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On the optimum design of reinforcement systems for old masonry railway tunnels

Soheil Ghyasvand[a], Ahamd Fahimifar* and Fereidoon Moghadas Nejad[b]

Faculty of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran

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Abstract. Safety is a most important parameters in underground railway transportation; Also stability of underground tunnel is very important in tunneling engineering. Design of a reliable support system requires an evaluation of both ground demand and support capacity. Iran's traditional railway tunnels are mainly supported with masonry structures or unsupported in high quality rock masses. A decrease in rock mass quality due to changes in groundwater regime creep and fatigue in rock and similar phenomena causes tunnel safety to decrease during time. The case study is an old tunnel in Iran, called “Keshvar”; it is more than 50 years old railway organization. In operating this Tunnel, until the several problems came up based on stability and leaking water. The goal of study is evaluation of the various reinforcement systems for supporting of the tunnel. The optimal selection of the reinforcement system is examined using TOPSIS Fuzzy method in light of the looming and available uncertainties. Several factors such as; the tunnel span, maintenance, drainage, sealing, ventilation, cost and safety were based to choose the method and system of designing. Therefore, by identifying these parameters, an optimal reinforcement system was selected and introduced. Based on optimization system for analysis, it is revealed that the systematic rock bolts and shotcrete protection had a most appropriate result for these kind of tunnel in Iran.

Keywords: multi-item optimal; railway tunnel; reinforcement system; TOPSIS

1. Introduction

There is a fundamental lack of knowledge about the mechanical behavior of old brick-lined tunnel under tunnel-induced ground movements. This is because of the complexity in modelling the brick lining and the load redistribution owing to the interactions between the masonry structure and the surrounding ground (Mohammad *et al*. 2010).

Site investigation with the aim to identify the tunnel surrounding rock mass, tunnel geometry, groundwater conditions, in situ stresses, joint conditions and structural geology of the surrounding medium, tunnel utilization conditions for data collection, is the first step in providing an optimal tunnel design plan. However, many of these parameters cannot be definitively and reliably selected. Using probabilistic methods, risk analysis and optimization methods can turn out to be of great benefit in achieving a reliable and also economical design (Oh *et al*. 2018, Wu *et al*. 2020).

One of the most significant issues in the design of tunnel reinforcement system is determination of the tunnel surrounding rock mass deformation due to the excavation (Rooh *et al*. 2018, Luo *et al*. 2018). Tunnel reinforcement is an effective approach to reduce tunnel deformation as a result of stress relief. However, there are few quantitative studies on the effect of reinforcement on tunnel deformation. Moreover, the reinforcement mechanism of the reinforced ground are not fully understood (Sun and Sun 2019).

Improvement of existing railway tunnels encounters various difficulties and limitations including the impossibility of long-term obstruction of rail lines and the interruption of trains passing through the tunnel, thereby treatment should be carried out with the operation. Also, due to the limited size (low cross-section) of the rail tunnels and the size of the trains, additional lining and structure within the tunnel cannot be used as they reduce the available space, thus reducing the number of ways which do not reduce the size of the tunnel. It should be noted that, removing the existing lining is not possible because of the weathering of the surrounding tunnel rock masses, the risk of total instability and tunnel failure. Therefore, treatment of ancient tunnels during the operation has various challenging issues which should be precisely considered. In this paper, strengthening of a 50-years-old railway tunnel in south-west of Iran, named “Keshvar tunnel”, was investigated. For this purpose, 45 combinations of reinforcement systems were evaluated and finally the optimum system was chosen using fuzzy optimization analysis.

2. Tunnel reinforcement

Tunnel reinforcement system such as fore-poling, steel

∗Corresponding author, Ph.D.
E-mail: fahim@aut.ac.ir
[a]Ph.D. Student
[b]Ph.D.

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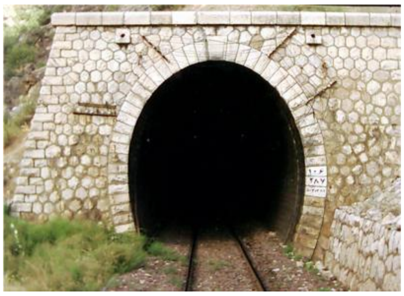


Fig. 1 Cross section of tunnel No. 68; location in Lorestan Province

Table 1 Common solutions to eliminate complications in a stone-lined tunnel (Bergeson and Ernst 2015)

Complication	Treatment solution
Masonry stone units	Separate lining units consisting of building materials such as stone blocks, bricks, etc. should be examined for displacement, fracture, cracking and even removal of units (detached blocks).
Mortar	The mortar between the rock units by connecting the detachable blocks provides stability; considering the importance of this component of the structure, missing mortar, depreciation and cracking should be investigated.
Shape	The interlocking rock blocks form a pressure arc that provides stability. The curvature of the roof bumps on the walls, and any other deformations may cause instability by the cracking in the lining.
Alignment	The horizontal and vertical alignment of the structure must be visually inspected. Using a Plumb or laser alignment can also help in this regard.
Water leakage	Connecting cracks provide a conduit for crossing and leakage of water to the lining, water leakage destroys the mortar between the rocks and threatens stability. Efflorescence can represent this phenomenon.

set, rock bolts and etc., are usually applied to prevent the local failure of tunnel. Design of tunnel reinforcement involves many sources of uncertainty and variability and is empirical as the factors influencing tunnel stability are hardly evaluated and their impacts have rarely been quantified against the stability of tunnel (Sagong and Lee 2006, Nejati *et al*. 2012).

Traditional Iranian tunnels are categorized on three types: without lining, with Non-structural lining (only for protection of weathering), and structural linings, which usually are masonry structures. Fig. 1 shows cross section of a masonry tunnels built with natural stone.

2.1. Masonry structures

This study focuses on tunnels supported by masonry materials. Table 1 summarizes the fundamental solutions regarding to the masonry tunnels (Bergeson and Ernst, 2015).

