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Complementary Site Groundwater Rating (SGR) method in the prediction of water inflow to tunnels in rock using real data

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Review Paper

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Abstract:

Groundwater inflow into rock tunnels depends on the geologic and hydrological conditions. There is no complete standard method for estimating the exact volumes and locations of groundwater inflow that may be encountered in the rock tunnels. The discharge rate of the water inflow into the tunnel depends on several factors like permeability and groundwater head. Site Groundwater Rating (SGR) system based on initial site investigations to classify tunnel length qualitatively and quantitatively from the point of groundwater seepage hazard view. In this rating system, we score parameters like frequency and aperture of joints, schistosity, crushed zones, karstification, soil permeability, water head above the tunnel, and annual rainfall. According to the SGR method, the conditions of the tunnel with respect to the main parameters of the risk of leakage of underground water and the way it is done are evaluated. But this method needs to be completed. Some parameters must be corrected and even deleted, and some new parameters must be proposed. In this paper, the SGR method has been optimized with respect to new parameters. According to the experiences of the Kerman and Karaj tunnel excavations, the authenticity of the SGR method validations was studied. As a result, the optimized SGR method (SGRm) is introduced. The results of SGRm compared to the results of SGR are closer to the actual results. This method is a new method to estimate the water entrance to the tunnel.

Keywords: Groundwater inflow; Tunnel; SGR method; Hydrogeological parameters; Iran

1. Introduction

Water problems have a great role in Tunnel Boring Machine (TBM) downtimes and reduce machine utilization considerably (Frough et al., 2012; Hassanpour et al., 2014) and tunnel route spring discharge (Hassanpour et al., 2021). The presence of groundwater and its effects are often considered in designing civil engineering projects, especially in hard rock tunnels (West, 1983; Brassington, 1986). Groundwater studies in fractured hard rock media are complicated (Liebel et al., 2012; Zareifard and Fahimifar, 2016). Geotechnical data is one of the most important tools for recognizing these environments. The complexity of the geological environment surrounding tunnels increases the difficulty of tunnel design (Jinfeng et al., 2023). Based on Spross and Larsson (2014), real geotechnical data is rare, and the projects should not depend on it completely. This difficulty comes from the complexity of the inflow mechanisms, which are mostly controlled by geological structures.

Groundwater inflow into the tunnels depends on the geologic and hydrological conditions of the area. There is no complete standard method for estimating the exact volumes and locations of groundwater inflow that may be encountered in the rock tunnels. Since it is impossible to identify all the factors affecting water inflow into tunnels, especially in the drilling phase, it is difficult to make an exact prediction of the water inflow rate. Therefore, analytical methods with some simplifications and assumptions must be used to calculate the seepage amount in tunnels.

Analytical equations are developed based on Darcy's Law and mass conservation (Liu et al., 2014). They consist of parameters like rock mass permeability, water table, tunnel radius, etc.

Many investigations consisting of analytical, empirical, and numerical approaches have been presented in the last decades to predict groundwater flow into rock tunnels (Sharifzadeh and Javadi, 2017; Golian et al., 2019; Barahouei et al., 2021). Goodman et al. (1965) were the earliest to use an analytical equation to estimate water infiltration into a tunnel. They developed an equation based on constant flow by using Darcy's equation and mass conservation. Furthermore, Freeze 1979 carried out the first corrections to Goodman's equation. Their corrections were based on the variation in the meaning of the water potential head around the tunnel. Then, Heuer (2001) concluded that the real amount of water is less than the estimated value by studying the empirical results of the many case studies of tunnel inflow. Consequently, he added the Heuer coefficient to the Freeze and Cherry equation based on the empirical results. Karlsrud (2001) also drew approximately similar conclusions. El Tani (2003) introduced estimation for tunnels with no decrease in water level and considered a more integrated equation. He used all the previously developed equations in his equation. Consequently, Cesano 2023 indicated that water entering the tunnel not only depends on hydraulic conduction but also is related to the overburden. Also, Coli 2008 considered the important role of the selection of hydraulic conduction. Li 2008 studied the relationship between pore pressure around the tunnel and water entering the tunnel. The role of geological structures in the potential for water to enter tunnels was studied by Zarei et al. (2010). He concluded that the evaluation of high local groundwater inflow to rock tunnels based on the characterization of geological features is more reliable than available analytical and empirical methods of estimation. Deliberation of the groundwater entering the shallow tunnels under the water table was carried out by Jurado et al. (2012). Font-Capo (2012) investigated the condition of the groundwater entering the tunnel in granitic rocks using TBM machines. Lo Russo et al. (2016) proposed a new conceptual model for the hydrogeological condition of tunnels (Lo Russo et al., 2016; Otari and Dabiri, 2015). Hydrogeochemistry analyses provide a good understanding of the complex hydrogeological system at the two major geological formations along the tunnel (Zainal et al., 2016; Golian et al., 2018). Nilsen (2014) stated that probe drilling and pre-grouting were the main important elements dealing with water ingress and ensuring stability. Lachassagne et al. (2015) presented a model for shallow tunnels in hard rocks based on the hydraulic and groundwater head. Farhadian 2016 evaluated the different methods (analytical, numerical, and SGR) used in the assessment of groundwater inflow into the middle-depth Amir-Kabir tunnel. Results show that analytical methods (Goodman's equation) provide an overestimated rate of groundwater inflow into a tunnel in comparison to numerical methods.

