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A New Approach for Determination of Tunnel Supporting System Using Analytical Hierarchy Process (AHP)

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A NEW APPROACH FOR DETERMINATION OF TUNNEL SUPPORTING SYSTEM USING ANALYTICAL HIERARCHY PROCESS (AHP)

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ABSTRACT: In underground mining, the selection of support system for mine tunnel development plays a significant role in safety and economics of operations. Traditionally, such selection is on the basis of the experience of the design engineer. Nevertheless, the validity of such selection is questionable. A new approach for selecting the optimum tunnel support system based on Analytical Hierarchy Process (AHP) is proposed. In this new approach, the selection of the tunnel support system is considered as a multi criteria decision-making problem. Firstly, by using the numerical Finite Difference Method (FDM), based on technical and stability parameters of the tunnel, different support systems are specified. Then, by considering the economics and performance indices of each support system, a decision tree based on AHP model is generated and the optimum support system is selected. As a field study, the method is applied to Tabas collieries in Iran. It is concluded that the proposed support system determination is advantageous compared to other alternatives. Therefore, the proposed approach can assist the engineer in selection of optimum tunnel support system in different underground mining situations.

INTRODUCTION

In many cases, the support system for tunnel construction is selected based on the experience of the design engineer, hence personal judgment is often the main basis in stead of intellectual and scientific criteria (Oraee K., 2001). There are various support systems for any particular situation but the selection of the optimum system depends on many technical and economical parameters.

The main aim of this study is to select proper support system by using the AHP model. As a field study, this technique was applied to tunnel C1, which is one of the main entries in various Tabas coalfield mines, which is located in the central part of Iran. Due to being a large reserve and of regular geometry of the coal seams, coal is mined by mechanized longwall mining. This method requires excavation of several tunnels; some must be stable for long time and even during entire life of the mine. Therefore, the selection of appropriate tunnel support system is an important aspect of tunnel construction.

GEOMECHANICAL PROPERTIES OF TABAS COAL FIELD

The validity of numerical modelling and the results of model analysis are dependent on the determination of the geomechanical parameters of surrounding rock mass. Hence, by field studies and existing technical reports (Hosseini Navid, 2008) the geomechanical properties of tunnel rock mass is collected. Based on laboratory and field data, the uniaxial compressive strength of surrounding rock mass of the tunnel is 10.7 MPa, and the obtained tensile strength, based on Brazilian test, is 1.3 MPa. The Young's modulus and Poisson's ratio are 4385 MPa and 0.25, respectively. Based on the triaxial compressive test results, the resultant friction angle is 35 degree and cohesion of rock mass is 5 MPa. The geomechanical parameters of rock mass are shown in Table 1.

Table 1: Geomechanical parameters of rock mass (Hosseini Navid, 2008)

σ_c	σ_t	E	ν	φ	C
10.7 MPa	1.3 MPa	4385 MPa	0.25	35 Deg.	5 MPa

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MODELING THE BEHAVIOR PARAMETERS OF SUPPORT SYSTEM

In this study, the states of various support systems (Hosseini Navid, 2008; Oraee K., 2005) were analysed by using numerical modelling. The defaulted mechanical properties of each support system such as Young's modulus, Poisson's ratio, bulk modulus and rigidity modulus for steel sets and rock bolts were defined according to relevant standards. In addition, the Young's modulus of shotcrete can be calculated by equation 1.

$$E = A.\sigma_b^n \tag{1}$$

Where *E* is the Young's modulus of shotcrete (MPa), σ_b s the concrete uniaxial compressive strength (MPa), and *A* and *n* are statistical constants, which depend on the cementation degree and compressive strength characteristics. Base on engineering judgment and long-term of the tunnel life (Oraee K., 2005) *A* and *n* are selected as 6500 and 0.5 respectively.

THE STATE OF IN-SITU STRESSES

In-situ stresses are one of important effective parameters on the state of tunnel support system. For the analysis of the support system state in numerical model the magnitude and direction of in-situ stresses in modelling must be defined. The in-situ stresses are calculated by using equation 2 and 3.

$$\sigma_V = \gamma.h \tag{2}$$

$$\sigma_H = \frac{v}{1-v}\sigma_V \tag{3}$$

Where σ_V and σ_H are the vertical and horizontal in-situ stress, respectively, γ is the average density of overlying strata, *h* is the depth below ground surface and *v* is the Poisson's ratio. Based on existing data (Hosseini Navid, 2008), the vertical and horizontal in-situ stresses are 17.4 MPa and 5.1 MPa, respectively.

