Selection of tunneling machines in soft ground by fuzzy analytic hierarchy process

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In tunneling, it is very important to select the correct tunneling machines. Choosing a wrong method may be very costly to the company. There are many parameters affecting the decision stage of selection of the tunneling machine. Geology (C1), ground conditions (C2), tunnel properties (C3), geo-environmental hazard (C4), technical properties of machines (C5), and project properties (C6) are the main selection criteria. Using these topics and the sub-criteria belonging to each topic, the fuzzy analytic hierarchy method is employed to select the most suitable tunneling machine. Tunnel boring machines are mainly divided into two as hard and soft ground machines. The number of tunnels under cities constitute a large amount due to subways, underground roads, etc. These tunnels are mostly shallow tunnels. Therefore, the variety of soft ground tunneling machines increase. In this research, soft ground type machines and their parameters are evaluated. After evaluation with the fuzzy analytic hierarchy process, geology (C1) turned out to be the factor most influencing the selection of machine type, and M3 (EPBM) is found to be the most suitable machine for soft ground conditions. In addition, the research method and the study results are thought to be helpful in selecting the machine type for other tunnels which will soon be started in Turkey.

Key words: *Tunneling, Soft ground, Fuzzy logic, Machine selection, Excavation.*

1. Introduction

Subway tunneling evolved in recent years in order to ease city traffic and, therefore, progress has been made on the soft ground machine types and diversity. Subway tunnels are generally shallow tunnels. That is why ground conditions should be taken into consideration carefully. Langmaack and Seven (2007) and Köse et al. (2007) mentioned that the three most important factors for soft ground tunneling, apart from the hard rock geology, are the soil permeability, ground water pressure, risk of clogging and adhesion.

There are many parameters affecting the decision stage of selection of the tunneling machine. Geology (C1), ground conditions (C2), tunnel properties (C3), geo-environmental hazard (C4), technical properties of machines (C5), and project properties (C6) are the main selection criteria. In this study, soft ground is studied and the corresponding machine types are investigated. Selection criteria are determined with the help of many different references from the literature. This section will be explained in Chapter 2. Alternative machines are selected according to the ITA (2000). These machines are the shield type (M1), the mechanical excavation type (M2), the earth pressure balance type (M3), slurry type (M4), hand excavation (M5), semi-mechanical excavation (M6), blind type (M7), roadheader (M8), and hydraulic hammer (M9), respectively. These criteria are evaluated by a fuzzy analytic hierarchy process (FAHP) and an application is made on an example case.

The objective of this fuzzy analytic hierarchy process problem is to select the most suitable machine for the tunnel under study. The study aims to determine the best machine for Izmir (Turkey) subway tunnel as given in Figure 1.

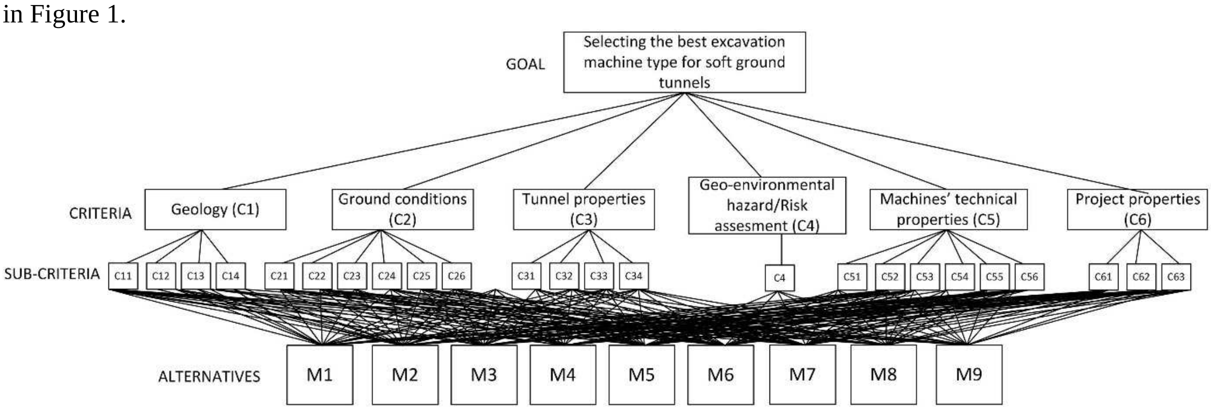

Fig. 1. Hierarchy of the selection process.