The solution is applied only for the minor and routine

Table 2 Old tunnels of Iran railway network

Region	Tunnel lining material (length meter)			Total length of tunnels (meters)
	Without lining	Masonry lining	masonry-concrete lining	
Shomal	-	9179	11415	20594
Arak	-	1658	-	168
Lorestan	-	1766	53947	55713
North-West	-	19222	-	19222
Azerbaijan	1530	11573	-	13103
Isfahan	1361	-	-	1361

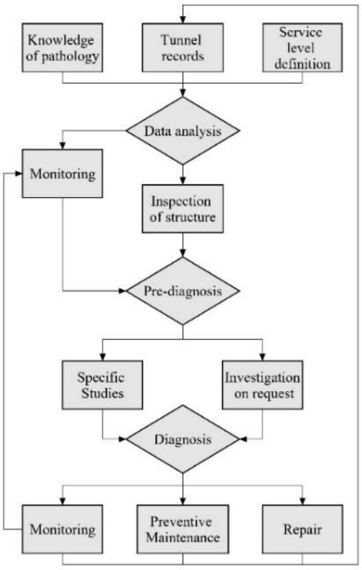


Fig. 2 Structural inspection steps to prevent an accident (ITA 1991)

problems; main problems need design and incorporation for a new tunnel support system. Fig. 2 shows a step-by-step procedure for investigating tunnel disorders, analysing the evidence, and recommending action on the problem.

3. Reviewing the routes to select a case study

Iran Railway Network in 2019 has 141 km of tunnels. In this research, the aim is to study old tunnels that are generally maintained by masonry materials or do not have a support system. According to Table 12, it is clear that Lorestan province, which is located on the national railway route from Tehran to Bandar-e Emam Khomeyni, has biggest number of tunnels, and unfortunately the statistic shows we have most of accident on this part of Railway network. According to the member of accident and big number of Tunnels the case study was selected.

The Tehran to Bandar-e Emam Khomeyni Railway Route enters the Zagros Mountains after crossing the Tamandar Mountains around Doroud Station. In the routing studies, the only acceptable route that could be used to build the north-south railway using the facilities and machinery available at that time was to cross the Dez-Cesar-Bakhtiari valleys and rivers using the aforementioned waterways.

The southbound railway crosses the cities of Dorood, Sepidasht, and Andimeshk on its southbound route. The target area is 208 km between the Dorood-Andimeshk stations. The tunnels are mainly made of silt, clay, quartzite, chert, and shale, but the most important lithofacies are problematic limestone. Low shear strength, high solubility, substitution by materials, and other elements have made these tunnels unstable and penetrate the water. Cracking and slipping of rock are appropriate bedding for transporting surface water and penetrating tunnel structures. The presence of any tectonic factor such as faulting and folding makes this capability increased (Motiee 2003).

After reviewing and studying, tunnel No. 68 (Keshvar tunnel), from the mentioned route was selected as a case study**.** This choice is made by reviewing safety reports as well as the ability to generalize the geological parameters and overburden to this route and with less accuracy to the entire railway network.

4. Design of reinforcement systems

In order to repair a tunnel, a technical certificate must be prepared for each tunnel including the purpose of the tunnel, type of operation, mechanical and natural features, and the supporting system at various stages. In the next step, the optimal system will be selected by identifying the factors that affect the tunnel with the aim of investigating the structure condition and aggravating factors of depreciation and even collapse during the project life of the system.

4.1 Analysis of the evolution of tunnel equilibrium equations with the convergence-confinement approach

As both lining and rock masses change over time, the tunnel equilibrium conditions evolve over time. Sandron and Labios (2010) conducted studies on the rock mass and lining degradations on the long-term stability conditions of the tunnel by means of the convergence–confinement method (Sandrone and Labiouse 2010, Lukic *et al*. 2020).

Several factors play a role in the amount of tunnel convergence and the extent of the yielding zone around the tunnel such as the geological and geotechnical conditions, the in-situ state of stress relative to rock mass strength, the ground-water flow and pore pressure, and the rock mass properties (Barla 2001).

The mechanical properties of rock and lining using creep models are evaluated and the results are generally interpreted by Factor of safety (FoS). The theory of the present approach, although valid for simple tunnel geometry and simple stress conditions, can almost influence to reviewing the demolition process of the tunnel lining and surrounding rock. Although this method leads to some simple steps, it can supplement the analysis by numerical methods.

Considering the initial conditions of the tunnel and the amount of rock mass and lining degradation, tunnel stability conditions can be investigated During operation. Since tunnel stability depends on the equilibrium of forces, the

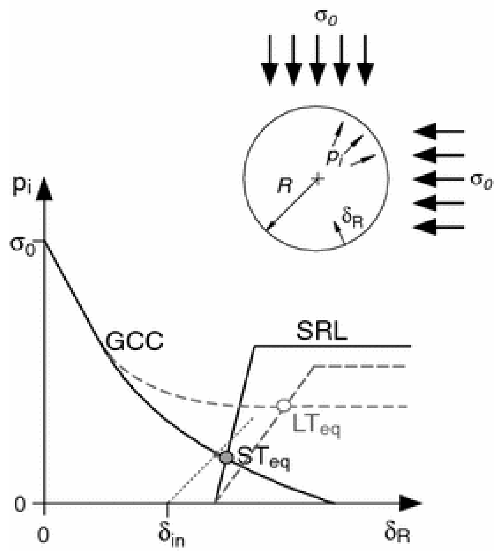


Fig. 3 The ground characteristic curve (GCC) and the Support reaction line (SRL) in CCM (Sandrone and Labiouse 2010)

convergence-confinement method (CCM) is a useful tool to illustrate the impacts of the tunnel demolition process over the life of the project (Sandrone and Labiouse 2010, Su *et al*. 2021). CCM although accompanied by basic assumptions such as plane strain and axisymmetric conditions, is widely used in tunnel design and is well developed. Fig. 3 shows a graphical representation of this method, in which the tunnel equilibrium is determined by the intersection point of the two ground characteristic curves (GCC) and the Support reaction line (SRL). In this figure, bold lines and their intersections (S_{teq}) are related to short-term conditions. The dashed lines and their intersections (L_{teq}) represent the long-term conditions of the tunnel (Sandrone and Labiouse 2010).

