Designing and Optimizing Support System - Case Study Tabriz of Metro Single Tunnel

A.H. Ghazvinian
K. Goshtasbi
N. Ghasempour

Tabriat Modares university,
Mining Engineering Department, Iran
E-mail: abdolhadi@yahoo.com

ABSTRACT

The designers need engineering judgment to select the optimum option among the alternatives. The optimum choice can be selected by the expert engineers taking into account their judgment and immediate insight. Nowadays, decision-making methods can help engineers to support their decision in the scientific way. The Analytical Hierarchy Process (AHP) is a decision making method and is a branch of multi attribute decision-making (MADM) methods utilizing structured pair-wise comparisons. This paper presents an application of the AHP method to the selection of the optimum support design for the Tabriz Urban Railway(TUR) tunnel line no 2, which has been planned for transporting passengers from vali-Asr Square to Gharamalek State in Tabriz, Iran. The methodology considers five main objectives, namely: displacements in the roof and bottom of the tunnel, the factor of Safety (FOS), the economic and possibility factor for the selection of support design. The displacements and stress values were obtained by using the finite difference program, FLAC^{3D} as the numerical studies have been widely used by the engineers examining the response of any opening in underground, in advance. After carrying out numerical models for different support design, the AHP method was incorporated to evaluate these support designs according to the pre-determined criteria. The result of this study shows that the AHP application is a good tool to effectively evaluate the support system alternatives for underground cavities.

Keywords: Analytical hierarchy process; Support design; Numerical modeling; FLAC^{3D}

1. INTRODUCTION

The city of Tabriz is located in the North-West of Iran and is the capital of East Azerbaijan province. It has about 1.5 million population and a floating population of 1.8 million travels inside the city. Line 2 of Tabriz metro project was started to develop railway transport system in this city to handle about 30% of these passengers. Line 2 of Tabriz metro connects the north-west of the city to the east-north by underground and surface railway. Tabriz has complex geological condition. The city is formed on third and forth geological periods.

Considering the geological study, two main different zones could be specified. The gray and the red zones are formed on south and the north part of Tabriz relatively as shown in figure 1. On the contrary of old ground, surface layer of the city is very young and includes Sand and Marl and Clay stone layers from surface to 30 meter depth. Tunnelling in such a soft ground is not easy and needs work of high quality.

The aim of this paper is to prepare a methodology for design and optimize lining of urban usage tunnels. The AHP techniques have been used for a variety of mining and civil projects in decision-making. All of the AHP applications are as early as 10 years. It is a modern decision making method which is developing in all field of engineering. The AHP method is explained in section 3. Numerical models are offered and the procedure of segmental lining design is briefly expressed. The design of lining in this paper is not a detailed design with exact geometrical and concrete grain size. But it is pre-design lining on which final lining could be expanded based on optimized lining. The most important criteria for support system design of the Tabriz metro tunnels are to estimate the values of stress distributions, displacements and failure zones in critical sections. Therefore, FLAC^{3D} software is used to estimate displacement in the top and bottom of tunnel. Behavior of lining is studied using this software. In order to obtain the results realistically, geotechnical parameters of the ground must be determined precisely. After conducting several numerical analyses, finally the AHP method was used optimizing lining design. Thus different support designs are evaluated by using the AHP method.

This paper focuses on the application of AHP for the selection of optimum support system design. Also it explains the AHP approach and gives a case study realized on the selection of optimum tunnel support design for Tabriz railway system.

Fig. 1 - Two main zone of the Tabriz city

2. GEOTECHNICAL STUDY

The geotechnical structure of the site has been investigated and the geotechnical properties of the formation, in which the tunnel will be driven, have been determined by experimental studies and by also utilizing the geotechnical report prepared by Rahvar Engineering Group (2008). The formations passed through the depth of the drillings are shown in Fig. 2.

This tunnel has diameter of 9.15 metes and overburden of 13.47 meter. The tunnel is located in marl and the surrounding soil has been assumed as marl in the model analyses since the thickness is enough to cover the whole of tunnel as seen in Fig. 2.

The success of the numerical modelling of underground cavities depends on precise values of the geotechnical parameters. The Young's modulus and the Poisson's ratio of marl were found as 40 MPa and 0.31 respectively. In three trixial tests, it was determined that marl has a friction angle of 28° and a cohesion value of 35 KPa [10].