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After evaluation with FAHP, geology (C1) turned out to be the factor most influencing the selection of machine type and M3 (EPBM) is found to be the most suitable machine for soft ground conditions.

2. Defining Selection Criteria

Many factors can affect the process of selection of the tunnel excavation machine. Generally, soft ground properties are more complex than hard rock. Therefore, firstly literature is reviewed for tunnel projects in detail. Then, six main criteria and different numbers of sub-criteria are selected. The selected criteria can be seen in Table 1. All of these criteria are determined under the light of studies in literature.

There are many studies on tunneling and tunnel boring machines in the literature. Some of these studies, which consider excavation of the tunnel, investigate the properties of tunnel boring machines and a number of parameters that are effective on excavation. Vardar and Bilgin (2007) emphasized that selection of suitable machine according to the project criteria is very important to excavate a tunnel economically and efficiently.

Tab. 1. Criteria affecting selection of tunneling machine.

C1: Geology **C11 Geologic failures**: faults, anisotropy, discontinuities, joints, fractures or classifications, fissures etc. **C12 Topography**: tunnel depth. **C13 Hydrogeology**: ground water, aquifer, permeability, karstic voids etc. **C14 Formation type**: origin, particle diameter, heterogeneous or homogenous, etc.
C2: Ground conditions **C21 Mechanic properties**: undrained strength, uniaxial compressive strength, shear strength, elasticity modulus, cohesion, poisson’s ratio. **C22 Physical properties**: density, swelling, squeezing, porosity, hardness, slake durability. **C23 Field and laboratory experiments**: Liquid limit, plastic limit, cone penetration test, standard penetration test (SPT), plasticity index, etc. **C24 Face stability** **C25 Soil classification system** **C26 Ground settlement**
C3: Tunnel properties **C31 Length of tunnel** **C32 Tunnel geometry**: Diameter, shape, cross-section area **C33 Depth of tunnel** **C34 Type of tunnel support**
C4: Geo-environmental hazard/Risk assessment
C5: Machines’ technical properties **C51 Power properties** **C52 Cutting head properties**: diameter, rotation speed, rotating or non-rotating, etc. **C53 Weight of machine** **C54 Shield type**: double, single, open, closed etc. **C55 Reaction force** **C56 Specific energy**
C6: Project properties **C61 Project duration time** **C62 Cost** **C63 Constructor reliability**
Alternative Tunneling Machines **M1 Shield type**: Can be used generally for soft ground. Cutting head is closed and rotation type. Reaction force is either gripper or segment type. **M2 The mechanical excavation type**: Tunneling machine is suitable for the diluvial deposit that has a self-standing face. **M3 The earth pressure balance type**: This type is suitable for silty and clayey grounds. Cut to the ground with a rotary cutter head and then muck removed by a screw conveyor. **M4 Slurry type**: This tunneling machine cuts the ground with a rotary cutter head. The cutter chamber is filled with a pressurized slurry mix to stabilize the face of the tunnel. **M5 Hand excavation**: These machines are non-rotating shield type machines. Front surface of the shield is open on these machines. **M6 Semi-mechanical excavation**: These machines are non-rotating shield type machines. Front surface of the shield is open on these machines. **M7 Blind type**: It has a semi open type machine. The shield is not rotating type in this machine. In these machines, as a shield is used for face stability, a boom excavates the face from an open surface. **M8 Roadheader**: It is a partial face cutting machine. It excavates by the help of a boom. There are bits on the cutter head which rotates parallel or perpendicular to the face. **M9 Hydraulic hammer**: Mounted on an excavator carrier or backhoe, it gains the ability for tunnel excavation. This machine excavates by impact.

Some of the efforts made on tunneling machine selections are given in the following text. Nord and Stille (1988); Einstein et al. (1992); ITA (2000) introduced standards for TBM selection. In addition, Bieniawski et al. (2009) presented rock mass excavability (RME) indicating when selecting excavation technique. Bilgin et al., (2008) studied the selection of a TBM using full scale laboratory tests in metro tunnels.