Generally, the discharge rate of the water inflow into the tunnel depends on several factors, such as hydrostatic pressure (water height around the tunnel) and rock mass permeability. The rock permeability is controlled by joint properties such as continuity of the joints, sizes of the joint spaces and openings, and the relationship between joints and discontinuities, or lithology. The permeability of hard rock is highest at the intersection of fractures (Faulkner et al., 2010). The permeability was measured using Lugeon tests in boreholes in the Nosoud tunnel (Morsali et al., 2017), Karaj tunnel (Morsali et al., 2017), and Kerman tunnel (Saberinasr et al., 2019). None of the analytical methods eventually leads to a precise prediction of the amount of water inflow into the tunnel. Hence, the need is to find more accurate solutions that are consistent with the geologic nature of this phenomenon. Katibeh and Aalianvari proposed a SGR rating system based on initial site investigations for the first time in 2009 in order to classify tunnel length qualitatively and quantitatively from the point of view of groundwater seepage hazards (Katibeh and Aalianvari, 2009; Rezapour Tabari and Yazdi, 2014). In this rating system, taking into account parameters like frequency and aperture of joints, schistosity, crashed zones, karstification, soil permeability, water head above tunnel, annual raining, and scoring them, tunnel length is divided into six classes from a groundwater leakage hazard point of view. According to the SGR method, the conditions of the tunnel with respect to the main parameters of the risk of leakage of underground water and the way it is done are evaluated. Some parameters must be corrected and even deleted, and some new parameters must be proposed. Actually, this method needs to be completed. There are effective hydrogeological parameters in water inflow into tunnels that are not considered. Also, given the experience gained, the way of estimating some of the parameters used should be changed. In this paper, the SGR method has been optimized with respect to new parameters.

2. Study area

The data from the Karaj and Kerman tunnels were used for the measurement of accuracy (Fig. 1). Kerman tunnel in central Iran, Kerman province, at a base level of ∼2370 m and a length of ∼38 km, is one of the longest tunnels in a volcanic area in the world. This tunnel provides water transfer from the Safa Dam (Rabour city) to Kerman city. Tunnel construction was divided into north and south portals, which were excavated separately. Construction work started there in September 2016. Kerman tunnel has been excavated in the southern part of about 5.3 km. The excavation was made by a 127 m long tunnel boring machine (TBM) with an 11 m shield. In this area, magmatic activity extended to Eocene and Oligocene to generate the Razak and the Hezar volcanic complex, which consists of andesite-basalt, andesite, trachyandesite, trachybasalt, and tuff. The average measured water head in boreholes on the tunnel was about 100 m. The minimum and maximum permeability values estimated are between 0.00000007 m/s and 0.000004 m/s, respectively. The permeability of water-bearing zones is estimated based on factors such as the measured values of the packer test in boreholes, the flow rate of water inflow into the tunnel, lithology, morphology, overburden pressure, density, and flow rate in springs in the area, and the general trend of water head in surrounding areas (Fig. 2). Most of the faults in the area are of normal type. In general, water flow in normal faults is more than reverse faults.

The Karaj Water Conveyance Tunnel is 16 km long and designed for transferring 16 m^3/s of water from the Amir-Kabir dam in the northeast of Karaj to the northwest part of the Tehran metropolitan area. The elevations of the two end-points of the tunnel are 1600 m and 1564.4 m above AMSL, rendering a slope of 0.013% towards the southeast

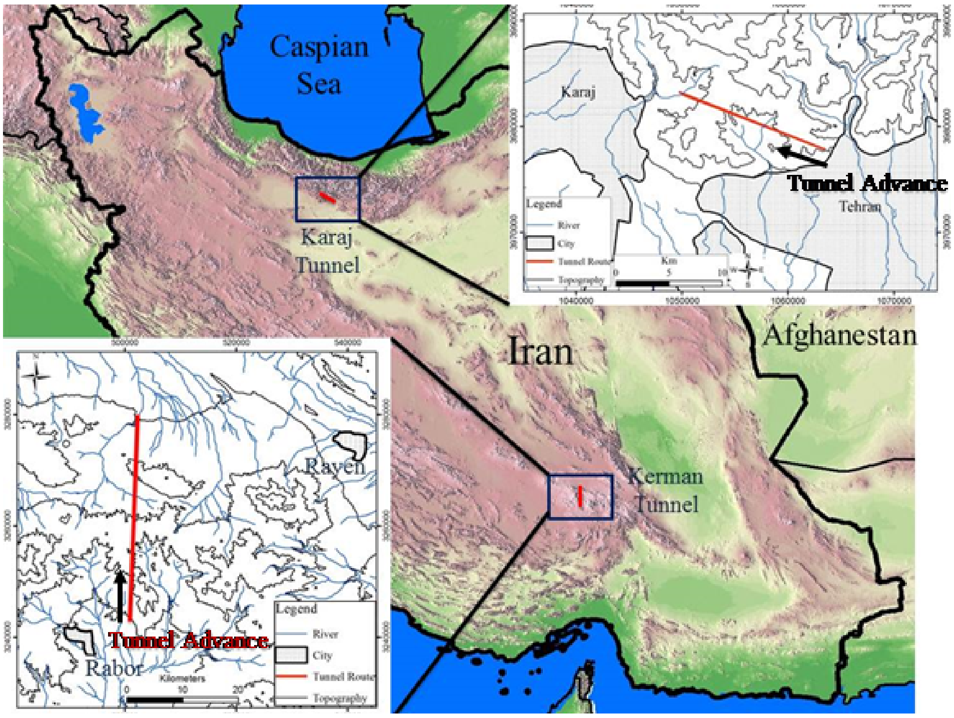


Figure 1. Karaj and Kerman tunnels location.