4.2 Design of reinforcement system

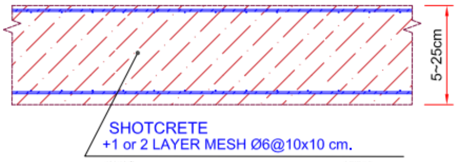
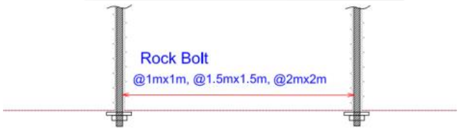
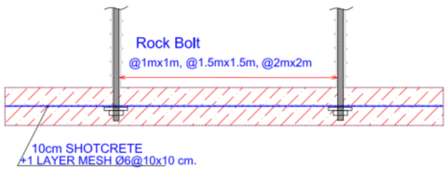
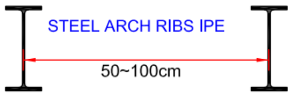
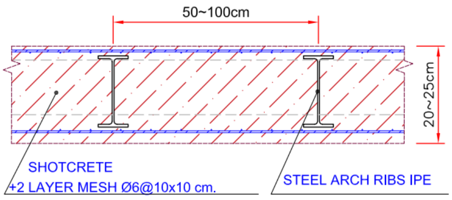
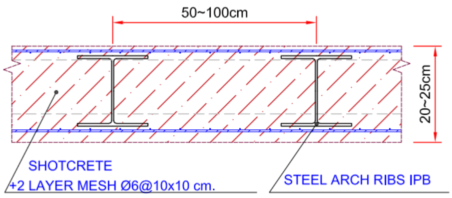
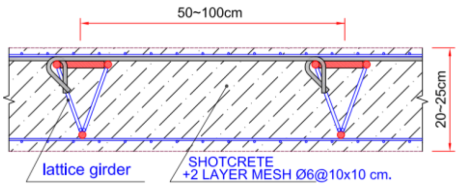
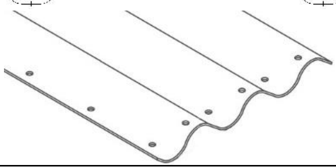
In this project, the GRC is modified by the "rock mass reduction coefficient" for the long-term conditions of the ground. This coefficient based on uniaxial compressive strength, cohesion, rock mass deformation, and other parameters that decrease over time. In this project, 45 conventional support systems in the tunneling industry were proposed to be incorporated to enhance its safety and then evaluated on the basis of operability, installation and conflict with operation, unit length costs, and safety factor. Each of the four categories has sub-categories based on which scoring system was assigned. Performance evaluation of the systems has been carried out by experts in the field. The types of systems mentioned are illustrated in Table 3.

4.2.1 Performance

Ventilation

In railway tunnels, maintaining proper rail system performance is an important issue. The main objectives of

Table 3 Types of Support systems designed for the up grading of railway tunnels

Shotcrete	
Rock Bolt	
Shotcrete + Rock Bolt	
IPE Steel Beams	
IPE Steel Beams + Shotcrete	
IPB Steel Beams	
IPB Steel Beams + Shotcrete	
Lattice girder	
Lattice girder + Shotcrete	
TH profile	
Sinusoidal steel profiles	

the rail tunnel ventilation system are to provide suitable conditions for passengers, workers and railway equipment

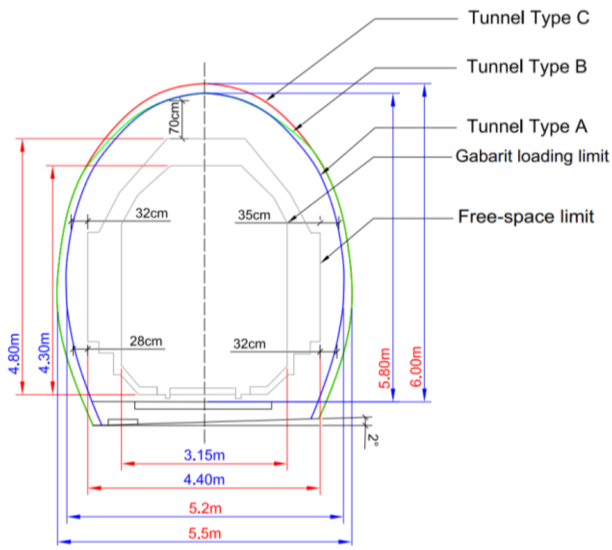


Fig. 4 Types of old tunnels in trans-Iranian railway and loading gauge

to transmit the intense heat generated by train movement and provide the safety required for passengers to escape during fire Gharouni Nik *et al*. 2006). Examination of the tunnels and galleries in the western rail network of Iran shows that the Lorestan region, located on the Tehran-Iran railway to Bandar-Imam Khomeyni, one of the most important problems is the lack of ventilation system for long tunnels. the low cross-section of the tunnels than Loading gauge, low-radius arcs and the hazardous gases from the combustion of diesel engines makes ventilation difficult (Gharouni Nik *et al*. 2006).

Sealing

Groundwater leakage into the tunnel increases the rate of deterioration and corrosion, which is accelerated if the water contains a variety of salts or metals. Due to the importance of water infiltration into the tunnel, it is important to have a sealed support system selected.

Maintenance

Effective maintenance leads to a reduction in direct and indirect costs (reducing the number of times tunnels are closed per year), increasing public safety and ensuring a sufficient level of service. To maximize efficient use of resources and minimize costs, the selective support system needs to be optimized. Maintenance activities include the following simple to complex activities:

- Removing Debris and ice
- Cleaning and unblocking of surface and deep tunnel drainage structures, tightening of joints
- Repairing equipment
- Experiments, tests, measurements, and calibrations
- Renovation

Occupying loading gauge

Loading gauge or Gabarit refers to standard dimensions for the train and its load that provide safety on the track. There are two definitions in this standard; Gabarit loading

Table 4 Statistical distribution of geotechnical and geological data

Property		In-Situ Stress (MPa)	Young's Modulus (MPa)	Poisson Ratio	Dilation Angle (degrees)	Compressive Strength of Intact Rock (MPa)	GSI (peak)	mi (peak)	Disturbance Factor (peak)
Division 1	dist.	Normal	Normal	None	None	Normal	Normal	Uniform	None
	Mean	0.32	2441.71	0.30	0.00	50.19	34.75	8.00	0.00
	Std. Dev.	0.10	482.96	0.00	0.00	5.31	2.96	0.00	0.00
	Rel. Min	0.23	1562.09	0.00	0.00	40.27	30.51	5.00	0.00
	Rel. Max	0.43	3345.28	0.00	0.00	58.02	39.70	11.00	0.00
Division2	dist.	Normal	Normal	None	None	Normal	Normal	Uniform	None
	Mean	2.06	9804.43	0.30	0.00	87.87	45.02	12.00	0.00
	Std. Dev.	0.87	1916.03	0.00	0.00	5.95	3.40	0.00	0.00
	Rel. Min	0.54	7025.95	0.00	0.00	78.82	40.15	9.00	0.00
	Rel. Max	3.18	12842.00	0.00	0.00	96.70	49.57	15.00	0.00
Division 3	dist.	Normal	Normal	None	None	Normal	Normal	Uniform	None
	Mean	0.33	1000.04	0.30	0.00	25.01	20.28	6.00	0.00
	Std. Dev.	0.20	311.26	0.00	0.00	0.53	3.04	0.00	0.00
	Rel. Min	0.07	533.85	0.00	0.00	24.20	15.33	4.00	0.00
	Rel. Max	0.58	1462.05	0.00	0.00	25.77	24.75	8.00	0.00