Geology is one of the important criteria in the selection of tunneling machines. Geology (C1) and its sub-criteria are seen in Table 1. Geologic failures cause machine advance speed to be left behind theoretical advance speed in tunnel projects. Yagiz et al., (2010); Kun and Onargan, (2013) studied geological controls in tunnels. For example, faults strongly affect the TBM cutter head. Barla (2002); Arioglu et al (2002b); Klados and Sivalingam, (2006); Lovat (2007); Hassanpour, (2011) have often used particle size diameter or granulometric curves in the selection of tunneling machines according to the formation types (C14). Also, tunnel depth is an important issue. On the other hand, groundwater level affects excavation method and support systems as mentioned in Kucuk (2011).

Ground conditions (C2) are investigated in many of tunnel projects or studies. Stille and Palmstrom (2003); Bilgin et al., (2004); Nunes and Meguid (2009); Solak (2009) made rock or ground classifications which help cutting and selection of tunnel excavation machine and tunnel support in their study. In addition, for "Basmane-Konak" line, value N, known as face stability, is found between 0.69-2.84 (Arioglu et al, 2002b). Minimum value corresponds to the little liquid-elastic zone and maximum value corresponds to the limited liquid conditions. Ground classification should be made in tunnel projects and then it is used to select machine types. Also, ground settlement is especially important in subway tunnel projects since these tunnels are mostly driven below residential areas.

Tunnel properties (C3) should be considered on tunnel studies and projects. Tunnel geometry is generally circular. For example Kunihiko and Kenichi (2006) stated that non-circular tunnel in the sandy ground were quite few compared with the circular section, since the problems with the reliability of excavation mechanism and the abrasion of bit cutters were still unresolved. Some of the other criteria and sub-criteria are given in Table 2.

Tab. 2. Effect of tunnel properties by selecting the excavation tunnel method (DAUB, 1997 and ITA, 2000).

Conditions/Excavation methods		**Drilling&Blasting**	**TBM**	
			Hard rock	**Soft ground**
Tunnel properties	**length**	Equipment cost is relatively low. Excavation cost is not affected by the tunnel length very much.	The cost of tunnel boring machines is generally high. It is suitable in longer tunnel excavations.	The cost of tunnel boring machines is generally high. It is suitable in longer tunnel excavations.
	shape of the cross-section	The shape of the cross-section can be changed during construction.	Basically the shape of the excavation is a circle. After boring, other shapes are possible using drilling and blasting as the result of enlargement.	Basically the shape of the excavation is a circle. Semi-circle, multi-circle etc. are also possible using special tunneling machines for excavation.
	size of the cross-section	Generally, it is possible up to 150 m^2. The largest record is bigger than 200 m^2.	The largest record is approximately 12 m for the maximum diameter of the tunnel.	The largest record is approximately 14 m for the maximum diameter of the tunnel.

Geo-environmental hazard (C4) is also very important in tunneling. Geo-environmental hazard is considered together with technical parameters. This is quite common in risk assessment and management literature. Barla and Pelizza (2000); Shariar et al. (2008); Hamidi et al. (2009b) mentioned geotechnical hazards, vulnerabilities and wrong machine selection risks. In addition, Hamidi (2010) and Beard (2010) conducted studies on tunnel safety, qualitative or quantitative risk assessment and decision-making.

Technical properties (C5) are considered in many studies on tunnel projects. Some of these focus on mechanical power, torque, cutting head properties, shield type, the head thrust system and specific energy issues. ITA (2000) stated that as the cross-section of the tunnel increases, TBM diameter increases too. In this case, selected machine should be the stronger one. Therefore, cutting disc space and thrust force per disc cutter increases. As TBM diameter increases, RPM (rev/min) rapidly decreases. In addition, weathering shapes of cutter bits in excavation machines are important in terms of specific energy. As weathering increases, cutter bits need more energy for excavation and hence their specific energy values will increase (Balci et al., 2004; Ozfirat, 1998).

The project features (C6) which are important factors in the selection of the tunnel excavation machine are project completion time, cost and reliability of the contractor. The project schedule should be well-planned according to the duration of the excavation and daily progress. Eskesen 2004 stated that the contractor must identify hazards and classify risks using systems which are compatible with the systems used by the owner and should propose mitigation measures to reduce the identified risks. The owner should approve the mitigation measures before the project starts. Tunneling cost is also an important factor in selection of excavation methods. As Sauer 2004 stated, using TBM in tunnels shorter than 2.4 km is not cost effective.