NUMERICAL MODELING AND SUPPORT SYSTEM SELECTION

In this study, FLAC^{3D} software (Itasca, 2002) was used for modelling. FLAC^{3D} is a numerical code, based on three-dimensional finite difference method, which has comprehensive usage in rock mechanics engineering study.

For modelling, the tunnel geometry was defined in FLAC^{3D} software as the first step. Then, the geomechanical properties of tunnel surrounding rock mass like, Young's modulus, Poisson's ratio, bulk modulus, rigidity modulus and also compressive strength, tensile strength, internal friction angle, density and cohesion were input in the model. Consequently, the behaviour of tunnel surrounding rock mass by FLAC^{3D} was analysed and the potential of failure and displacement was calculated. In the next stage, the various support systems were applied and the mechanical state of the tunnel after applying each support system was determined. Based on this modelling, the proper support system was selected from technical viewpoint. The grid model of FLAC^{3D} is shown in Figure 1.

To analyse the support system capability, four critical points were selected according to Figure 2. As can be seen in the figure, point 1 is at tunnel roof; point 2 at tunnel floor and points 3 and 4 are locating at the wall and floor intersections of, horizontal and vertical directions, respectively.

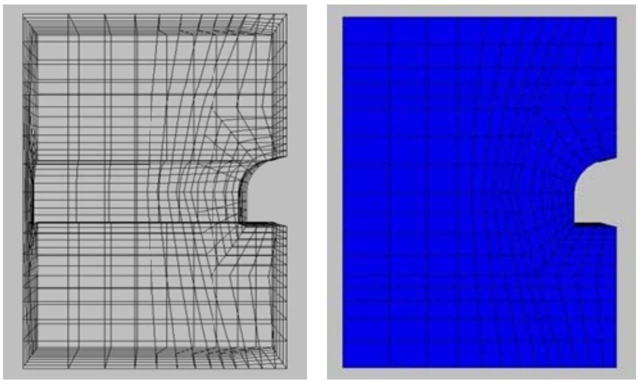

Figure 1 - Grid 3D model of tunnel

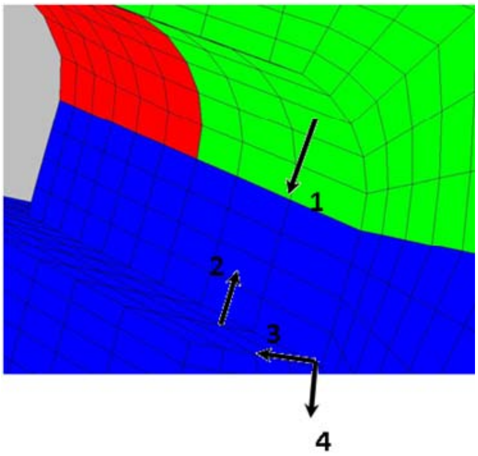

Figure 2 - Selected critical points at tunnel

In total 10 different support systems (Oraee K., 2005) were applied in model and the stability state for each support system was analysed as presented in Table 2.

Table 2 - Studied support systems with index

No.	Support system explanation	Index
1	Supporting by B40 shotcrete 5 cm in thickness	A
2	Supporting by B40 shotcrete 8 cm in thickness	B
3	Supporting by B40 shotcrete 8 cm in thickness together with rockbolt	C
4	Application of roof piping together cement injection	D
5	Application of rockbolt to the gallery roof and sides	E
6	Application of steel arches with 1m spacing	F
7	Application of steel arches with 0.5 m spacing	G
8	Supporting by B50 shotcrete 5 cm in thickness	H
9	Supporting by B50 shotcrete 8 cm in thickness	I
10	Application of steel arches with 1 m spacing together with rockbolt	J

After the applying the support system, the displacement state of tunnel's surrounding rock mass, was determined at the four points as depicted in Figure 2. The maximum stress at the tunnel surrounding was also estimated. Based on the above results and the maximum pressure of support system, the safety factor for each support system was calculated. Displacement at these four points and safety factor are shown in Table 3.