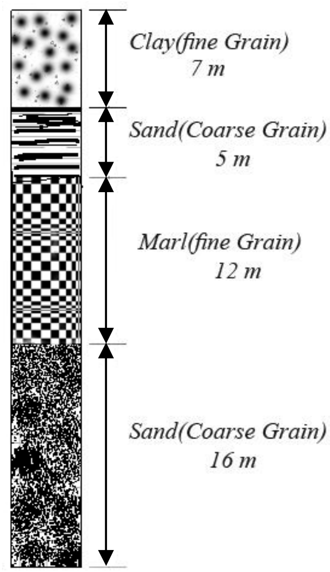

Fig. 2 - A borehole section of Tabriz formation

The mechanical properties of the support system are Young's modulus, Poisson's ratio, bulk modulus and shear modulus which should be introduced to program as default. In situ stresses have been calculated by using the following equations. Field stresses were introduced to the program for vertical and lateral stresses as 0.149 MPa on the top of tunnel.

$$\sigma_z = \gamma h \tag{1}$$

$$\sigma_x = \sigma_y = \frac{\sigma_z}{\frac{1}{\upsilon} - 1} \tag{2}$$

Where σ_z, is the vertical stress, γ is the density of soil, h is the depth, σ_x and σ_y are the lateral stresses and ν is the Poisson's ratio.

3. ANALYTICAL HIERARCHY PROCESS

Multi criteria decision making (MCDM) is widely used in any field of engineering to select best alternative considering effective parameters. There are two main aspects in MCDM including Multi-Objective Decision Making (MODM) and Multi-Attribute Decision Making (MADM). The AHP is a part of the MADM methods based on bipolar scale.

The AHP method was incorporated to the selection of open cast mining equipment in 2002 (Samanta et al., 2002). Also, the AHP was used to analyze different mining scenarios such as drilling technology investment analysis, ground support design, tunnelling systems design, shaft location selection, mine planning risk assessment by Kazakidis et al. (2004) and to comparing two different excavation alternatives, micro tunnelling and trench excavation for an urban sewer construction project in civil projects (Bottero and Peila, 2005). Chen and Liu (2007) presented a new methodology for evaluation and classification of rock mass quality that can be applied to rock tunnelling. They offered an evaluation model based on combing the analytical hierarchy process (AHP) and the fuzzy Delphi method (FDM) for assessing the rock mass. Pan (2008) worked at the project where contractor wanted to determine the most appropriate excavation construction alternative among four choices, slurry wall, sheet pile, bored pile, and soldier pile. Also Sasmal and Ramanjaneyulu (2008) developed a systematic procedure and formulations for condition evaluation of existing bridges using analytical hierarchy process in a fuzzy environment. This review shows that the AHP is a new and modern decision making system and also engineers used it widely in recent years.

To optimize an object in operation research problems, we need to have an objective function which includes all effective parameters. After making this function, the AHP method is used to optimize this function. All effective parameters include the first relative measurement and the second absolute measurement. In relative measurement, each alternative is compared with many other alternatives and in absolute measurement each alternative is compared with one ideal alternative we know of or can imagine, a process we call rating alternatives (Saaty and Ozdemir, 2003). After rating both of criteria and alternatives, the value of object function is obtained for every alternative. Final judgment is based on these values. Here we offer the procedure of this method step by step.

3.1 Stating the Problem

In the first stage of the deciding process, the objectives of the problem, alternatives and influenced criteria must be determined. Then structure of the problem is made in a hierarchy of different levels constituting goal, criteria, sub-criteria and alternatives. For case of TUR, it was concluded that the ‘‘A, B, C, D and E’’ alternatives should be evaluated and included in the decision process. It was planned to evaluate these selected alternatives in terms of displacements at top and bottom of tunnel, FOS, economic factor and possibility criteria named as C_1 to C_5. The smallest value of FOS is determined as 3 by the expert team. To support this tunnel a segmental lining will be used because of many advantages. There are five main alternatives to support this tunnel as shown in Table 1.

During the numerical modeling, the tunnel was stabilized by using each support system. Fig. 3 shows a scheme of support system selection for TUR line 2 tunnels.