3. FAHP (Fuzzy Analytic Hierarchy Process)

In the proposed approach, FAHP is employed in order to overcome some of the drawbacks of AHP such as the vagueness and subjective comparisons of individuals. The fuzzy prioritization method is used to compute priorities of both selection criteria and alternative tunneling machines. The flow of the proposed algorithm can be seen in Figure 2.

Classical AHP is composed of mainly three steps which are;

- problem structuring,
- evaluation of local priorities,
- computing the overall priorities of alternatives to come to a decision (Ozfirat 2012, Straka et. al. 2014).

In problem structuring, the decision maker determines selection criteria and lists the alternative choices. In the second stage, pairwise comparisons are made, local priorities of selection criteria and alternatives are determined. Finally, in the third stage global priorities of each alternative are computed. Among these the best one is selected by the decision maker.

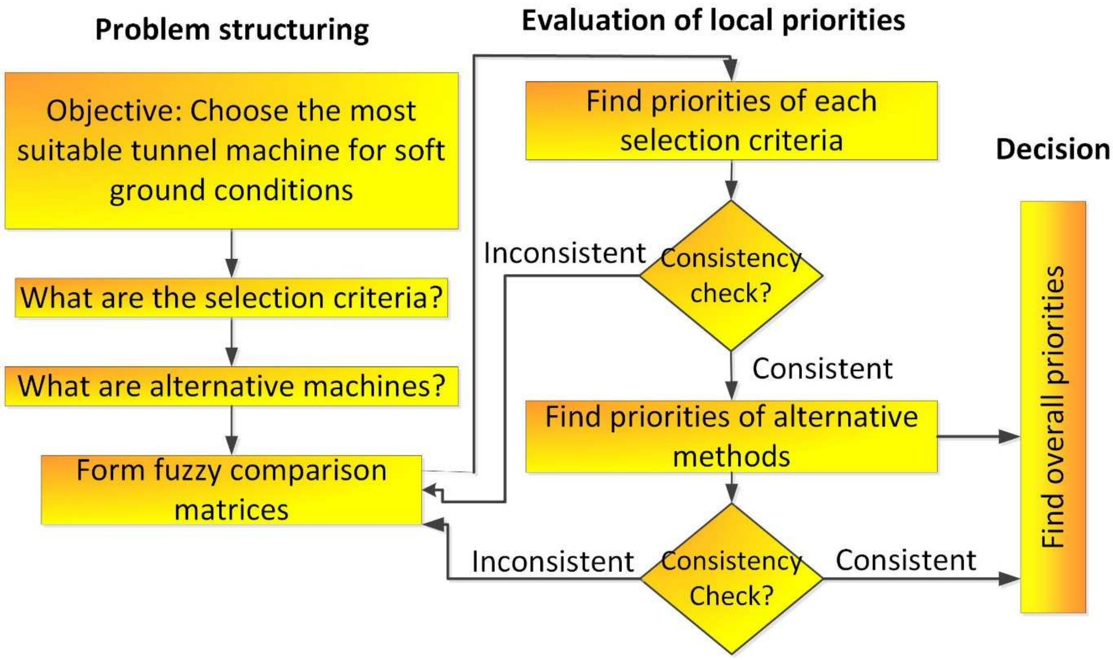

Fig. 2. Proposed algorithm of the study (Ozfirat, 2012).

In FAHP, the second stage of classical AHP is fuzzified. In other words, fuzzy comparisons are made for the pairwise comparison matrices. By this way, it would be easier for the decision maker to make true comparisons and it would be more accurate.

In fuzzy comparison matrices, a lower bound, an upper bound and a most likely value is stated for the comparison of two criteria and/or alternatives. For example; let us say the comparison between criteria 1 and 2 be (4,5,6). This means:

"Criteria 1 is likely to be strongly important (degree 5) than criteria 2, but it is between degree 4 and degree 6 compared to criteria 2".