Table 3 - Results of numerical model

Model index	Displacement at point (cm)				The maximum stress on tunnel circumference (MPa)	Safety factor
	1	2	3	4		
A	11.51	26.82	12.25	4.03	36.44	1.04
B	8.92	24.00	11.03	2.08	29.93	1.47
C	1.89	3.72	1.33	0.50	24.75	2.32
D	2.10	3.92	1.02	0.43	23.73	2.44
E	10.30	23.36	8.19	5.11	29.47	1.15
F	4.14	6.35	4.12	3.19	22.82	1.79
G	2.81	3.63	1.30	0.61	25.70	2.13
H	10.62	25.11	11.83	3.29	35.61	1.25
I	8.13	23.91	10.09	2.01	30.04	1.59
J	3.50	4.01	2.61	0.82	25.11	2.28

As, the minimum acceptable factor of safety is two (2), for this result, the four support systems of C, D, G and J are the only accepted from technical viewpoint. Therefore, the final optimum support system will be selected from one of them.

Consequently, based on experience and viewpoints of expert engineers the decision criterions should be determined for the selection of the proper support system (Yavuz M., Iphar M., Once G., 2007). The considered decision criterions for the selection of the proper support system are given in Table 4.

Table 4 - Considered decision criterions for proper support system selection

No.	Criterions explanation	Index
1	The vertical displacement at point 1	C1
2	The vertical displacement at point 2	C2
3	The vertical displacement at point 3	C3
4	The horizontal displacement at point 3	C4
5	The support system costs	C5
6	The support system performance	C6
7	Safety factor	C7

THE HIERARCHY DESIGN

After determination of goal, options and criterions the hierarchy tree of AHP model (Saaty T.L., 1980) were designed. placed in the first level of hierarchy, is the goal, which is support system selection. In second level, is criterions and in the third level, options are arranged. The hierarchy designed for this study is presented in Figure 3.

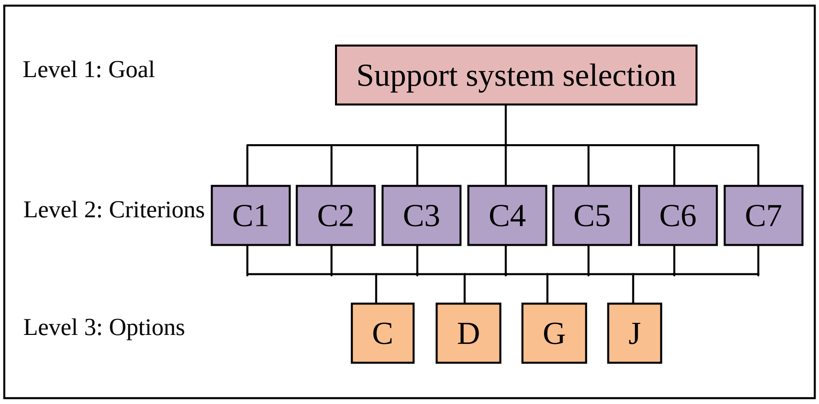

Figure 3 - Hierarchy designed for proper support system selection

Among the ten support systems studied, four were technically acceptable and were arranged in level 3, as options.

Generally, in AHP model the elements of each level with its respective element in above level are compared as pair-wise, and therefore the local priority are calculated. Then, with assimilating the local priorities, overall priority was calculated. As expressed, in AHP model all comparisons were pair-wise and based on oral judgments that expressed by Preference values as mentioned in Table 5.

In this stage, the relative weight of each support system must be determined by the mathematical mean method (Amirafshari M., Qolinejad Mehran., Hosseini Navid, 2005). The pair-wise comparison of acceptable support systems (C, D, G and J), the summation weights matrix, and the average weights matrix of each rows, all based on criterion C1 are shown in Tables 6, 7 and 8, respectively.