3.2 Rating

The AHP, since its invention, has been a tool at the hands of decision makers and researchers. This is a value of eigenvector approach to the pair-wise comparisons. It also provides a methodology to calibrate the numerical scale for the measurement of quantitative as well as qualitative performances. This requires n (n-1)/2 comparisons, where n is the number of elements with the considerations that diagonal elements are same or equal to 1 and the other elements will simply be the reciprocals of the earlier comparisons. We must use integer values for the comparisons (Saaty, 2000). The scale ranges from 1–9 for least valued, to 1, and to 9 for absolutely most important - covering the entire spectrum of the comparison. The fundamental scale used for this purpose is shown in Fig. 4. The numbers 3, 5, 7, and 9 correspond to the verbal judgments “moderately more dominant”, “strongly more dominant”, “very strongly more dominant”, and “extremely more dominant” (with 2, 4, 6, and 8 for compromise between the previous values) (Saaty and Ozdemir, 2003). Zero and ten values are not used in this method. When two cases are the same this comparison takes 1 value. In this scale, the value of 9 means the evidence favoring one over another is of the highest possible order of affirmation. Negative criteria have negative sign in objective function and have bad effect on the main aim for example displacement of tunnel bottom. When one rates alternatives, they must be independent of one another. The presence or absence of an alternative must have no effect on how one rates any of the others (Saaty, 2004).

Table 1 - Support system alternatives

Alternative	Steel type	Lining thickness	Bar arrangement
A	S-400	40 cm	16Φ16
B	S-400	35 cm	16Φ18
C	S-300	40 cm	16Φ20
D	S-300	35 cm	14Φ18
E	S-400	40 cm	14Φ20

Criteria	Description
C_1	displacements at top of tunnel
C_2	displacements at bottom of tunnel
C_3	FOS
C_4	economic factor
C_5	possibility

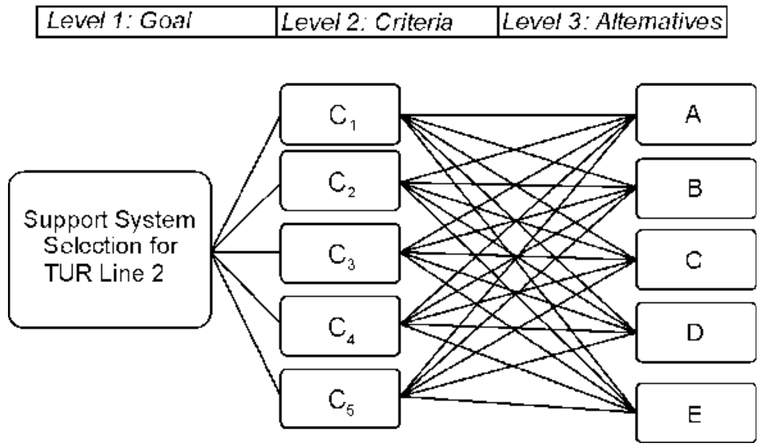

Fig. 3 - Hierarchy structure for TUR line 2 tunnel support system design

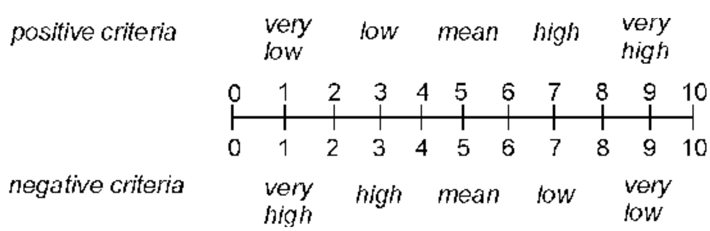

Fig. 4 - Bipolar scale for pair-wise comparison

Unlike rating alternatives where we compare them to the best possible standard or ideal alternative, in the comparative judgment process we compare each alternative with some or all of the other alternatives. In that case an alternative that is ideally poor on an attribute could have a relatively high priority when compared with still poorer alternatives on that attribute but have low priority on another attribute where it is almost ideally good but is compared with better-valued alternatives. Thus the final rank of any alternative depends on the quality of the alternatives with which it is compared. Hence in making comparisons among alternatives, the priority of any alternative is influenced not only by how many alternatives it is compared with but by their quality (Saaty, 2004). Table 2 shows comparative matrixes for both of minimization and maximization of object function.