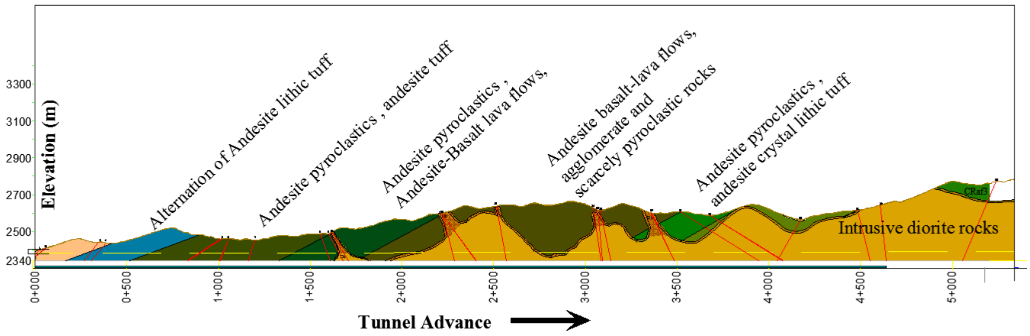


Figure 2. Kerman tunnel geological section.

tunnel portal. The maximum thickness of the overburden is approximately 800 m, with an average tunnel depth of approximately 250 m. The main outcrop of the geological units in the project area is the Karaj formation (middle to late Eocene), a well-known formation in the Alborz Mountains. This formation is composed of a variety of pyroclastic rocks, often interbedded with sedimentary rocks. The main rock type is green vitric to crystal lithic tuff, but other tuffs, such as breccia tuffs, sandy, and silty tuffs, exist together with shale, siltstones, and sandstones along the tunnel path (Fig. 3). Also, large volumes of intrusive rocks, such as Monzogabro and Monzodiorite, have intruded into the pyroclastic rocks of the Karaj formation at various locations. The minimum and maximum permeability values estimated are between 8E-8 m/s and 6E-6 m/s. The average water head was estimated from the water level in the borehole to be about 120 m.

3. Methodology

Based on the preliminary studies of the tunnel site, provided the SGR method for dividing the tunnel path at different rates regarding the risk of groundwater seepage. In this rating system, from a groundwater seepage point of view, the tunnel path rate was divided into No risk, Low risk, Moderate risk, Risky, and High risk. Critical classes were considered by parameters like joint frequency and aperture, schistosity, crashed zones, karstification, soil permeability coefficient, tunnel location in the water table or piezometric surface, and annual rain. Based on this method, the total score of the site, SGR, is calculated using the following equation:

$$\mathrm{SGR} = [(S_1 + S_2 + S_3 + S_4) + S_5]S_6S_7$$

where S_1 is the score of joint frequency and aperture, S_2 is schistosity, S_3 is crash zones, S_4 is karstification, S_5 is soil permeability coefficient, S_6 is tunnel location to the water

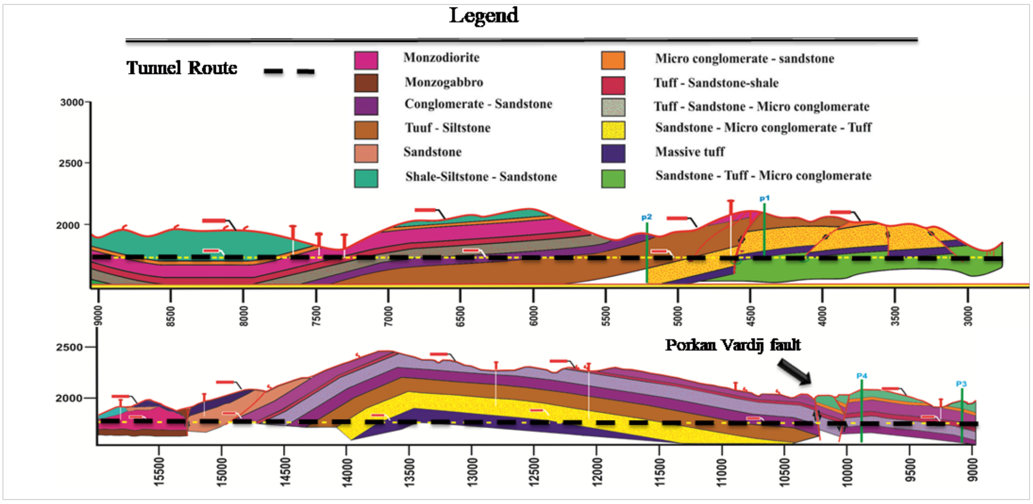


Figure 3. Karaj tunnel geological section.

table or piezometric surface, and S_7 is the annual rainfall of the area. The method for calculating these parameters will be explained in Section 4.

It is clear that in rock sites, parameters like fracture, joints, and karstification are important but on the contrary, in soil sites, the permeability coefficient parameter is important. In rock sites, this factor is hidden in joint frequency, and aperture, and other factors. The annual rainfall of the area is concerned when the tunnel is excavated in unsaturated zone. In the case of tunneling in a saturated zone, the score of this factor is considered equal to 1 automatically.

After the calculation of SGR coefficients for the intended sections in the tunnel, there must exist a criterion to evaluate the amount and size of this coefficient, based on which groundwater seepage risk into the tunnel (with a qualitative and quantitative view) can be evaluated.

Based on the value obtained, the amount of water entering the tunnel is estimated in Table 1.

Predicting the rate of inflow of water into the tunnel can lead to the appropriate design of drainage systems and even the choice the most appropriate excavation method, so the required preparations are performed to prevent possible risks (Katibeh and Aalianvari, 2009).

The larger the SGR coefficient, the more permeated water there isin the tunnel (at least for a short time), and therefore drainage tools and methods must be stronger and more expensive. Even sometimes, tunnel excavation methods must be revised so that the possibility of sudden and damaging incidents occurring is decreased (Farhadian et al., 2013).

Table 1. SGR rating for groundwater inflow into tunnels.

SGR	*Tunnel rating*	*Class*	*Inflow (Liters/ second/meter)*
0 – 100	No risk	1	0 – 0.04
100 – 300	Low risk	2	0.04 – 0.1
300 – 500	moderate risk	3	0.1 – 0.16
500 – 700	risky	4	0.16 – 0.28
700 – 1000	high risk	5	0.28
>1000	critical	6	0.28<

Estimation of groundwater inflow according to the preliminary investigation data called Site Groundwater Rating (SGR): after calculation of all parameters, S_1-S_7, the SGR factor of the site is computed by means of the above equation, then according to the value of SGR and using Table 1, the tunnel site category can be found in six cases as: No risk, Low risk, Moderate risk, Risky, High risk, and Critical classes.