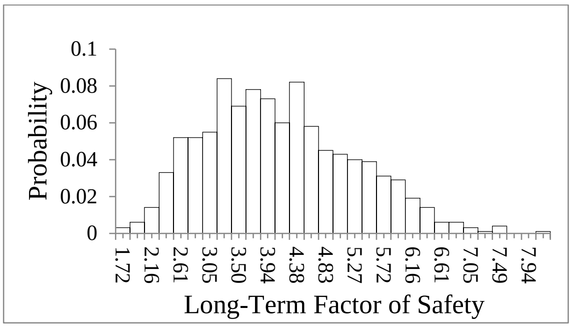


Fig. 5 Probability distribution of long-term safety factor of the structure based on Monte Carlo Simulation

limit and Free space limit, which is the gabarit loading limit that the train and their loads should not exceed outside, and the Free-space limit represents a boundary where components of the railroad structure should not be placed. Old tunnels are built in three types with slight differences, in order to find the maximum thickness of the support system, the dimensions of the tunnel were compared with the free-space limit (Fig. 4).

4.2.2. Installation and conflict with operation

This category deals with the technical issues involved in installing and monitoring of systems, this category includes the following subcategories:

- Availability in the market
- Technical knowledge and experience in implementation
- The time required to install
- Easy to install

4.2.3 Cost per unit length

In order to calculate the cost per meter of system implementation, a list of prices for the year 2017 related to the following categories was used.

4.2.4. Safety factor

As mentioned, the long-term CCM was used to reviewing the balanced equation between ground and support system. Due to the uncertainty in data selection, the ground properties were classified into three categories included in. This category is based on statistical data of geological information into three categories of poor to medium, medium to good and poor.

The Monte-Carlo method is a computational algorithm that uses random sampling to calculate the results. Monte-Carlo methods are commonly used to simulate physical, mathematical, and economic systems. Because they rely on duplicate computation and false or random numbers, Monte Carlo simulations are configured to be computer-implemented, with the tendency to use Monte Carlo methods increasing when the exact answer is impossible or unjustified by the use of deterministic algorithms. Monte Carlo simulations are particularly relevant in studying systems where there are many variables or high uncertainties in their inputs (Nejati *et al*. 2012, Rubinstein and Kroese 2016). Statistical distribution of geomechanical parameters were presented in Table 4. The safety factors for each support system were simulated 1000 times by the Monte Carlo simulations and the result was displayed as a function of the long-term safety factor histogram (Fig. 5).

5. Optimization

Attainment to best results under the imposed conditions is called optimization. In designing, manufacturing and maintaining any engineering system, engineers must make decisions based on technical and management expertise. The ultimate goal of such decisions is to minimize cost and maximize profit. The cost or benefit required in each practical situation can be expressed as a function of the decision variables. Therefore, optimization can be defined as the process of finding conditions that obtain the maximum or minimum value of a function.

As mentioned, for the purpose of support systems assessment, two measures of performance and installation and conflict with operation by evaluation forms were reviewed by experts in this field and the cost per unit length criterion was adjusted by the List price and safety factor were calculated by the convergence-confinement method modified for the long term. These studies were calculated for 45 proposed support systems in three sections: poor to medium, medium to good, and poor. The results of calculations for the criteria of performance and installation and conflict with operation and cost per unit length are shown in Table 5 and the values calculated for safety factor (statistical distribution including maximum, minimum, mean, and standard deviation) for each division presented in Table 6. It should be noted that the description of each support system has a reference code, which is specified in Table 6.

5.1. Fuzzy sets and fuzzy numbers

The fuzzy set theory proposed by Lotfi Asgharzadeh in 1965 is a theory of uncertainty that can account for many of the concepts and variables and systems that are inaccurate, mathematical formulation, and control the ground for reasoning, deduction and control, thereby paving the way for decision making under uncertainty (Tsaur *et al*. 2002). One of the accepted principles in classical set theory is to state the boundaries of these sets in such a way that the membership and non-membership of an element in the set is clearly and reliably determined (Kahraman *et al*. 2002).

Any fuzzy subset A in the reference set X can be defined by the characteristic function. This function, called Membership function, assigns a number A(x) in closed interval (1, 0) to each member of the reference set X, denoting the membership degree of X in fuzzy set A. Use logical methods to express calculations The human mind prefers the exclusive use of probabilistic predictions and this attitude to irrational human behavior has led to the emergence of new studies in fuzzy decision making (Lai and Hwang 1994). The sign "~" denotes the fuzzy set. A Triangular Fuzzy Number (M) is denoted as (l, m, u). Where l, m and u represent the smallest possible value, the most probable value, and the largest possible value, respectively. Each triangular fuzzy number at the central point has the highest degree of membership and on the other side the maximum membership degree decreases linearly to reach zero as the degree of membership at each point is as follows (Kahraman *et al*. 2002).

$$\mu(x/\tilde{M}) = \begin{cases} 0, & x < l \\ (x-l)/(m-l), & l \le x \le m \\ (u-x)/(u-m), & m \le x \le u \\ 0, & x > u \end{cases} \tag{1}$$

There are several methods for converting fuzzy numbers to definite numbers, the most popular of which is the Minkowski method if, {a, b, c} F = be a triangular fuzzy number, the corresponding definite number is determined by Eq. (2) (Zammori*et al*. 2009).

$$GM(F) = \frac{a+4b+c}{6} \tag{2}$$

5.1.1 Fuzzy TOPSIS method

TOPSIS, known as one of the most classical Multi-criteria decision making (MCDM) methods, was first developed by Wang and Lee (2007), the basic concept of this method is that the chosen alternatives should have the shortest distance from the positive ideal solution and the farthest distance from negative ideal solution. In many researches, this method have been used to find the best alternative among a set of feasible choses (Yazdani-Chamzini and Haji Yakhchali 2012, Wang and Chen 2017, Mathew *et al*. 2020).