Table 2 - Pair-wise comparison matrix

minimization	Criterion 1	Criterion 2	…	Criterion n
a .for minimization problems				
Criterion1	1	w_2/w_1	…	w_n/w_1
Criterion2	w_1/w_2	1		w_1/w_2
⋮	⋮	⋮	1	⋮
Criterion n	w_1/w_n	w_1/w_n	…	1
b. for maximization problems				
Criterion1	1	w_1/w_2	…	w_1/w_n
Criterion2	w_1/w_2	1		w_2/w_n
⋮	⋮	⋮	1	⋮
Criterion n	w_n/w_1	w_n/w_2	…	1

3.3 Solution

According to previous sections, each alternative is compared with the goal base on its influence of objective function and just a matrix is made for these comparisons. We called this matrix AO matrix. Also, each criterion affecting the support design selection is compared with the others and the pair-wise comparison matrix is constructed. These types of matrices are called CA in this paper. Then value of each alternatives is obtained by Eq. 3 (Torabei, 2007).

$$V_i = \Sigma k_{ij} c_j \tag{3}$$

Where V_i is value of each alternative, k_{ij} is weight of jth criterion for ith alternative and c_j is weight of jth criterion comparing with goal. Before using this equation, the pair-wise comparison matrix must be normalized.

Some calculations must be done to find the maximum value of eigenvector, consistency index CI, consistency ratio CR, and normalized values for each criteria or alternative as follows (Yavuz et al., 2008).

$$\lambda_{max} = \frac{1}{n} \Sigma_i^n \left(\frac{\sum_j^n a_{ij} w_j}{w_i} \right) \tag{4}$$

Where λ_{max} is the maximal or principal Eigenvector, and n is the matrix size, a_{ij} is an element of pair-wise comparison matrix, w_j and w_i is the jth and ith element of values of eigenvector, respectively. Further, CI and CR are defined as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

Where, RI is the random indices. To find out whether the resulting consistency index is acceptable, the consistency ratio should be calculated. The consistency indices of randomly generated reciprocal matrices from the scale 1–9 are called the random indices, RI. The ratio of consistency index to RI for the same-order matrix is called the consistency ratio, CR. Random indices are given in Table 3 (Saaty, 2004). As a general rule, a consistency ratio of 0.10 or less is considered acceptable. This means that the result here is less than a prescribed limit (Torabei, 2007).

Table 3 - The consistency indices

n	1	2	3	4	5
RI	0	0	0.58	0.9	1.12
n	6	7	8	9	10
RI	1.24	1.32	1.41	1.45	1.45

If the maximum value of Eigenvector, CI and CR are satisfactory then decision is taken based on the normalized values; or else the procedure is repeated till these values lie in a desired limit. Before incorporating the decision-making process, the numerical values of some objectives which affect the stability of the main transport road are obtained by using numerical analyses.

Also, consistency of hierarchy process must be calculated. Weight of each criterion in AO matrix is assumed as AO_i therefore consistency of hierarchy process, CH is calculated by Eq. 7.

$$CH = \frac{\sum_{1}^{\text{number of criteria}} (CI_i \times AO_i)}{\sum_{1}^{\text{number of criteria}} (RI \times AO_i)} \tag{7}$$

Where CI_i is consistency index and obtained for criterion i via previous section. Acceptable value of CH is less than 0.1 (Torabei, 2007).

After calculating any alternative's value decision based on these values. The optimum choice is which one has maximum alternative value.

4. NUMERICAL MODELLING STUDIES

4.1 Building numerical model

The numerical model has been designed with the model boundary 8 times larger than the tunnel diameter and suitable mesh has been created for the model. The FLAC^{3D} grid is shown in Fig. 5. The geotechnical properties of soil were introduced as input to the FLAC^{3D} program.