The fuzzy pairwise comparison matrix (A^{Fuzzy}) is built as in equation 1 where:

l_{ij}: lower bound on the comparison between criterion i and j.
m_{ij}: most likely value of the comparison between criterion i and j.
u_{ij}: upper bound on the comparison between criterion i and j.
w_i: weight coefficient of criterion i.

$$A^{Fuzzy} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} \cdots & \frac{w_2}{w_n} \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} \cdots & \frac{w_n}{w_n} \end{bmatrix} = \begin{bmatrix} 1 & (l_{12}, m_{12}, u_{12}) \ldots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & 1 \ldots & (l_{2n}, m_{2n}, u_{2n}) \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) \ldots & 1 \end{bmatrix} \tag{1}$$

In addition, the reader should note that:

$$l_{ij}=1/ l_{ji} \;,\; m_{ij}=1/ m_{ji} \;,\; u_{ij}=1/ u_{ji} \tag{2}$$

Once the fuzzy comparison matrices (A^{Fuzzy}) are built, local priorities (w_i) should be computed. In the proposed approach the fuzzy prioritization method, developed by Mikhailov & Tsvetinov (2004), is employed to compute the priorities of the selection criteria and the alternative tunneling machines.

The fuzzy membership functions are defined using fuzzy triangular numbers as in Equation (3). One should note that in the proposed approach $l_{ij} < m_{ij} < u_{ij}$.

$$\mu_{ij}\left(\frac{w_i}{w_j}\right) = \begin{cases} if \quad \frac{w_i}{w_j} \le m_{ij} \;\; then & \frac{\left(\frac{w_i}{w_j} - l_{ij}\right)}{m_{ij} - l_{ij}} \\ if \quad \frac{w_i}{w_j} > m_{ij} \;\; then & \frac{\left(u_{ij} - \frac{w_i}{w_j}\right)}{u_{ij} - m_{ij}} \end{cases} \tag{3}$$

In fuzzy prioritization method (Mikhailov & Tsvetinov, 2004), since we want to maximize consistency within our decisions, the value of all membership functions should be maximized as much as possible. This is made using mathematical modeling. A new variable, λ, is introduced and represents the consistency level of the decision maker. In order to maximize consistency, value of all membership functions should be maximized. This is provided by the mathematical model built in formulation (4):

maximize λ

subject to

$$\lambda \le \mu_{ij}\left(\frac{w_i}{w_j}\right) \quad \forall i = 1..n-1,\; j = 2..n,\; j > i \tag{4}$$

$$\textstyle\sum_i w_i = 1$$
$$w_i > 0 \qquad \forall i = 1..n$$

The values of membership functions are given in equation 3. Therefore, formulation 4 turns into formulation 5 when membership functions are put into the right place.

maximize λ

subject to

$$\begin{aligned} &\lambda w_j(m_{ij} - l_{ij}) \le w_i - l_{ij} w_j \quad \forall i = 1..n-1, j = 2..n,\; j > i \\ &\lambda w_j(u_{ij} - m_{ij}) \le u_{ij} w_j - w_i \quad \forall i = 1..n-1, j = 2..n,\; j > i \\ &\textstyle\sum_i w_i = 1 \\ &w_i > 0 \end{aligned} \tag{5}$$

When this model is solved, we get the priorities of each decision criteria ($\mathbf{w_j}$). In other words, the relative importance levels of each decision criteria are found. For example, if W_1 is found to be 0.35, this means first criterion is 35% important for the decision maker. In addition, the value of the objective function (λ) gives us the consistency level. The acceptable level of λ is 0.9. The model is solved using OPL Studio 3.7 (ILOG, 2003) optimization software (Ozfirat, 2012).

4. Field Under Study

The Izmir subway tunnel project, which is selected as a case study is planned so that its length reaches total 45 km and covers a large portion of residential regions as a high capacity system by the Izmir city municipality.

There are a total of 10 stations in the system. “Ucyol”, “Konak”, “Cankaya”, “Bornova” and “Basmane” are underground stations; “Hilal”, “Halkapinar” and “Stadyum” stations are constructed as viaducts. “Sanayii” and “Bolge” stations are located on the surface. The first stage under construction, having the highest population density, and so the highest passenger movement, “Ucyol-Bornova” line was built, 11.6 km long. In the study, it is focused on “Basmane-Çankaya-Konak” line due to soft ground and using the tunneling machine. These lines are 2752.5 m in length and consisting of four tunnels (Figure 3). These tunnels are side-by-side double tunnels due to archaeological remains and less covering layer.