Following the introduction of the TOPSIS model and the use of fuzzy set theory, many TOPSIS fuzzy models were developed (Li 2007). Following is the solution of fuzzy TOPSIS with triangular fuzzy numbers presented by Chen (2000):

Step 1: If D is a Fuzzy decision matrix that contains n criterion (Cn to C1) and m alternative (Am to A1) and $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ is the matrix elements (based on triangular fuzzy numbers) then scalarization (normalization) The data are obtained using the following equations that result in the formation of a Fuzzy normalized decision matrix (R).

$$\tilde{D} = (\tilde{x}_{ij})_{m\times n} = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ A_1 & \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ A_2 & \tilde{x}_{11} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \cdots & \cdots & \cdots & \cdots \\ A_m & \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{matrix} \tag{3}$$

$$\tilde{R} = (\tilde{r}_{ij})_{m\times n} = \begin{matrix} & C_1 & C_2 & \cdots & C_n \\ A_1 & \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n} \\ A_2 & \tilde{r}_{11} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n} \\ \vdots & \cdots & \cdots & \cdots & \cdots \\ A_m & \tilde{r}_{m1} & \tilde{r}_{m2} & \cdots & \tilde{r}_{mn} \end{matrix} \tag{4}$$

Eqs. (5) - (6) and Eqs. (7) - (8) are used, respectively, for positive (Benefit criteria) and negative affect (Cost criteria).

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_i^{\max}}, \frac{b_{ij}}{c_i^{\max}}, \frac{c_{ij}}{c_i^{\max}}\right) \tag{5}$$

$$c_i^{\max} = \max\{c_{ij} \,|\, \tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})\} \tag{6}$$

$$\tilde{r}_{ij} = \begin{cases} \left(\frac{a_i^{\min}}{c_{ij}}, \frac{a_i^{\min}}{b_{ij}}, \frac{a_i^{\min}}{a_{ij}}\right), & a_i^{\min} \ne 0 \\ \left(1-\frac{c_{ij}}{c_i^{\max}}, 1-\frac{b_{ij}}{c_i^{\max}}, 1-\frac{a_{ij}}{c_i^{\max}}\right), & a_i^{\min} = 0 \end{cases} \tag{7}$$

$$a_i^{\max} = \min\{a_{ij} \,|\, \tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})\} \tag{8}$$

Step Two: In this step, considering the fuzzy normal

Table 5 Evaluate support systems in terms of performance score, installation and conflict with operation score and cost per unit length

System No.	Description	Cost per unit of length (IRR millions)	Performance score				Installation and conflict with operation			
			Mean	min	max	STD	Mean	min	max	STD
S1	5 cm_shot	2.55	8.94	8.25	9.75	0.36	9.47	8.75	9.50	0.06
S2	10 cm_shot	3.25	8.59	7.75	9.50	0.10	8.88	8.50	9.25	0.05
S3	15 cm_shot	6.58	7.96	6.50	9.00	0.08	8.54	8.00	10.00	0.20
S4	20 cm_shot	8.60	7.24	5.00	8.75	0.21	8.44	7.75	9.00	0.09
S5	25 cm_shot	10.61	5.97	3.25	7.50	1.38	8.14	6.25	8.50	0.82
S6	IPE140@1 m	2.92	7.77	5.75	8.50	0.55	8.63	7.75	9.75	0.09
S7	IPE180@1 m	4.26	8.49	8.25	9.50	0.32	7.80	6.75	8.75	0.21
S8	IPE240@1 m	6.95	8.10	6.25	9.50	0.42	8.16	7.75	9.75	0.60
S9	IPB140@1 m	7.63	8.10	6.25	9.75	0.45	8.00	7.75	9.75	0.85
S10	IPB180@1 m	11.60	8.09	6.50	9.00	0.04	7.59	5.75	8.00	0.10
S11	IPB240@1 m	18.84	7.82	7.00	8.75	0.99	7.28	6.00	9.75	0.41
S12	20 cmShot+IPE140@1 m	11.52	7.28	4.50	8.75	1.02	8.13	7.50	9.75	0.63
S13	25 cmShot+IPE180@1 m	14.87	8.73	7.75	9.50	0.57	7.58	5.00	8.00	1.13
S14	20 cmShot+IPB140@1 m	16.23	7.96	7.75	8.25	0.39	6.91	4.50	9.25	0.16
S15	25 cmShot+IPB180@1 m	22.21	7.19	6.50	9.50	0.49	7.04	6.75	8.50	0.41
S16	20 cmShot+IPE140@0.5 m	14.44	6.69	4.25	8.50	1.16	7.37	6.75	10.00	1.29
S17	25 cmShot+IPE180@0.5 m	19.13	8.65	7.50	9.50	0.06	7.44	7.25	7.75	0.53
S18	20 cmShot+IPB140@0.5m	23.86	7.89	7.25	9.00	0.39	6.62	6.00	10.00	1.63
S19	25 cmShot+IPB180@0.5m	33.80	6.53	5.00	7.75	0.57	5.91	5.50	6.75	2.00
S20	bolt:2 ml_1×1_Phi18 mm	1.38	6.20	4.00	9.25	0.51	8.98	8.50	9.50	0.34
S21	bolt:2 ml_1.5×1.5_Phi18 mm	0.61	8.17	7.75	9.25	0.17	9.01	8.00	9.25	0.16
S22	bolt:2 ml_2×2_Phi18 mm	0.35	7.27	5.00	9.00	0.11	8.75	8.50	9.00	0.41
S23	bolt:2 ml_1×1_Phi32 mm	8.67	6.80	6.50	7.25	0.19	9.02	8.25	10.00	0.44
S24	bolt:2 ml_1.5×1.5_Phi32 mm	3.85	8.44	8.00	9.50	0.44	9.06	8.00	9.25	0.38
S25	bolt:2 ml_2×2_Phi32 mm	2.17	7.91	7.25	8.75	0.73	8.79	8.50	9.25	0.09
S26	lattice 3bar φ 20 h 15 cm @ 1 m	1.76	7.21	4.50	9.00	0.80	8.62	7.50	9.75	0.13
S27	lattice 3bar φ 20 h 15 cm @ 0.5 m	3.52	8.14	6.25	9.50	0.39	8.36	7.75	9.50	0.15
S28	lattice 3bar φ 25 h 20 cm @ 1m	2.75	8.10	7.50	9.50	0.15	8.49	7.75	9.50	0.44
S29	lattice 3bar φ 25 h 20 cm @ 0.5 m	5.49	8.43	7.00	9.75	0.09	8.60	7.50	9.25	0.34
S30	lattice 3bar φ 20 h 15cm @ 1 m+ 20 cm Shot	10.36	8.36	7.75	10.00	0.51	8.07	7.00	9.00	0.10
S31	lattice 3bar φ 20 h 15cm @ 0.5 m + 20 cm Shot	12.12	8.92	8.50	9.50	0.36	7.92	6.75	10.00	0.83
S32	lattice 3bar φ 25 h 20cm @ 1 m + 25 cm Shot	13.43	9.09	8.25	9.50	0.14	7.87	7.75	8.25	1.01
S33	lattice 3bar φ 25 h 20cm @ 0.5 m + 25 cm Shot	16.17	9.41	9.00	9.75	0.04	7.83	7.25	8.50	0.74
S34	ARMCO t 8 mm	24.73	7.93	6.00	8.25	0.84	4.87	0.75	5.75	2.21
S35	ARMCO t 5 mm	15.46	7.87	7.25	8.75	0.69	5.15	0.25	7.00	0.99
S36	TH 21 @ 1 m	4.73	6.27	5.50	7.25	1.01	7.25	4.50	7.50	0.70
S37	TH 21 @ 0.5m	9.47	6.82	6.50	8.50	0.73	7.31	5.25	8.00	0.86
S38	TH 29 @ 1 m	6.57	6.83	5.50	8.25	0.83	7.41	6.75	7.75	1.21
S39	TH 29 @ 0.5 m	13.14	7.18	7.00	8.25	0.97	7.35	5.75	8.75	0.44
S40	bolt:2 ml_1×1_Phi18 mm+10 cmShot	4.63	7.28	5.50	9.25	1.02	9.41	8.75	9.50	0.07
S41	bolt:2 ml_1.5×1.5_Phi18 mm+10 cmShot	3.87	9.31	8.75	9.50	0.07	9.22	9.00	10.00	0.26
S42	bolt:2 ml_2×2_Phi18 mm+10 cmShot	3.60	7.53	6.00	8.00	0.27	8.92	8.50	9.25	0.14
S43	bolt:2 ml_1×1_Phi32 mm+10 cmShot	11.92	7.00	5.50	7.25	1.09	9.30	8.75	10.00	0.01
S44	bolt:2 ml_1.5×1.5_Phi32 mm+10 cmShot	7.11	9.48	9.25	9.75	0.13	9.63	9.25	10.00	0.13
S45	bolt:2 ml_2×2_Phi32 mm+10 cmShot	5.42	8.93	8.00	9.00	0.15	8.91	8.75	9.50	0.05