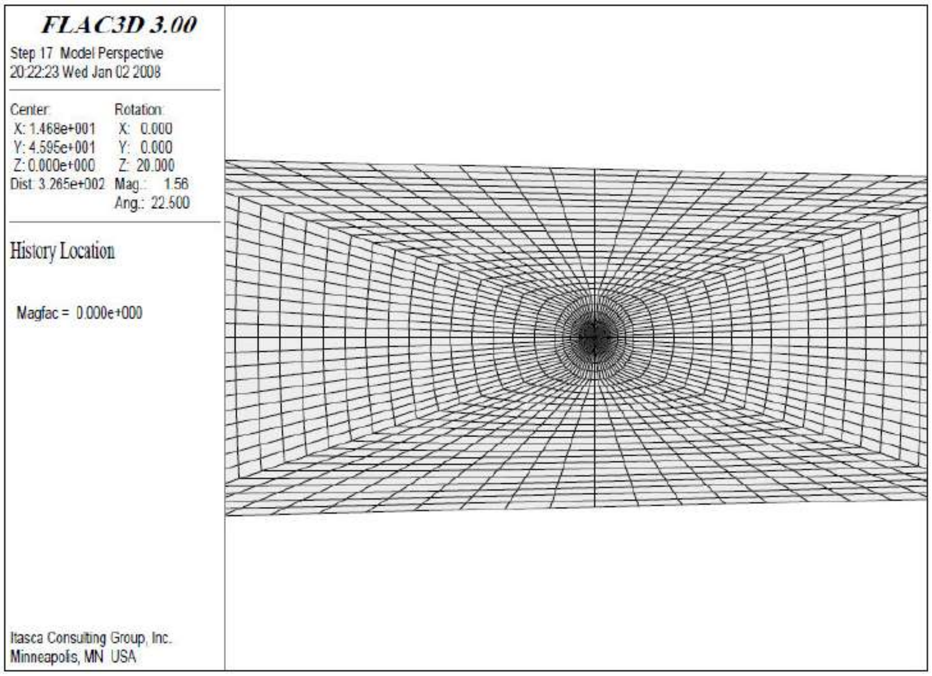

Fig. 5 - 3D model of TUR line 2 tunnel

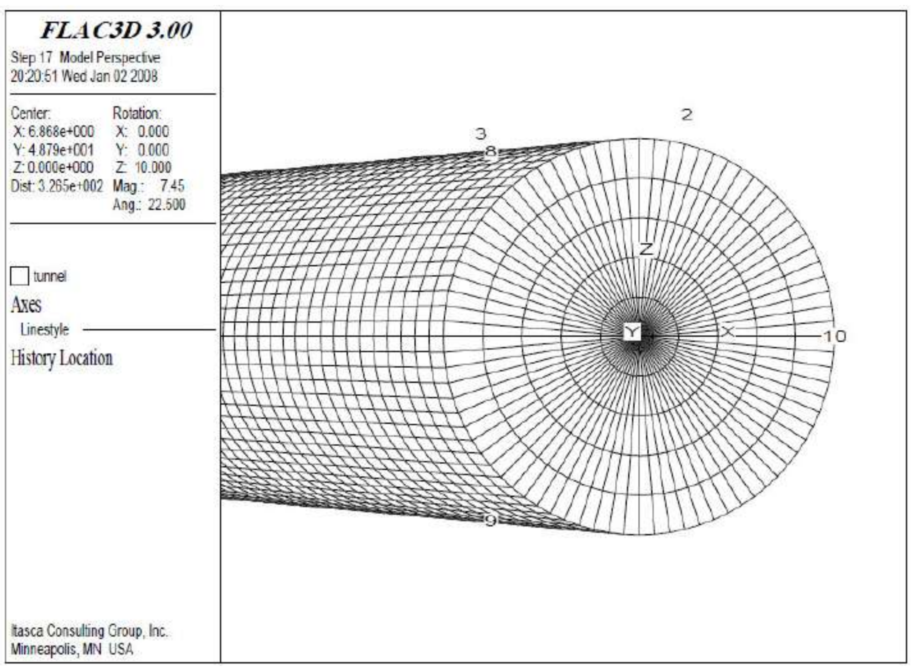

Fig. 6 - History of numerical model

The model was run after preparing and some displacement happened. Then all velocity in grid and displacements were set to zero and the model become ready to work (Itasca Consulting Group, 1997). The first model in relation to the opening after excavation (without support) has been studied in order to investigate the soil behavior around the opening. The present work demonstrated huge displacements and failure zones around the tunnel; therefore it revealed that supporting the opening was necessary.