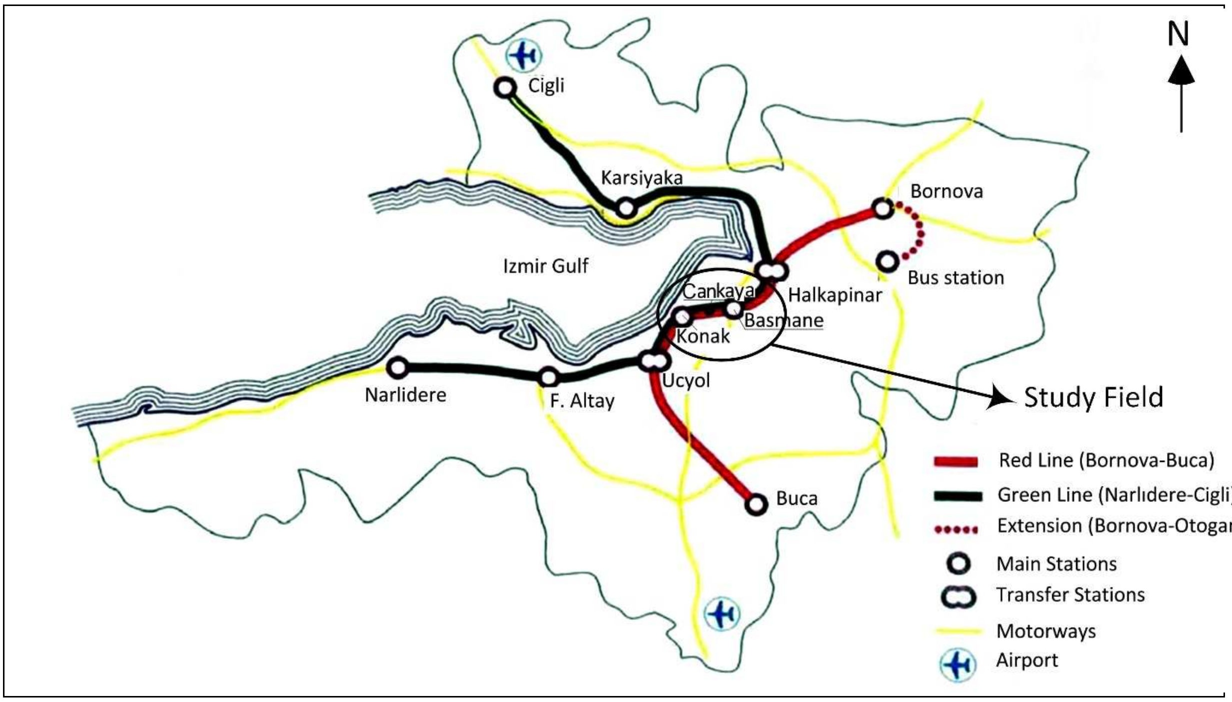

Fig. 3. İzmir Subway System (Arioglu et al., 2002d).

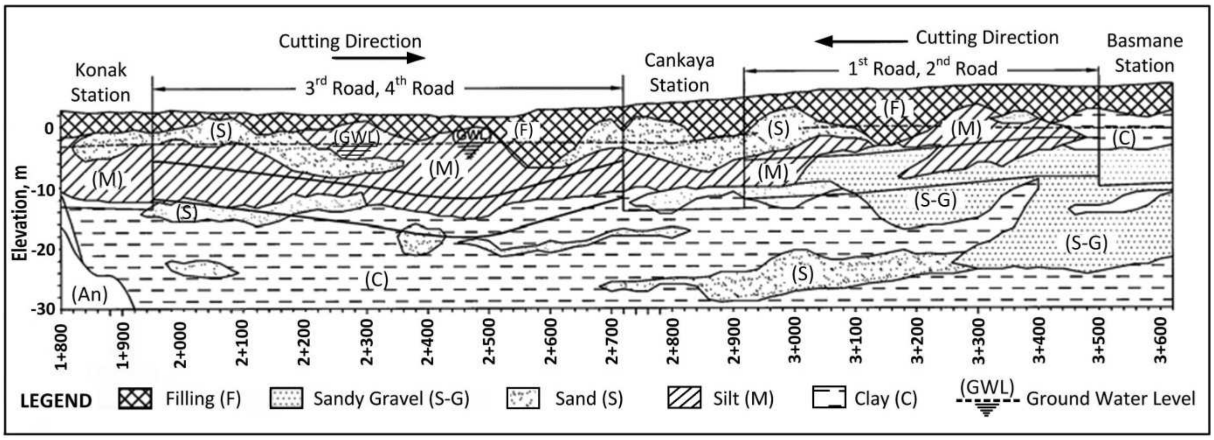

Fig. 4. Geological cross-section of “Basmane” and “Konak” line (Arioglu et al., 2002a; Arioglu et al., 2002b)