matrix elements ($\tilde{r}_{ij}$) and also the weight vector of the importance of the criteria ($\tilde{w}_j$) given the Eq. (9) fuzzy-weighted normalized matrix ($\tilde{V}$) is obtained.

$$\tilde{V} = (\tilde{v}_{ij})_{m\times n}, \tilde{v}_{ij} = \tilde{w}_j \otimes \tilde{r}_{ij} \tag{9}$$

Step Three: At this point we can define the ideal fuzzy positive solution (Eq. (10)) and the fuzzy negative ideal solution (Eq. (11)).

Table 6 Statistical evaluation of Support systems in terms of safety factor separately for each division

#	Division 1				Division 2				Division 3			
	Mean	σ	Min	Max	Mean	σ	Min	Max	Mean	σ	Min	Max
S1	8.96	3.66	3.44	30.36	3.48	1.07	1.02	7.49	4.11	1.13	1.61	8.27
S2	11.37	4.49	4.56	37.38	3.79	1.12	1.19	7.94	6.05	1.57	2.47	11.97
S3	13.77	5.33	5.69	44.33	4.09	1.18	1.37	8.39	7.98	2.02	3.34	15.28
S4	16.38	6.25	6.91	51.90	4.42	1.25	1.55	8.89	10.06	2.52	4.28	18.70
S5	18.78	7.11	8.03	58.93	4.72	1.31	1.72	9.33	11.98	2.99	5.15	21.86
S6	13.75	5.92	4.61	48.98	6.33	2.06	1.69	14.20	4.48	1.54	1.64	10.36
S7	14.22	6.07	4.87	50.10	6.42	2.07	1.74	14.30	4.99	1.62	1.88	10.89
S8	15.13	6.37	5.37	52.40	6.56	2.08	1.84	14.45	5.84	1.78	2.21	11.91
S9	15.42	6.47	5.54	53.35	6.61	2.09	1.86	14.51	6.11	1.83	2.31	12.25
S10	16.82	6.93	6.32	57.34	6.81	2.11	1.97	14.77	7.30	2.07	2.82	14.62
S11	19.33	7.79	7.54	64.74	7.14	2.17	2.15	15.26	9.36	2.51	3.72	18.83
S12	20.12	7.80	8.28	64.91	6.07	1.76	2.01	12.50	11.54	2.93	4.82	22.20
S13	22.96	8.81	9.61	73.08	6.42	1.83	2.21	13.02	13.81	3.48	5.84	25.95
S14	21.66	8.35	9.00	69.55	6.26	1.80	2.12	12.78	12.77	3.23	5.37	24.23
S15	25.36	9.66	10.73	80.41	6.72	1.89	2.38	13.47	15.72	3.94	6.71	29.10
S16	21.08	8.14	8.73	67.67	6.19	1.79	2.08	12.68	19.50	4.86	8.41	35.35
S17	24.35	9.30	10.26	77.13	6.60	1.87	2.31	13.28	14.92	3.74	6.34	27.79
S18	24.16	9.24	10.17	76.87	6.57	1.86	2.30	13.25	14.76	3.71	6.27	27.53
S19	29.15	11.02	12.50	91.41	7.20	1.99	2.65	14.19	18.75	4.67	8.07	34.08
S20	13.20	5.74	4.30	47.63	6.22	2.06	1.61	14.08	4.15	1.57	1.30	10.67
S21	12.93	5.66	4.09	46.81	6.17	2.06	1.56	14.00	3.58	1.49	0.87	10.13
S22	12.83	5.63	4.01	46.68	6.14	2.06	1.54	13.99	3.32	1.46	0.67	9.91
S23	14.42	6.14	4.98	50.71	6.45	2.07	1.77	14.32	5.88	1.84	2.25	12.40
S24	13.48	5.83	4.45	48.23	6.28	2.06	1.65	14.14	4.62	1.64	1.64	11.14
S25	13.14	5.73	4.26	47.35	6.21	2.06	1.60	14.05	4.04	1.56	1.23	10.57
S26	14.94	6.47	4.92	53.49	6.96	2.30	1.82	15.72	4.53	1.63	1.58	11.05
S27	15.72	6.73	5.35	55.56	7.11	2.30	1.92	15.88	5.51	1.78	2.11	12.01
S28	15.38	6.61	5.17	54.62	7.05	2.30	1.88	15.81	5.11	1.72	1.96	11.62
S29	16.60	7.01	5.85	57.72	7.26	2.32	2.02	16.06	6.43	1.94	2.45	13.01
S30	22.06	8.57	9.06	71.23	6.72	1.95	2.22	13.84	13.19	3.30	5.42	26.47
S31	22.79	8.82	9.40	73.35	6.81	1.97	2.28	13.97	13.80	3.44	5.69	27.62
S32	25.15	9.66	10.51	80.53	7.11	2.03	2.44	14.42	15.80	3.93	6.57	31.36
S33	26.29	10.07	11.04	83.47	7.25	2.05	2.53	14.64	16.77	4.16	6.99	33.14
S34	32.86	12.65	13.69	105.16	9.70	2.74	3.38	19.54	22.54	5.60	9.41	44.54
S35	30.88	11.94	12.76	99.56	9.14	2.63	3.07	18.72	18.82	4.69	7.77	37.64
S36	19.61	8.39	6.67	69.43	8.89	2.88	2.40	19.86	6.89	2.23	2.64	15.02
S37	21.55	9.03	7.76	74.62	9.20	2.91	2.60	20.23	8.82	2.56	3.36	17.18
S38	19.66	8.41	6.70	69.28	8.88	2.88	2.40	19.84	6.84	2.22	2.62	14.98
S39	21.61	9.05	7.79	74.58	9.21	2.91	2.61	20.23	8.87	2.57	3.38	17.26
S40	16.73	6.71	6.57	55.80	6.04	1.82	1.84	12.84	6.04	1.82	1.84	12.84
S41	16.43	6.61	6.43	54.91	6.00	1.81	1.82	12.78	6.00	1.81	1.82	12.78
S42	16.33	6.57	6.38	54.74	5.99	1.81	1.82	12.76	5.99	1.81	1.82	12.76
S43	18.09	7.18	7.20	59.70	6.22	1.85	1.94	13.11	6.22	1.85	1.94	13.11