Score of frequency and aperture of joints, S_1:

Massive rocks in tunnel alignment include one or more joint sets, and tunnels cut them. The amount of water inflow into tunnels depends on joint frequency and joint aperture, so the reprehensive parameter, S_1, is calculated using:

$$S_1 = 25 \times \left(\sum_{i=1}^{n} \frac{\lambda_i g e_i^2}{12v} \right)$$

where λ, the joint frequency (1/m), e_i, the mean hydraulic joint aperture (m) g from Chen and Zhao (1998), the earth gravity (m/sec^2), v, the kinematic viscosity of water (m^2/sec), and b, the unit factor (sec/m) converting S_1 to dimensionless form. The constant coefficient in this equation, 25, is obtained according to the experiments to normalize the parameter S_1 (Katibeh and Aalianvari, 2009).

Schistosity, S_2:

Commonly, clay-base rocks are supposed to schistose during tectonic processes so that water can flow through schist planes. However, the relevant permeability is very low compared to the other discontinuities. In spite of low permeability, in SGR, the parameter S_2, reprehensive of schistosity, is supposed to be in the range of 1 to 5, depending on the degree of schistosity (Katibeh and Aalianvari, 2009). Number 1 shows a small degree of schistosity, and number 5 shows a high degree.

Crushed zone, S3:

Crushed zones are the major path of groundwater flow through the rock. Crashed zones considerably increase rock permeability; however, this increase depends on the rock type. In clay-based rocks, such as marl, shale schist, etc., clay minerals fill fractures and discontinuities, resulting in a considerable decrease in the permeability of the crashed zone, but in other rock types such as limestone, the permeability in the crushed zone is very high; Table 2 shows the equations to calculate S_3 in different rock types in SGR. Crashed zones in both saturated and unsaturated zones are suitable paths for groundwater flow; thus, crashed zones are of the utmost important in SGR (Table 2). By increasing the fracture density in collapse zones, the fragment size of cuttings in tunnel excavation is mainly controlled by the spacing and orientation of the fractures and joints, rather than cutter head characteristics (Zolfaghari et al., 2011). This will increase the water inflow into the tunnel.

Based on SGR, analytical, and numerical methods, groundwater seepage into tunnels is concentrated in crash zones (Farhadian and Katibeh, 2015).

Karstification, S_4:

Karstification is the geologic process of chemical and mechanical erosion by water on soluble bodies of rock, such as limestone, dolomite, gypsum, or salt, at or near the earth's surface. Karstification is exhibited best on thick, fractured, and pure limestone in a humid environment in which the subsurface and surface are being modified simultaneously. The resulting karst morphology is usually characterized by some types of cavities and a complex subsurface drainage system, so these cavities can conduct groundwater into tunnels. Groundwater inflow into tunnels can be very sudden and dangerous. According to the degree of karstification, S_4 is estimated to be between 10 and 100. The number 10 shows low karstic areas, and the number 100 shows very high karstic areas.

Soil permeability, S_5:

Parameters S_1 to S_4 are related to rock tunnels, but if a tunnel is excavated in soil, parameters S_1 to S_4 are automatically equal to zero. In SGR, soil permeability is a very important factor, which is scored in S_5. S_5 is calculated as follows:

$$S_5 = k \times c$$

where k is the soil permeability (m day^{-1}), c is the unit factor (day m^{-1}) converting S_5 to dimensionless form.

Water head above tunnel, S_6:

Head of water (H) above the tunnel is one of the most effective parameters for groundwater inflow into tunnels. Parameter S_6 is calculated using:

$$S_6 = \frac{H}{\ln(H)} \times d$$

where H is the water head above the tunnel and d is the unit factor (1/m) converting S_6 to dimensionless from. When a tunnel is excavated above water table S_6 is equal to unit.

Annual rainfall, S_7:

Table 2. Method to estimate S_3 in crashed zones.

Type of rock	Crashed zone width	S_3
Clay base rocks	Czw	Log(10Czw) *b *2
Other rock type	Czw	Log(10Czw) *b*100

b is the unit factor(1/m),Czw is the crash zone width

Just when tunnel is excavated in unsaturated zones, annual raining is effective on groundwater inflow into tunnels. In such in unsaturated zones quantity and intensity of raining affect the groundwater inflow into tunnels, but here only annual raining is considered. S_7 for unsaturated tunnels is calculated using:

$$S_7 = \frac{P_y}{5000}$$

$$\begin{aligned} \text{Unsaturated tunnel} \quad & S_7 < 1 \\ \text{Saturated tunnel} \quad & S_7 = 1 \end{aligned}$$

where, P_y is annual rainfall (mm).

4. Result and Discussion

According to the hydrogeological conditions, the following point should be taken into account to correct and complete the SGR method. All items have been quantified using the geological, hydrogeology and engineering geology of the tunnel route.:

S_1:

It is recommended that in addition to the items raised in SGR method based on the calculation of S_1, the value of the slope of joints to the given tunnel must also be considered. In fact, when the joints are vertical, more water transfer is observed. The more slope of the joints, the more water inflow risks will be. If the slope joint is more than 60, we will have the most risk in similar lithological and geological Karaj tunnel route. The slope degree between 30 to 60 degree has the medium hazard and less than 30 degrees has the lowest hazard. This issue was experienced in Karaj tunnel. The joints trends are also of great importance. If the direction of the tunnel and joints is perpendicular, the likelihood of inflow of water into the tunnel will be increased. Percentages presented in relation to the slope can be generalized along the reverse mode as well.