To support this tunnel a segmental lining is going to be used because of many advantages. There are 4 main alterative to support this tunnel. During the numerical modelling, the tunnel was stable by using every choice.

Vertical and lateral displacements at the top of the tunnel roof were monitored in all models (Fig. 6).

4.2 Segmental Lining Design for Metro Tunnel

Lining design for metro tunnels is a delicate approach because it involves both of technical and economical factors. Any wrong decision results in bad effect on project and could stop it.

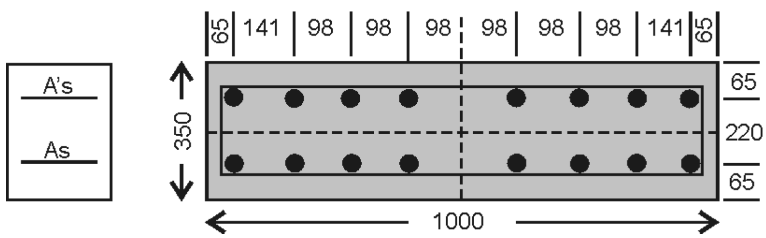

Fig. 7 - Cross-section of segment

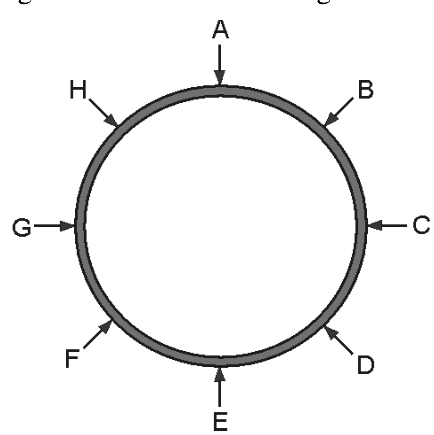

Fig. 8 - Critical points to evaluate stability

Table 4

Point	Shear force (N)	Axial force (N)	Bending moment (N.m)	Axial strain	Safety factor
A	2.82E+03	9.73E+05	1.24E+04	-1.12E-04	5.02
B	7.63E+03	8.93E+05	-1.01E+04	-1.03E-04	6.11
C	-3.43E+03	1.08E+06	-1.75E+03	-1.24E-04	4.47
D	1.39E+04	1.08E+06	2.59E+03	-1.24E-04	4.47
E	5.79E+03	1.30E+06	-7.04E+03	-1.49E-04	3.72
F	8.07E+03	1.10E+06	-2.23E+03	-1.26E-04	4.38
G	9.57E+03	1.10E+06	4.68E+03	-1.26E-04	4.38
H	1.67E+03	8.92E+05	-1.30E+04	-1.03E-04	6.32

Similar project experience could be studied to start lining designing. Here just a pre-design segmental lining is offered based on its strength and tunnel stability and consular company will develop this design and offer a detailed scheme of lining.

We use line 1 of Tabriz metro tunnel lining as a first choice. Therefore a 35 cm lining with S-400 steel and 16Φ14 bar arrangement was considered. But this choice was not suitable because of low safety factor obtained. Cross-section of segment is shown in Fig. 7.

After analyzing this choice it is found that a 35 cm lining with S-400 steel and 16Φ14 bar arrangement is not adequately stable. Therefore a choice with same number of bars and 40 cm thick lining using S-400 steel 16 Φ16 was considered. Also whole of lining ring was divided to 8 critical points to evaluate stability of lining as shown in Fig. 8. Inner forces on lining at 8 points were evaluated using $FLAC^{3D}$ numerical software as seen in Table 4. Numerical study is explained in next section. Axial strain is less than 0.2 mm and therefore it would be a good choice potentially.

Then safety factor at each point is evaluated by axial force-bending momentum diagrams. PCACOL software is used for drawing the diagram shown in Fig. 9. The value of safety factor is given in Table 4. Minimum value of safety factor is used as safety factor of lining and here it is 3.72 and happens at the bottom of lining. It is acceptable value because of expansive nature of Tabriz soil and its swelling effect. Also this software gives us axial strength of lining as 4.8 MN. This is minimum amount of axial force which can break the lining.