S44	17.04	6.81	6.71	56.72	6.08	1.83	1.87	12.90	6.08	1.83	1.87	12.90
S45	16.67	6.69	6.54	55.50	6.03	1.82	1.84	12.84	6.03	1.82	1.84	12.84

Step Four: In order to calculate the distance of each option from the ideal positive and negative steps. The Eqs. (12) and (13) is used, respectively.

$$d_i^+ = \sum_{i=1}^{m} d(\tilde{v}_{ij}, \tilde{v}_j^+), i = 1, 2, ..., n \quad (12)$$

$$d_i^- = \sum_{i=1}^{m} d(\tilde{v}_{ij}, \tilde{v}_j^-), i = 1, 2, ..., n \quad (13)$$

It is also worth noting that the distance between two triangular fuzzy numbers $\tilde{A}$ and $\tilde{B}$ is calculated as follows(Chen 2000):

$$d(\tilde{A}, \tilde{B}) = \sqrt{(\frac{1}{3}[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2])} \quad (14)$$

Step 5: In the last step, in order to rank the options, the relative closeness index (Ci) is calculated (Eq. (15)) and so the higher the value of the index the higher the option.

Table 7 Comparison of 9 hourly quantities for binary comparisons of criteria

Definition	Points
Very little importance	1
Low importance	3
Medium importance	5
Very important	7
Too much importance	9
The importance of intermediate states	2,4,6,8

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-}, i = 1, 2, 3, ..., n \quad (15)$$

5.2 Evaluation criteria for support systems

Criteria for evaluating support systems in this study were presented in both quantitative and qualitative categories. The more positive these criteria are for a support system, the greater the preference for that support system. Criteria that have a negative impact on the support system preference decrease with increasing value of these criteria for a support system. For quantitative criteria, including long-term cost and safety factor, the cost of each support system was determined by accurate metering and estimation calculations, and the F.O.S criterion was calculated based on the convergence-adjacency method taking into account the structural life. The two criteria for ease of use and time of installation are the qualitative criteria in the evaluation, which are presented based on expert opinions (Section 4-3-Design of Reinforcement Systems) and integers ranging from 1 to 10 for support systems, such that 1 represents very low quality state and 10 represents very high quality state (Table 7). Table 8 is also used to determine the relative importance of the criteria.

Several methods have been proposed by researchers to integrate information with a fuzzy approach, which is summarized as one of the integration methods; If the fuzzy K decision-maker is as follows:

$$\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}) \quad ,i = 1, 2, 3, .., m \quad ,j = 1, 2, 3, ..., m \quad (16)$$

Where i represents the choice (Support system) i and j represent the criterion j, so the cumulative fuzzy number ($\tilde{x}_{ij}$) of the alternatives to the criteria is obtained by the following equation:

$$\begin{aligned} &\tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}) \\ &\mathrm{a}_{ij} = \min_k \{a_{ijk}\}, \mathrm{b}_{ij} = \min_k \{b_{ijk}\}, \mathrm{c}_{ij} = \min_k \{c_{ijk}\} \end{aligned} \quad (17)$$

5.3. Support system ranking by TOPSIS fuzzy method

To create a fuzzy decision matrix, taking into account the initial decision matrix (which includes definite cost estimates, factor of safety, performance, and installation and conflict), calculate the standard deviation of the data by subtracting the standard deviation from the values. The lower and upper limit for each criterion is obtained for each storage system. Fuzzy decision matrix for division 1 was reported in Table A1.