Table 5 - Preference values for pair-wise comparison (Saaty T.L., 1980)

Oral judgments	Numeral value
Extremely preferred	9
Very strongly preferred	7
Strongly preferred	5
Moderately preferred	3
Equally preferred	1
Intermediate values	2, 4, 6 and 8

Table 6 - The pair-wise comparison of support system based on criterion C1

	C	D	G	J
C	1.00	3.00	5.00	7.00
D	0.33	1.00	4.00	6.00
G	0.20	0.25	1.00	5.00
J	0.14	0.17	0.20	1.00

Table 7 - Summation weights matrix based on criterion C1

	C	D	G	J
C	1.00	3.00	5.00	**7.00**
D	0.33	1.00	4.00	**6.00**
G	0.20	0.25	1.00	**5.00**
J	0.14	0.17	0.20	**1.00**
Summation of each columns	**1.68**	**4.42**	**10.20**	**19.00**

Table 8 - Average weights matrix of each rows based on criterion C1

	C	D	G	J	The average of each rows
C	0.60	0.68	0.49	0.37	**0.53**
D	0.20	0.23	0.39	0.32	**0.28**
G	0.12	0.06	0.10	0.26	**0.13**
J	0.09	0.04	0.02	0.05	**0.05**
Summation of each columns	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Similarly, for criterions C2 to C7 the pair-wise comparison of support system were constructed, then the summation weights matrix and also the average weights matrix of each rows based on criterion C2 to C7 were calculated as shown in Tables 9 to 26, respectively.

Table 9 - The pair-wise comparison of support system based on criterion C2

	C	D	G	J
C	1.00	0.50	0.20	0.14
D	2.00	1.00	0.33	0.50
G	5.00	3.00	1.00	0.13
J	7.00	2.00	8.00	1.00

Table 10 - Summation weights matrix based on criterion C2

	C	D	G	J
C	1.00	0.50	0.20	0.14
D	2.00	1.00	0.33	0.50
G	5.00	3.00	1.00	0.13
J	7.00	2.00	8.00	1.00
Summation of each columns	**15.00**	**6.50**	**9.53**	**1.77**

Table 11 - Average weights matrix of each rows based on criterion C2

	C	D	G	J	The average of each rows
C	0.07	0.08	0.02	0.08	**0.06**
D	0.13	0.15	0.03	0.28	**0.15**
G	0.33	0.46	0.10	0.07	**0.24**
J	0.47	0.31	0.84	0.57	**0.54**
Summation of each columns	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table 12 - The pair-wise comparison of support system based on criterion C3

	C	D	G	J
C	1.00	3.00	2.00	0.50
D	0.33	1.00	0.50	0.17
G	0.50	2.00	1.00	0.25
J	2.00	6.00	4.00	1.00

Table 13 - Summation weights matrix based on criterion C3

	C	D	G	J
C	1.00	3.00	2.00	0.50
D	0.33	1.00	0.50	0.17
G	0.50	2.00	1.00	0.25
J	2.00	6.00	4.00	1.00
Summation of each columns	**3.83**	**12.00**	**7.50**	**1.92**

Table 14 - Average weights matrix of each rows based on criterion C3

	C	D	G	J	The average of each rows
C	0.26	0.25	0.27	0.26	**0.26**
D	0.09	0.08	0.07	0.09	**0.08**
G	0.13	0.17	0.13	0.13	**0.14**
J	0.52	0.50	0.53	0.52	**0.52**
Summation of each columns	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table 15 - The pair-wise comparison of support system based on criterion C4

	C	D	G	J
C	1.00	3.00	0.50	0.25
D	0.33	1.00	0.20	0.13
G	2.00	5.00	1.00	0.33
J	4.00	8.00	3.00	1.00

Table 16 - Summation weights matrix based on criterion C4

	C	D	G	J
C	1.00	3.00	0.50	0.25
D	0.33	1.00	0.20	0.13
G	2.00	5.00	1.00	0.33
J	4.00	8.00	3.00	1.00
Summation of each columns	**7.33**	**17.00**	**4.70**	**1.71**

Table 17 - Average weights matrix of each rows based on criterion C4

	C	D	G	J	The average of each rows
C	0.14	0.18	0.11	0.15	**0.14**
D	0.05	0.06	0.04	0.07	**0.06**
G	0.27	0.29	0.21	0.20	**0.24**
J	0.55	0.47	0.64	0.59	**0.56**
Summation of each columns	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table 18 - The pair-wise comparison of support system based on criterion C5