Finally, stability of lining should be checked against the implemental loads such as TBM thrust load and putting segments over themselves. Thrust force of TBM is 1 MN and 5 segments maximum could be put over a segment. Therefore maximum load on a segment in depository is 50 KN. Therefore this lining is stable and selected for Tabriz metro lining. Other possible choices were considered in same way. Three other choices were stable too and was candidate to optimum lining of tunnel.

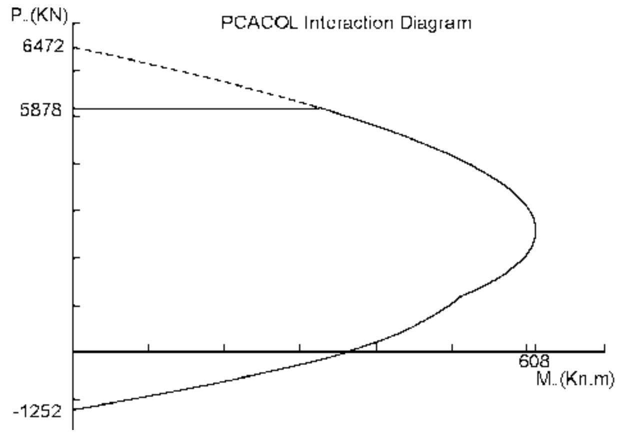

Fig. 9 - Axial force- bending momentum diagram

4.3 Results of Numerical Modeling

Maximum stress obtained in the model studies has been included in Table 5 as well. The factor of safety (FOS) values for the linings of these models have been calculated by dividing the compressive strength values of the studied lining of the models by the maximum stress values occurred in these linings. The results of numerical modelling of TUR line 2 tunnel after supporting are summarized in Table 5.

Table 5 - Results of numerical modeling

Model	Displacement (cm)		Maximum stress (MPa)	FOS
	Bottom	Roof		
A	6.2	4.7	0.27	3.72
B	7.2	5.2	0.39	4.19
C	6.4	4.8	0.31	4.14
D	6.2	4.6	0.25	4.02
E	6.3	4.7	0.29	3.85

5. OPTIMUM MODEL SELECTION BY USING THE AHP METHOD

Different models have been carried out in order to obtain the FOS and the displacement (deformation) values for the main transport road tunnel which will be foreseen to serve for a long period of time. It was aimed to minimize the displacements and maximum stress in concrete lining as shown in Table 2a, and to maximize the FOS as shown in Table 2b.

In the process of deciding on the selection of the optimum support type, the AHP method was utilized by considering the results obtained from numerical studies and also evaluating some criteria by interviewing the experts working in the mine management for several years.

Therefore, the four different types of support systems were evaluated according to the five criteria. The number of criteria and alternatives should be paid attention in the AHP applications because of the consistency and validity of the decision-making process as stated by Saaty et al. (2003). The number of alternatives should be 7±2; otherwise the grouping method should be applied (Saaty and Ozdemir, 2003).

Table 6 - Comparison of criteria with respect to object function

	C_1	C2	C3	C4	C5	Priority
C_1	1	0.5	0.14	0.2	0.33	0.06
C_2	2	1	0.29	0.4	0.67	0.11
C_3	7	3.5	1	1.4	2.33	0.39
C_4	5	2.5	0.71	1	1.67	0.28
C_5	3	1.5	0.42	0.6	1	0.17
λ_{max}=5.04 CI=0.01 CR= 0.009						

Table 7 - Pair-wise Comparing between economic factor and alternatives

	A	B	C	D	E	Priority
A	1	0.33	0.14	1	0.2	0.06
B	3	1	0.43	3	0.6	0.18
C	7	2.33	1	7	1.4	0.41
D	1	0.33	0.14	1	0.2	0.06
E	5	1.67	0.71	5	1	0.29
λ_{max} =5 CI=0 CR= 0						