S_2:

It is recommended that layered parameter instead of schistosity parameter should be put into consideration. Because the layered rock after fractures is one of the main factors of flowing underground water. The vertical layering plays more roles than the layering which approaches to the horizontal level. When the slope of layers was about 30 to 40 degrees (chainage 13500 area up to 15000), the water entrance to the tunnel was about 100 liters per second. This number of water compared to the water entrance to the tunnel in the horizontal layer, nearly at about 11000 to 13500, is very low. While the conditions of the joints of the two regions were the same.

When the slope of the layers is more than 30 to 40 degrees in Karaj tunnel, the water entry to the tunnel is actually more than of horizontal mode (Morsali et al., 2017). Therefore, the slope of the layers must enter into the relationships somehow. For example, by increasing the slope of the layers, the amount of effective water head increases. The effective water head estimated based on the water inflow is within 25 to 50% of the observed water head in the boreholes. Furthermore, ratio of effective water head to measured water head, is lower in tunnel sections where the quality of rock mass is low probably because of the increase in the conduit flow at lower GSI values (Morsali et al., 2017).

Crushed zone, S_3:

Crushed zone in saturated groundwater environment can lead significant amounts of water into the tunnel. As such it is of great importance. Such ability exists in unsaturated condition as well. Of course, it is certain that it is of less importance compared to the saturated environment. In unsaturated environment, when water penetrates into the crushed zone (resulting from atmospheric precipitation or subsurface water reserves), a considerable amount of water can be brought to the tunnel, though, in other cases the water influx may not be significant. Therefore, even if the tunnel is excavated in the non-saturated zone, the importance of saturated zone in water transfer and penetration should not be ignored. Sudden and severe inflow of water to the Emamzadeh Hashem tunnel (East of the Tehran) and its high financial damages was caused by clashing a crushed zone of aquifer fault in the Mobarak formation. The structure of any faults should be reviewed separately (Sibson, 2000). The existence of an impermeable core in the structure of fault makes the rock aquifer to separate in its two sides. This issue is observed in Karaj tunnel 2 of the Porkan-Vardij fault. In this region, before drilling the tunnel reaches the Porkan-Vardij fault, no significant water entered the tunnel. There was no problem in the fault core either. But after passing the fault zone, the water volume of more than 100 liters per second enters the tunnel. This issue is of an indicative of the dam's performance like a fault. In many cases, the hydraulic behavior of faults leads them to act as a conduit for passing the flow and as obstacles against the stream or a combination of both of them (Singhal 1999). By examining the characteristics of each fault, the width of the crashed zone should be determined with regard to hydrogeological view. By examining the characteristics of each fault, the amount of crush zone affects by the hydrogeological view is determined.

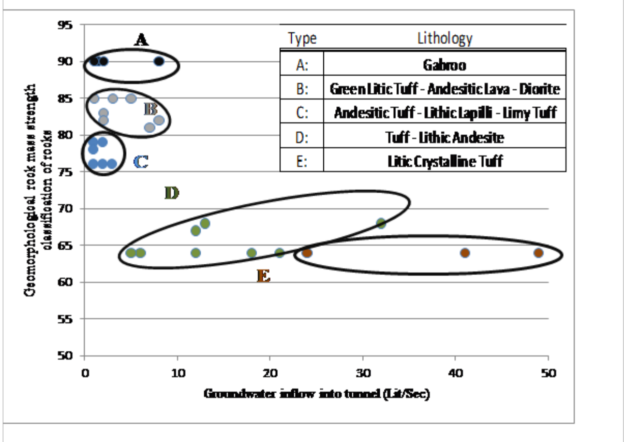


Figure 4. Relation between geomorphological rock mass strength classification of rocks and groundwater inflow into the Karaj tunnel.

Karstification S_4:

In limestone, the joints and fractures play key roles in controlling the orientation and the extent of karst features (Milanovic, 2007). Accordingly, the major water inflow occurs in limestone of karstic Formation (Morsali et al., 2017; Lijun et al., 2021). The proposed method is qualitative and roughly approximate. It is recommended to use the classification of Ford and Williams (2007) in order to calculate the morphological aspect quantitatively and to add a fraction of the 100 in the SGR method. A significant correlation was observed between the amount of water entrance to the tunnel and the results of Ford and Williams' geomorphological rock mass strength classification. These relationships in the two tunnels of the Karaj and the Kerman, were evaluated. The relationship between these two in the Karaj tunnel is presented in Figure 4. Therefore, for the first time, it is recommended to use this criterion to estimate the water entrance to the tunnel. Taking into consideration factors of rock composition, texture and compressive strength, and the frequency of penetrable bedding planes, joints and faults, the Geomorphological Rock Mass Strength Classification and Rating as proposed by Selby (1980) is a useful guide to the strength of karstifiable rocks at the scale of the principal karst landforms, i.e. cave systems, dolines, karren fields, residual hills and towers. The classification is intended to rate the strength of hillslope masses. However, it is developed from mining engineering applications (Bieniawski, 1976; Brady and Brown, 1985); thus it is also pertinent to the stability of cave roofs, the likelihood of catastrophic sinkhole collapse, etc. The Selby classification is presented in a slightly modified form in Table 3. It has not been applied widely in karst terrains as yet. Most that display well developed landforms seem likely to range across the middle categories, Strong-Weak. Moon (1985), applying the classification to hillslopes of quartzite or shale in South Africa, considered that it should contain a further parameter for the roughness of fissures of all kinds (bedding planes, joints,

Table 3. Geomorphological rock mass strength classification of rocks (Ford and Williams, 2007).