	C	D	G	J
C	1.00	0.17	0.25	3.00
D	6.00	1.00	2.00	9.00
G	4.00	0.50	1.00	5.00
J	0.33	0.11	0.20	1.00

Table 19 - Summation weights matrix based on criterion C5

	C	D	G	J
C	1.00	0.17	0.25	3.00
D	6.00	1.00	2.00	9.00
G	4.00	0.50	1.00	5.00
J	0.33	0.11	0.20	1.00
Summation of each columns	**11.33**	**1.78**	**3.45**	**18.00**

Table 20 - Average weights matrix of each rows based on criterion C5

	C	D	G	J	The average of each rows
C	0.09	0.09	0.07	0.17	**0.11**
D	0.53	0.56	0.58	0.50	**0.54**
G	0.35	0.28	0.29	0.28	**0.30**
J	0.03	0.06	0.06	0.06	**0.05**
Summation of each columns	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table 21 - The pair-wise comparison of support system based on criterion C6

	C	D	G	J
C	1.00	0.50	5.00	3.00
D	2.00	1.00	8.00	6.00
G	0.20	0.13	1.00	0.33
J	0.33	0.17	3.00	1.00

Table 22 - Summation weights matrix based on criterion C6

	C	D	G	J
C	1.00	0.50	5.00	3.00
D	2.00	1.00	8.00	6.00
G	0.20	0.13	1.00	0.33
J	0.33	0.17	3.00	1.00
Summation of each columns	**3.53**	**1.79**	**17.00**	**10.33**

Table 23 - Average weights matrix of each rows based on criterion C6

	C	D	G	J	The average of each rows
C	0.28	0.28	0.29	0.29	**0.29**
D	0.57	0.56	0.47	0.58	**0.54**
G	0.06	0.07	0.06	0.03	**0.05**
J	0.09	0.09	0.18	0.10	**0.12**
Summation of each columns	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table 24 - The pair-wise comparison of support system based on criterion C7

	C	D	G	J
C	1.00	2.00	0.25	0.33
D	0.50	1.00	0.17	0.25
G	4.00	6.00	1.00	3.00
J	3.00	4.00	0.33	1.00

Table 25 - Summation weights matrix based on criterion C7

	C	D	G	J
C	1.00	2.00	0.25	0.33
D	0.50	1.00	0.17	0.25
G	4.00	6.00	1.00	3.00
J	3.00	4.00	0.33	1.00
Summation of each columns	**8.50**	**13.00**	**1.75**	**4.58**

Table 26 - Average weights matrix of each rows based on criterion C7

	C	D	G	J	The average of each rows
C	0.12	0.15	0.14	0.07	**0.12**
D	0.06	0.08	0.10	0.05	**0.07**
G	0.47	0.46	0.57	0.65	**0.54**
J	0.35	0.31	0.19	0.22	**0.27**
Summation of each columns	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

In fact, the last columns in average weights matrix tables (Tables 8, 11, 14, 17, 20, 23 and 26) shows the relative directions vector for support system options based on criterions. Therefore, the weights of support system options relative to criterions are shown in Table 27.

Table 27 - Weights of support system options relation to criterion

	C1	C2	C3	C4	C5	C6	C7
C	0.53	0.06	0.26	0.14	0.11	0.29	0.12
D	0.28	0.15	0.08	0.06	0.54	0.54	0.07
G	0.13	0.24	0.14	0.24	0.30	0.05	0.54
J	0.05	0.54	0.52	0.56	0.05	0.12	0.27

After determination of support system options weight relative to criterions, consideration was given next to the pair-wise comparison of criterions. In other word, the role and share of each criterion in the selection of the proper support system should be understood. For this purpose, the criterions must be compared as pair-wise. The results are given in Table 28.

Table 28 - The pair-wise comparison of criterions relative to itself

	C1	C2	C3	C4	C5	C6	C7
C1	1.00	0.50	0.33	0.20	2.00	2.00	4.00
C2	2.00	1.00	0.50	0.25	5.00	3.00	3.00
C3	3.00	2.00	1.00	0.33	7.00	3.00	5.00
C4	5.00	4.00	3.00	1.00	8.00	5.00	9.00
C5	0.50	0.20	0.14	0.13	1.00	0.50	2.00
C6	0.50	0.33	0.33	0.20	2.00	1.00	3.00
C7	0.25	0.33	0.20	0.11	0.50	0.33	1.00

Similarly, the summation weights matrix and the average weights matrix were calculated and the results are shown in Tables 29 and 30, respectively.

