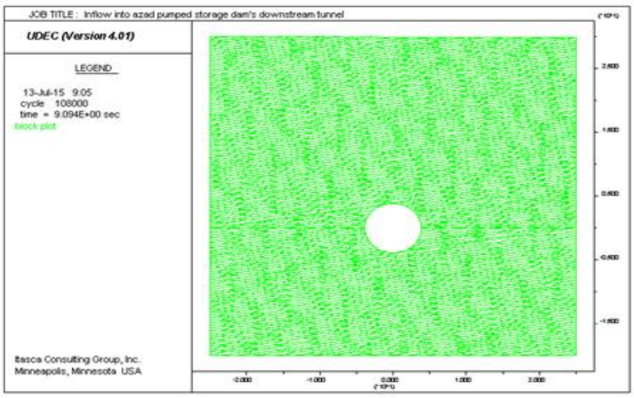

Fig. 6 Generated model using UDEC software

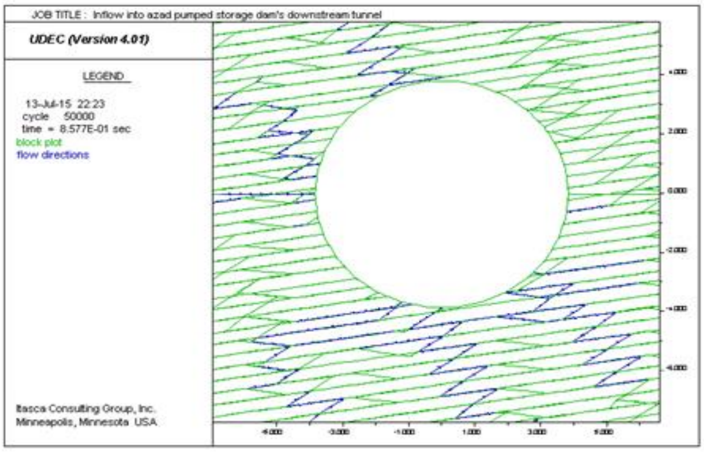

Fig. 7 Distribution of water pressure and water flow around the tunnel

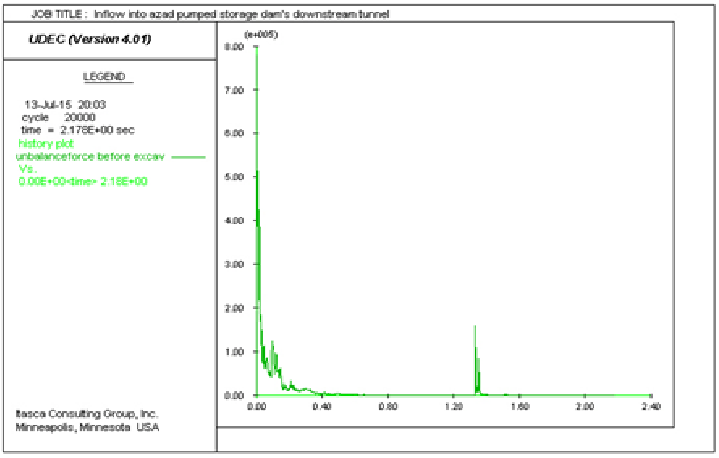

Fig. 8 Unbalanced force history before excavation

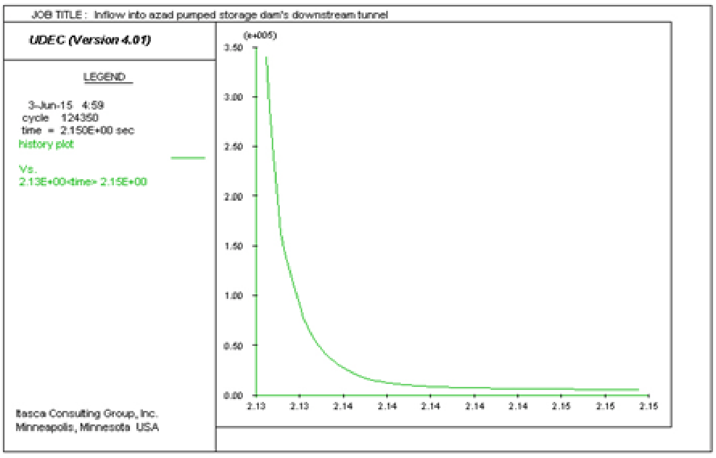

Fig. 9 Water pressure history around the tunnel

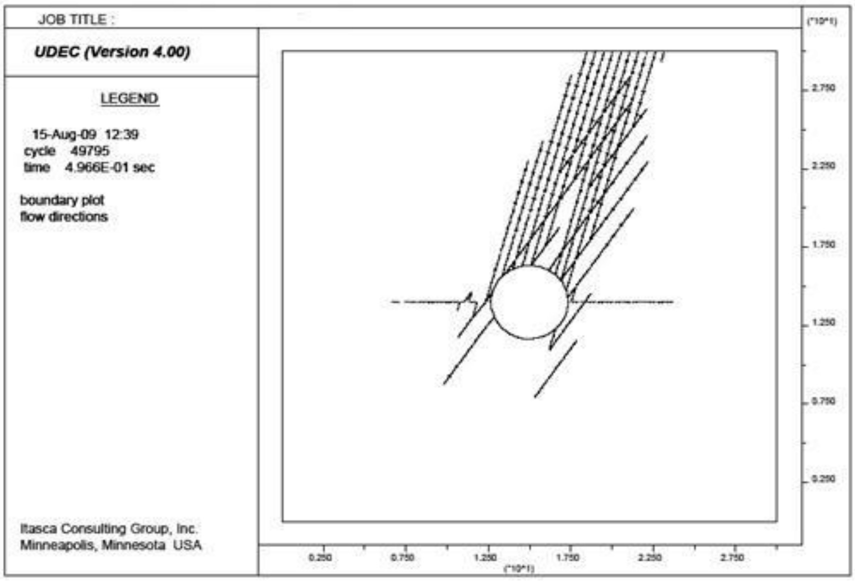

Fig. 10 Generated model for the fault with 5 m crashed zone width

3.4 Results of numerical methods

Defining the boundary conditions, material properties, rock mass and joints characteristics are the most parameters to generate the numerical model. Based on the geological investigations, the DEM model has been generated and the seepage rate into tunnel foe different sections have been calculated. It is obvious that the accuracy of calculations by software is totally depends on the accuracy of input parameters

The numerical model simulating a jointed rock mass is initially confined by horizontal stress along the vertical boundaries to balance with the in-situ stress. The initial horizontal to vertical stress ratio, K_0 is equal to 1.0 for most cases in order to simulate an isotropic stress condition. The equivalent hydraulic conductivity decreases with depth because the joint closure increases with depth. But the equivalent permeability doesn’t change with horizontal location. The total pressure on each element of the model is equal all around pressure. Figs. 6 to 9 show the generated model for tunnel.

Faults and major joints have the significant roles in water flow. So the fault zones have been modeled separately. Fig. 10 shows the generated model for Fault zone.

Results of DEM method are shown in Table 4.

Table 5 Amount of water flow measurements

Estimated Cumulative Water Inflow (lit/sec)	Equivalent Length (m)	Chainage (km)
938	80	3400-3480
1092	170	3480-3650
1366	280	3650-3930
1700	270	3930-4200

3.5 Observed water flow into tunnel

The actual water inflow into tunnel has been measurement for each section of tunnel. Table 5 shows the amount of cumulative water observed in tunnel.

4. Comparison between observed and predicted water inflow

Comparing between observed water flows into tunnel and estimated using analytical Equations have been shown in Figs. 11 and 12.

Based on Fig. 12, the actual water inflows into the tunnel are in good agreement with the estimated groundwater inflow into tunnel. In addition, distinct geological features (i.e., shear, fault, or crashed zones), which might not be intersected by conventional packer intervals, have been considered in the method.