Then according to the calculated decision matrix, the ranking of support systems for 3 types of ground (Division 1-3) was calculated based on 4 criteria using TOPSIS Fuzzy method. The ranking of support systems for the three different divisions was presented in Table 9. The calculations and results for the Division 1 are attached in Table A1 to Table A4. The fuzzy decision matrix in Table A1 calculated based on Eqs. (5) to (8) of the fuzzy normal matrix (Table A2). Then considering the relative importance of the criteria based on Table A2 and also the Eq. (9) of the fuzzy weighted normal matrix (Table A3 Table).

Then, by calculating the distance of the options from the positive and negative ideal solution Eqs. (10) and (11), finally the relative closeness index Eq. (15) is determined for each support system (Table A4). Support systems are ranked in descending order (from high to low) Ci values, meaning that the higher the Ci value for a support system (close to one) Indicates the optimal case. In other words, the most optimal case of the available options is the system that has been ranked 1st. Based on similar calculations for Division 2 and 3, the results of the ranking and selection of the optimal support system are listed in Table A4.

Fig. 6 shows the results of the evaluation of tunnel support systems based on relative closeness index (Ci). On the basis of performed analysis, shotcrete protection is a suitable suggested in poor rock mass but it is not recommended to use in high quality rock masses.

Table 8 Seven spectrum of verbal variables for scoring criteria based on support systems

Linguistic Variables	Triangular Fuzzy number
Very low (VL)	(0,0, 1)
Low (L)	(0, 1, 3)
Medium low (ML)	(1, 3, 5)
Medium (M)	(3, 5, 7)
Medium high (MH)	(5, 7, 9)
High (H)	(7, 9, 10)
Very high (VH)	(9, 10, 10)

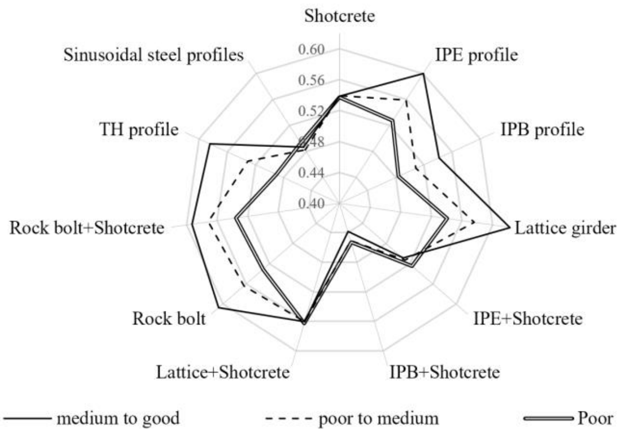


Fig. 6 Evaluation of different classes of tunnel reinforcement systems according to average of relative closeness index (Ci)

Table 9 Ranking of support systems by different geology classes

System No.	Div. 1	Div.2	Div.3
S1	13	22	7
S2	15	23	5
S3	25	30	15
S4	29	36	25
S5	40	41	32
S6	19	13	23
S7	16	11	19
S8	23	19	28
S9	24	20	30
S10	36	31	38
S11	42	37	44
S12	30	33	29
S13	31	35	26
S14	39	39	35
S15	41	42	40
S16	38	38	9
S17	37	40	31
S18	43	43	43
S19	45	45	45
S20	20	14	24
S21	3	1	10
S22	11	9	21
S23	33	27	36
S24	7	5	13
S25	8	6	17
S26	12	7	22
S27	6	4	14
S28	4	2	11
S29	9	8	16
S30	17	24	3
S31	18	25	4
S32	21	28	2
S33	22	29	6
S34	44	44	42
S35	32	34	27
S36	27	17	37
S37	28	21	34
S38	26	15	33
S39	34	26	39
S40	10	16	18
S41	1	3	1
S42	14	18	20
S43	35	32	41
S44	2	10	8
S45	5	12	12

Furthermore, rock bolt system is the most appropriate system for reinforcing the under study tunnel. The 1.5 × 1.5 pattern is the best layout for rock bolts and the combining shotcrete with rock bolt is very efficient on low quality environment.

6. Conclusions

This study was conducted to optimize the tunnel support system in Iran Railway Network. South Tehran Railway axis was selected as the case study and after study of this route tunnel No. 68 (Keshvar tunnel) was selected as a control sample due to differences in geomechanical properties variation. These Tunnels categorize to 3 classes: poor to medium (Division 1), medium to good (Division 2), and poor (Division 3).

45 support systems were designed for all three classes and calculated according to the modified convergence-confinement method for long-term Factor of Safety values. Scores of performance and installation and conflict of the support systems were assessed from experts and the cost required estimated. The optimization of support systems was performed by the TOPSIS algorithm. The proposed systems in order of preference are as follows:

- In tunnels with poor to medium environments:
  1) Rock bolts with diameter of 18 mm in of 1.5 × 1.5 m^2 pattern with 10 cm shotcrete.
  2) Rock bolts with diameter of 18 mm in of 1.5 × 1.5 m^2 pattern with 10 cm shotcrete.
  3) Rock bolts with diameter of 18 mm in of 1.5 × 1.5 m^2 pattern
- In tunnels with medium to good environments:
  1) Rock bolts with diameter of 18 mm in of 1.5 × 1.5 m^2 pattern
  2) Lattice girder with 3 bars by 25 mm diameter and height of 20 cm and in 1m steps
  3) Rock bolts with diameter of 18 mm in of 1.5 × 1.5 m^2 pattern whit 10 cm shotcrete.
- In tunnels with poor environments:
  1) Rock bolts with diameter of 18 mm in of 1.5 × 1.5 m^2 pattern whit 10 cm shotcrete.
  2) Lattice girder with 3 bars by 25 mm diameter and height of 20 cm and in 1m steps with 25 cm shotcrete.
  3) Lattice girder with 3 bars by 20 mm diameter and height of 15 cm and in 1m steps with 25 cm shotcrete.
- The use of shotcrete alone is suggested in poor environments but it is not recommended to use it in high quality rock masses.
- Rigid steel profiles (IPB and IPE) are more acceptable in medium to good grounds with wedge discontinuities and tend to use lighter Profiles.
- Lattice girder is one of the best reinforcing systems, and its combination with shotcrete has good results, but combining steel profiles with shotcrete is not a priority.
- According to the results of the optimization, a systematic 1.5 × 1.5 rock bolt pattern is the most appropriate system for reinforcement of the under study tunnel. In the section with low quality rock mass, composite system of shotcrete and rock bolt will be an efficient reinforcement.

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