Each criterion affecting the support design selection was compared with the others and the AO pair-wise comparison matrix was constructed as shown in Table 5. The priority value for each criterion was calculated by normalizing the geometric mean of each row of the pair-wise comparison matrix. The consistency ratio of this matrix was also calculated and it is equal to 0.009 and less than 0.1. Therefore the matrix and comparison are acceptable and it is not necessary to repeat operation. The comparison of each support design system according to each criterion was made by constructing the comparison matrices. The comparisons including bottom and roof displacement criteria were carried out by using minimization process as the way shown in Table 2a, while the maximization process in Table 2b was used for FOS criterion. They are quantitative values obtained by numerical modeling and PC ACOL diagrams. In the comparison process, there is no need to give the comparison matrix for the criteria from C_1 to C_3 because the numerical values of criteria in Table 5 were considered. The other comparison matrices constructed according to the expert team's opinion are given in Tables 6 and 7 for the C_3 and C_4 criteria in evaluating the alternatives. The priority value for each alternative was calculated by normalizing each column of the matrix of pair-wise comparison between each criterion and alternatives. The overall rating of each alternative is calculated by adding the products of the relative priority of each criterion with the relative priority of the alternatives considering the corresponding criteria in Table 5 (for C1 and C2) and Tables 6 and 7 (for C3–C4). Similarly, the final matrix is constructed as shown in Table 9. From Tables 6 to 8, it can be seen that the maximum values of Eigenvector are near to the size of the matrix and CR values are less than 0.1. As these values are in desired range, the decision is taken without repeating the procedure. Consistency ratio of each matrix was finally less than permitted value after trying some operation. And consistency ratio of whole of hierarchy process is:

$$CH = \frac{0.00238}{1.12} = 0.0023$$

This value shows that process is consistent and the decision could be made. This value is less than 0.1 and the operation for selecting optimum support system is valid.

Table 8 - Pair-wise Comparing between possibility and alternatives

	A	B	C	D	E	Priority
A	1	0.33	0.25	0.17	1	0.07
B	3	1	0.75	0.5	3	0.20
C	4	1.33	1	0.67	4	0.27
D	6	2	1.5	1	6	0.40
E	1	0.33	0.25	0.17	1	0.07
λ_{max} =5.06 CI=0.015 CR= 0.014						

Table 9 - Overall results

Alternative	C1	C2	C3	C4	C5	Overall results
A	0.21	0.20	0.19	0.06	0.07	0.136
B	0.18	0.19	0.21	0.18	0.20	0.198
C	0.20	0.20	0.21	0.41	0.27	0.276
D	0.21	0.21	0.20	0.06	0.40	0.199
E	0.20	0.20	0.19	0.29	0.07	0.201
Object function	0.06	0.11	0.39	0.28	0.17	1

Considering the overall results in Table 9, the alternative ‘‘C’’ must be selected as the optimum support system to satisfy the goals and objectives of the TUR management because the priority of this alternative (0.276) is the highest value than that of the others.

Therefore segmental lining must be made from S-300 steels in Iranian standard steel which is corresponded to AII steel. Thickness of suggested segment is 40 cm that surrounds 16 bars with 20 mm diameters. This procedure was for segment with 0.4×1 m sections. In some projects TBM uses a 1.20 or 1.5 meter width segment. Steel density must be adopted in these cases. After selecting this alternative a detailed stability analysis must be carried out to be sure about its safety. Safety factor of alternative “C” is 4.14, which is above 3, i.e. the minimum acceptable value for it. Also before implementation this support system feasibility study must be done. This study must be carried out after clearance of detail of support system.

6. CONCLUSIONS

Optimum support system selection for a metro tunnel involves the consideration of several criteria. Many methods have been used for optimum support system determination such as numerical analyses. However, the importance of each criterion cannot be considered in the numerical analyses but it is very useful tool for the engineers to inspect the tunnel behavior by trying different support alternatives in advance. The AHP is a scientific method to evaluate these criteria. In this paper, application of the AHP method to the selection of support system for Tabriz urban railway tunnel in Iran is introduced. In the proposed AHP model; five criteria, namely: displacement values at roof and bottom of the tunnel, safety factor, economic factor, and possibility were evaluated according to the importance on the selection of support system. Some alternatives are to use as support system for TUR tunnel supporting. Among the considered 4 support system alternatives, ''D'' was the best choice as support system when the alternatives were evaluated according to the considered criteria. Therefore a 40 cm concrete lining by 14 bars around each 1 meter sections using 18 mm (A II)-S-300 steel was suggested to support TUR tunnel.

In the AHP method we focus in two pairs to compare in any time rather than whole of case. It makes this method to become more precise and useful in tunnelling industry. Also, the AHP method requires less data and reduces the time consumed in the decision making process. Besides, both of quantitative and qualitative criteria can be considered in this method.

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