Intact rock strength(N-type Schmidt Hammer "R")					
Parameter	100-60	60-50	50-40	40-35	35-10
Rating	20	18	14	10	5
Weathering					
Parameter	Unweathered	Slightly	Moderately	Highly	Completely
Rating	10	9	7	5	3
Spacing of fissures					
Parameter	>3 m	3-1 m	1-0/3 m	300-50 mm	<50 mm
Rating	30	28	21	15	8
Fissure orientations					
Parameter	Very facourable	Favourable	Fair	Unfavourable	Very unfavourable
Rating	20	18	14	9	2
Width offissures					
Parameter	<0/1 mm	0/1-1 mm	1-5 mm	5-20 mm	>20mm
Rating	7	6	5	4	2
Continuity of fissures					
Parameter	None continuous	Few continuous	Continuous no infill	Continuous thin infill	Continuous thick infill
Rating	7	6	5	4	1
Outflow of groundwater					
Parameter	None	Trace	Slight	Moderate	Great
Rating	6	5	4	3	1
Total rating and classification					
Parameter	1	2	3	4	5
Parameter	Very strong	Strong	Moderate	Weak	Very weak
Rating	100-91	90-71	70-51	50-26	<26

Table 4. Geomorphological rock mass strength classification of rocks in the Karaj tunnel.

Intact rock strength (N-type Schmidt Hammer 'R')					
Parameter	100 – 60	60 – 50	50 – 40	40 – 35	35 – 10
Rating	20	18	14	10	5
Tunnel Hydrogeologic zone	*DIO, GAB, MO*	*AL, LL, BG, LT, LA, MLT, GT, LLT, AT, CT, GLT, ALT*	*LC, LCT, TU LA, LT*		
Weathering					
Parameter	Unweathered	Slightly	Moderately	Highly	Completely
Rating	10	9	7	5	3
Tunnel Hydrogeologic zone		*DIO,GAB,AL,LL,LC,MLT,MO,LLT, CT,GLT,TU,ALT*	*LCT,AL,BG,LT,LA, AT,TU,GT,ALT*		
Spacing of fissures					
Parameter	>3 m	3 – 1 m	1 – 0.3 m	300 – 50 mm	<50 mm
Rating	30	28	21	15	8
Tunnel Hydrogeologic zone	*MO*	*DIO,GAB,AL,LL,BG,LT, LA,MLT,CT,GLT*	*LCT,LC,LA,MLT, GT,AT,TU,ALT*		
Fissure orientations					
Parameter	Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
Rating	20	18	14	9	2
Tunnel Hydrogeologic zone		*GAB,MO,*	*AL, BG, LT, LC, MLT, AT, GL,*	*DIO,LL,LA, LLT, ALT, GT, LCT, TU*	
Width of fissures					
Parameter	<0.1 mm	0.1 – 1mm	1 – 5mm	5 – 20 mm	>20 mm
Rating	7	6	5	4	2
Tunnel Hydrogeologic zone		*BG, LT, T*	*DIO, GAB, AL, LL, BG,LC,LA,MLT, MO, GT , CT, GLT, ALT, AT, LCT,*	*LA, MLT, TU, ALT*	
Continuity of fissures					
Parameter	None continuous	Few continuous	Continuous, no infill	Continuous, thin infill	Continuous, thick infill
Rating	7	6	5	4	1
Tunnel Hydrogeologic zone		*AT,CT,TU,ALT, MO*	*DIO,GAB,LL,BG,LA*	*LCT,LT,LC,MLT,GT, LLT,GLT*	
Outflow of groundwater					
Parameter	None	Trace	Slight	Moderate	Great
Rating	6	5	4	3	1
Tunnel Hydrogeologic zone		*AL, LL, BG, LT, LC, LA, MLT,, LLT, AT, CT, GLT, TU, ALT, DIO GAB, MO*	*LCT-LA- GT*		

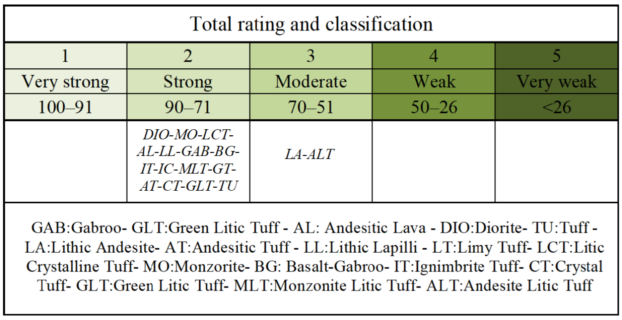
GAB:Gabroo- GLT:Green Litic Tuff - AL: Andesitic Lava - DIO:Diorite- TU:Tuff - LA:Lithic Andesite- AT:Andesitic Tuff - LL:Lithic Lapilli - LT:Limy Tuff- LCT:Litic Crystalline Tuff- MO:Monzorite- BG: Basalt-Gabroo- IT:Ignimbrite Tuff- CT:Crystal Tuff- GLT:Green Litic Tuff- MLT:Monzonite Litic Tuff- ALT:Andesite Litic Tuff

faults). This is a particularly complex parameter in karst because the roughness (interlocking) on the fissure planes becomes progressively reduced by dissolution. In many regions, limestone and dolomite dip slopes are preferred sites for large landslides because of this factor (Ford and Williams, 2007) (Tables 3, 4 and 5).

Soil permeability, S$_5$:

It is recommended to remove the parameter S$_5$ from this method, because the calculation methods of the rocky and alluvium environments are very different. On the one hand, if the drilling environment is alluvium, the estimation of all cases will be more different. Generally, the SGR method must not be used in alluvium environments. The parameter related to the soil must be removed in rock calculation in

Table 5. Total rating and classification of the Karaj Tunnel.



Total rating and classification				
1	2	3	4	5
Very strong	Strong	Moderate	Weak	Very weak
100–91	90–71	70–51	50–26	<26
	DIO-MO-LCT-AL-LL-GAB-BG-IT-IC-MLT-GT-AT-CT-GLT-TU	*LA-ALT*		

GAB:Gabroo- GLT:Green Litic Tuff - AL: Andesitic Lava - DIO:Diorite- TU:Tuff - LA:Lithic Andesite- AT:Andesitic Tuff - LL:Lithic Lapilli - LT:Limy Tuff- LCT:Litic Crystalline Tuff- MO:Monzorite- BG: Basalt-Gabroo- IT:Ignimbrite Tuff- CT:Crystal Tuff- GLT:Green Litic Tuff- MLT:Monzonite Litic Tuff- ALT:Andesite Litic Tuff order to reduce the errors.