Table 29 - Summation weights matrix of criterions

	C1	C2	C3	C4	C5	C6	C7
C1	1.00	0.50	0.33	0.20	2.00	2.00	4.00
C2	2.00	1.00	0.50	0.25	5.00	3.00	3.00
C3	3.00	2.00	1.00	0.33	7.00	3.00	5.00
C4	5.00	4.00	3.00	1.00	8.00	5.00	9.00
C5	0.50	0.20	0.14	0.13	1.00	0.50	2.00
C6	0.50	0.33	0.33	0.20	2.00	1.00	3.00
C7	0.25	0.33	0.20	0.11	0.50	0.33	1.00
Summation of each columns	**12.25**	**8.37**	**5.51**	**2.22**	**25.50**	**14.83**	**27.00**

Table 30 - Average weights matrix of each row

	C1	C2	C3	C4	C5	C6	C7	The average of each rows
C1	0.08	0.06	0.06	0.09	0.08	0.13	0.15	**0.09**
C2	0.16	0.12	0.09	0.11	0.20	0.20	0.11	**0.14**
C3	0.24	0.24	0.18	0.15	0.27	0.20	0.19	**0.21**
C4	0.41	0.48	0.54	0.45	0.31	0.34	0.33	**0.41**
C5	0.04	0.02	0.03	0.06	0.04	0.03	0.07	**0.04**
C6	0.04	0.04	0.06	0.09	0.08	0.07	0.11	**0.07**
C7	0.02	0.04	0.04	0.05	0.02	0.02	0.04	**0.03**
Summation of each columns	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

In fact, the last column of Table 30 is the total utilization vector, as follow:

$$(0.09, 0.14, 0.21, 0.41, 0.04, 0.07, 0.03) \quad (4)$$

By multiplying this vector in matrix of Table 27, the final weight of each support system options were obtain. Therefore:

The weight of C:

$$(0.53 \times 0.09) + (0.06 \times 0.14) + (0.26 \times 0.21) + (0.14 \times 0.41) + (0.11 \times 0.04) + (0.29 \times 0.07) + (0.12 \times 0.03) = 0.1964$$

The weight of D:

$$(0.28 \times 0.09) + (0.15 \times 0.14) + (0.08 \times 0.21) + (0.06 \times 0.41) + (0.54 \times 0.04) + (0.54 \times 0.07) + (0.07 \times 0.03) = 0.1491$$

The weight of G:

$$(0.13 \times 0.09) + (0.24 \times 0.14) + (0.14 \times 0.21) + (0.24 \times 0.41) + (0.30 \times 0.04) + (0.05 \times 0.07) + (0.54 \times 0.03) = 0.2048$$

The weight of J:

$$(0.05 \times 0.09) + (0.54 \times 0.14) + (0.52 \times 0.21) + (0.56 \times 0.41) + (0.05 \times 0.04) + (0.12 \times 0.07) + (0.27 \times 0.03) = 0.4374$$

By arranging the final weight of support system options, the preferences of support systems options are demonstrated in Table 31.

Table 31 - Preference of support system options

preference	Support system	Final weight
1	J	0.4374
2	G	0.2048
3	C	0.1964
4	D	0.1491

Based on the result of AHP model, option J, i.e., application of steel arches with 1 m spacing together with rockbolt is the most preference option. In sequence, option G (application of steel arches with 0.5 m spacing), option C (supporting by B40 shotcrete 8 cm in thickness together with rockbolt), and option D (application of roof piping together cement injection), are the next preference, respectively.

CONCLUSIONS

This study shows that the AHP model is an adequate technique for selection of tunnel support system. Usually the system selection based on experience with consideration of the many decision criterions not only is confusing task, but also the share of each criterion in final selection is not well understood. However, the organization problem based on AHP model can result to valuable decision criterion. In this study, among the technical viewpoint acceptable options, the option J, i.e., application of steel arches with 1 m spacing together with rockbolt was selected. Combined of steel arches with rockbolt provides the stability and reduce the costs of support system as well. Of course, before the usage of the AHP model, for safety factor determination, the support system should be analysed based on empirical, analytical or numerical conventional methods. However, based on this case study, it is concluded that the combination of the numerical model for determination of safety factor and the AHP model for preferential, is a suitable approach in selection of main tunnel support system.

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