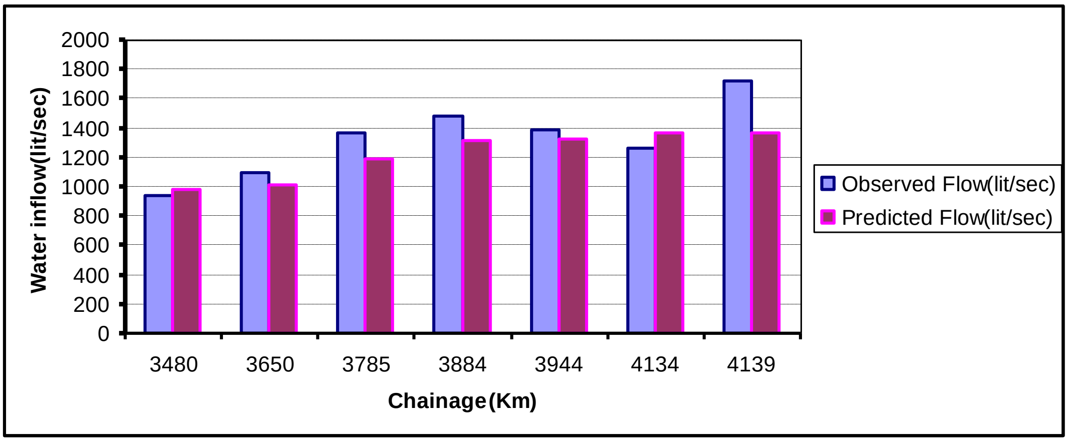

Fig. 11 Comparsion between observed and estimated waterflow

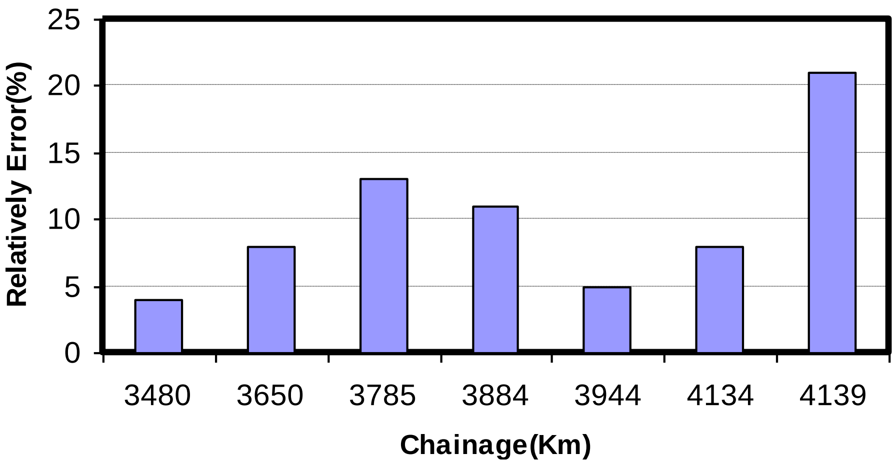

Fig. 12 Relatively error

Table 6 Classification of Zagros tunnel

Class	Chainage (km)
Low Risk	3400-3480
Low Risk	3480-3650
High Risk	3650-3930
High Risk	3930-4200
High Risk	4200-4400
Low Risk	4400-4470
Critical	4470-4500
High Risk	4500-4950
Critical	4950-4980
High Risk	4980-5050
Risky	5050-5150
Risky	5150-5240
High Risk	5240-5270
Risky	5270-5400
Risky	5400-5650
Risky	5650-5900
High Risk	5900-5930
Risky	5930-6100

5. Classification of Zagros tunnel from groundwater flow point of view

Due to the good agreement between estimated water inflow and observed flow into Zagros tunnel, the tunnel can be classified based on the estimated flow. Aalianvari *et al*. proposed the new method to classification of tunnel (Aalianvari *et al.* 2010). Based on the method mention above, the Zagros tunnel can be divided into different classes from groundwater flow point of view.

6. Conclusions

The major results of this paper are twofold. The first is that based on the geological investigations such as water head above Zagros tunnel, rock mass permeability, the groundwater inflow into tunnel has been estimated and the second result of paper presents that the calculated flow are in a good agreement with the observed and measurement flow. Therefore due to the calculations, the tunnel route can be successfully categorized from the amount of groundwater inflow point of view. Results show that amount of 50% of tunnel length can be classified as a low risk and around of other 50% has a high risk and critical conditions. Applying these results, according to preliminary investigations conducted by designers, provides a more suitable design of the drainage system, drilling method, and tunnel support.

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