Water head above tunnel, S_6:

According to the results of Morsali et al. (2017), the water head should not be considered as an effective actual one (Morsali et al., 2017). According to this research, 30 up to 50 percent of the water head is through the observation of the boreholes. Shrestha and Panthi (2014) found a 30% deformation level for the tunnel studied in their work owing to the weak fractured ground and lack of lateral support to the tunnel. Water head is the one of the main factor in tunnel stability (Bour and Goshtasbi Goharizi, 2019) Nilsen (2014) reported that probe drilling and pre-grouting are the most important elements dealing with water ingress and ensuring stability. Moon and Fernandez (2010) indicated that water table drop is proportional to the water inflow during the drilling and introduced its trend as a parameter for prediction of the water inflow. Fernandez and Moon (2010) studied the joints near a tunnel and their effect on water inflow. A study of the groundwater inflow in shallow tunnels below the water table was carried out by Jurado et al. (2012); Font-Capo (2012) detailed the conditions of groundwater inflow in granitic rocks tunneled using a TBM. According to Morsali et al. (2017), a comparison is made between the ratio of the calculated water head (Hc) to the observed water head (Ho) and rock mass quality. The GSI classification (Hoek et al., 1998) and its related chart were selected as a suitable parameter for rock mass quality assessment. To do this comparison, the Hc/Ho ratio values are drawn on the GSI chart. As shown, by a drop in GSI values, the Hc/Ho ratio also reduces. According to direct measurements in the Karaj tunnel, the groundwater head above the tunnel in boreholes is very high (over 400 meters in some boreholes). In addition, the water pressure measured in the installed piezometers inside the tunnel is very low (about 0.5 bars or 5 m). To find more accurate values, the estimation of the water head was carried out based on the measured water inflow into the tunnel. The water head on the tunnel is a value between the two measured values of geotechnical boreholes and installed piezometers in the tunnel. Generally, the water head estimated based on the water inflow is within 25 to 50% of the observed water head in the boreholes. Furthermore, the Hc/Ho ratio is lower in tunnel sections where the quality of rock mass is low probably because of the increase in the conduit flow at lower GSI values (Morsali et al., 2017). In SGRm method, water head on the tunnel is effective head.

Annual rainfall S_7:

There is a direct relationship between the water inflow into the tunnel and the precipitation. Therefore, if it is to use this parameter, it must be considered in the saturated zone as well. But as a whole, it is recommended to remove this parameter. This parameter is actually observed in the water head (S_6). In this article, in order to optimize the model, at the end of every sub-factors of SGR, supplementary or corrected parameters will be proposed according to the achieved experiences.

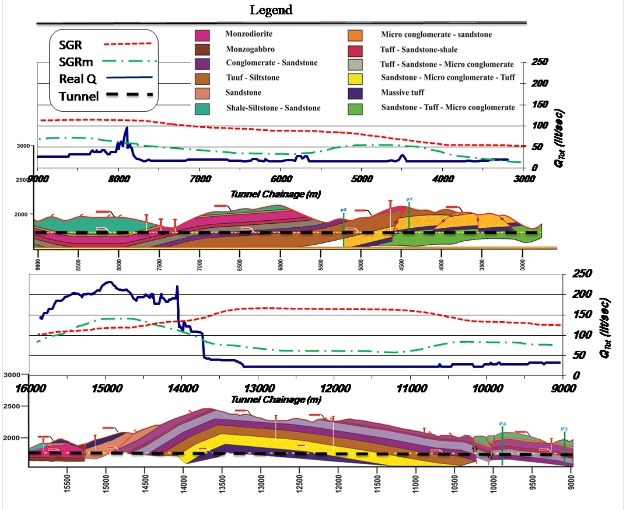


Figure 5. Comparison of methods of SGRm and SGR with real data of water inflow into the Karaj tunnel.

Finally, in this research, according to the SGR procedures provided by the Katibeh and Aalianvari (2009) and considering additional tips provided, the calculation of the coefficient of SGR as a SGRm supplementary is propose as the following:

$$\mathrm{SGRm} = [\mathrm{Sm}_1 + \mathrm{Sm}_2 + \mathrm{Sm}_3 + \mathrm{Sm}_4]\mathrm{Sm}_6$$

Comparison of the numbers of SGR and SGRm is shown in Table 6. parameters S_5 and S_7 were removed. Other values have been modified according to the concepts described and field observations results. The role of some of the changes is very significant. In fact, the above changes are highly suitable to the logics of geology and hydrogeology. In both of the Karaj (Fig. 5) and the Kerman (Fig. 6) tunnels, SGR and SGRm values along with the actual measured values of water entrance to the tunnel were compared. Water inflow into tunnel measured daily and according to excavation area, the rate of discharge was determined for each zone.

The water head, which is considered as a water column, causes a large error when the tunnel depth is large. By applying the correction factor in the revised method, this problem is closer to reality. This issue can be clearly seen in km 5 – 14 of the Karaj tunnel. Also, correcting the role of the slope of the joints in the Kerman tunnel has had a great impact on the accuracy of the estimation of the water entering the tunnel.

This method was obtained for the geological conditions of the Kerman and Karaj tunnels. It is recommended that it

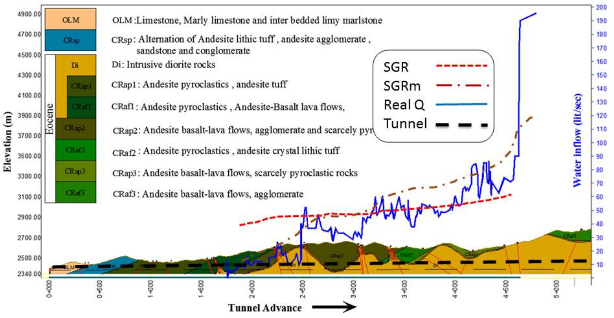


Figure 6. Comparison of methods of SGRm with SGR and real data of water inflow to the Kerman tunnel.

Table 6. Details of the SGR and SGRm numbers in two tunnels examined based geological and hydrogeological zones.

A: Kerman tunnel

SGR

Zone	L(m)	H(m)	k (m/day)	S1	S2	S3	S4	S5	S6	S7	SGR	q (l/s/m)	Q(lit/s)
HG1	670	100	0.043	5.4E-05	2	1.398	10	0.0432	21.71	0.04	11.67	0.047	31.3
HG2	700	110	0.006	1.8E-05	2	2.000	10	0.006	23.40	0.04	13.11	0.052	36.7
HG3	1280	120	0.086	2.7E-05	1	2.352	10	0.0864	25.07	0.04	13.47	0.054	69.0
HG4	960	150	0.009	4.5E-04	1	2.000	10	0.0086	29.94	0.05	18.69	0.075	71.8

SGRm

Zone	L(m)	H(m)	k (m/day)	S1	S2	S3	S4	S5	S6	S7	SGRm	q (l/s/m)	Q(lit/s)
HG1	670	30	0.043	3.3E-05	1	2.000	6	-	8.82	-	3.18	0.013	8.5
HG2	700	80	0.006	1.5E-05	2	3.204	12	-	18.26	-	12.56	0.050	35.2
HG3	1280	90	0.086	3.3E-05	4	3.690	15	-	20.00	-	18.15	0.073	92.9
HG4	960	150	0.009	5.4E-04	3	3.204	22	-	29.94	-	33.77	0.135	129.7

B: Karaj tunnel

SGR

Zone	L(m)	H(m)	k (m/day)	S1	S2	S3	S4	S5	S6	S7	SGR	q (l/s/m)	Q(lit/s)
H1	1000	110	0.00864	3.8E-05	1	1.398	10	-	23.402	-	13.936	0.056	55.745
H2	1100	100	0.0095	1.4E-05	2	2.000	10	-	21.715	-	14.602	0.058	64.250
H3	1400	140	0.00864	3.5E-05	1	1.257	10	-	28.331	-	16.679	0.067	93.405
H4	2300	100	0.00864	1.7E-04	2	1.398	10	-	21.715	-	13.974	0.056	128.560
H5	2200	100	0.0095	2.0E-05	2	2.261	10	-	21.715	-	15.184	0.061	133.617
H6	2400	140	0.007	3.6E-02	1	1.204	10	-	28.331	-	17.002	0.068	163.218
H7	1600	170	0.00864	3.2E-05	2	1.398	10	-	33.101	-	21.745	0.087	139.167
H8	1300	110	0.0095	8.9E+00	1	1.398	10	-	23.402	-	24.425	0.098	127.008

SGRm

Zone	L(m)	H(m)	k (m/day)	S1	S2	S3	S4	S5	S6	S7	SGR	q (l/s/m)	Q(lit/s)
H1	1000	70	0.00864	1.7E-03	1	1.398	10	-	16.476	-	9.812	0.039	39.253
H2	1100	50	0.0095	3.4E-02	2	2.000	15	-	12.781	-	11.662	0.047	51.406
H3	1400	60	0.00864	7.8E-05	1	1.257	10	-	14.654	-	8.628	0.035	48.315
H4	2300	50	0.00864	1.7E-04	1	1.398	10	-	12.781	-	7.611	0.030	70.025
H5	2200	50	0.0095	5.1E-06	2	2.511	15	-	12.781	-	11.975	0.048	105.384
H6	2400	45	0.007	1.5E-03	1	1.204	10	-	11.821	-	6.950	0.028	66.525
H7	1600	130	0.00864	3.2E-03	3	1.398	10	-	26.708	-	18.469	0.074	118.226
H8	1300	100	0.0095	1.0E+01	1	2.352	15	-	21.715	-	28.407	0.114	154.849

can be used for similar geological conditions. Obviously, in different circumstances, it should be reviewed again.

As the above figures show, the results of the SGRm method are closer to the real results than the results of initial SGR method. This issue has more effects especially on the fault zone and certain geological structures.

5. Conclusion

As to inefficiency of the analytical methods in the estimation of water entrance to the tunnel, the SGR method is introduced as a new method for reducing the errors of the analytical methods resulting from the previous annual experiences. The results of the SGR method, in spite of having more accuracy compared to analytical methods, still showed a high difference with the actual results. The cause is related to the ignorance of some of the hydrogeological and geological concepts. In analytical methods, the main parameters for estimation are permeability, water load and tunnel radius. But in this method, the water entering the tunnel is estimated with more concepts of underground water and geological conditions. For example, the amount of karstification, layering of rocks and effective water head are included in it and a new classification is presented. this classification is not recommended for alluvial tunnels. In this research, according to the experiences of the Kerman and the Karaj tunnels excavation, the authenticities of the SGR method validations were studied. Two of the seven parameters introduced in the SGR method, which are related to the permeability of the soil (due to certain condition in hard rock formation) and the effect of rain (due to its impact on the water head) are deleted. The amount of the slope of joints in the S_1 parameter, layering instead of schistosity in the S_2 parameter, the calculation of the status of the crushed zone type in S_3 parameters (the structure of any faults should be reviewed separately), the use geomorphological rock mass strength classification instead of relative criteria of karst, the use of the coefficient of 30 to 50 percent of the measured water load in boreholes and using the GIS classification criteria in S_6 parameter, are among the changes introduced in this paper. As a result, optimized SGR method is introduced (SGRm). The results of SGRm compared to the results of SGR are closer to the actual results. Therefore, this method as a new method to estimate the water entrance to the tunnel is recommended.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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