As seen in Figure 4, there are terrestrial and marine sediments which occur above the in-situ weathered andesitic product clayey in the line between the “Konak-Basmane”. In the “Konak” side which is closer to the sea, there are sediments in the marine Silt and Clayey Silt layers which contain cross stratified sand bands and lenses. In the “Basmane” side there are sediments in the terrestrial places sandy gravel layers which contain coarse blocks and rubble. The ground water level is about 1.5 m deep from the surface in the “Konak” side and 4-6 m deep from the surface in the “Cankaya”-“Basmane” side (Saglamer et al., 1996). Ground types, tunnel cross-sections and geomechanical values are given in Figure 5.

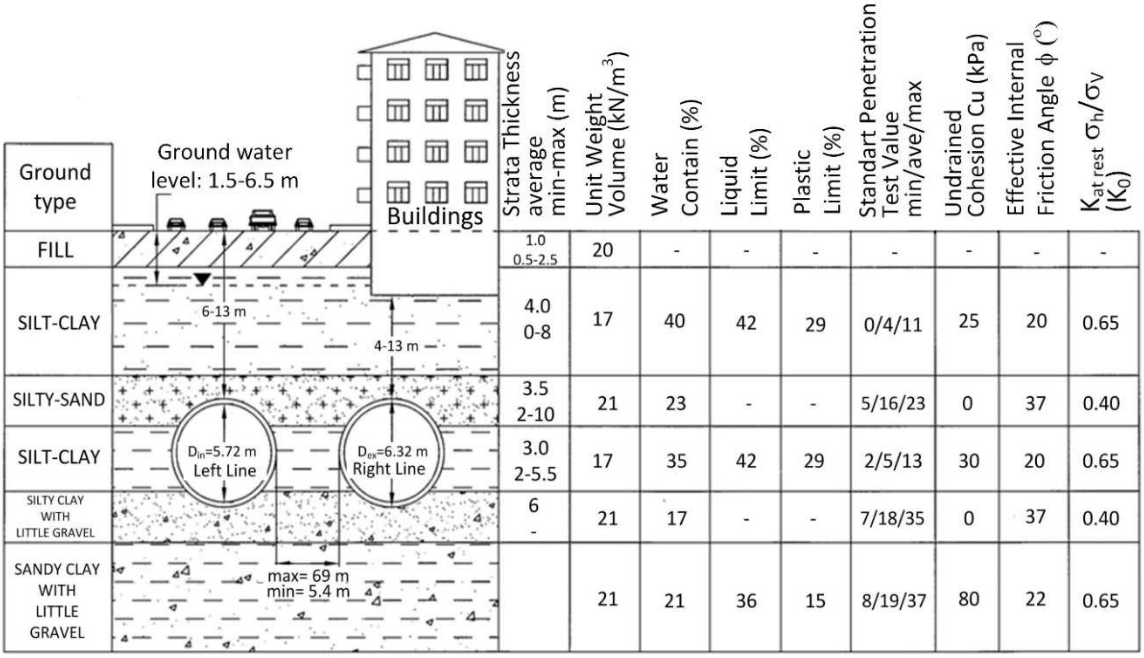

Fig. 5. Typical soil profile and the average geomechanical values of "Konak-Cankaya-Basmane" Tunnels (Arioglu et al., 1999; Saglamer et al., 1996).

5. Fuzzy Comparison Matrices

In this step, firstly the fuzzy comparison matrix of the main selection criteria is developed. In developing the pairwise comparisons, a number of important studies on tunneling are used (Kose et. al. 2007, Langmaack and Seven 2007, ITA 2000, Vardar and Bilgin 2007). The matrix is given in Table 3. In Table 3, it can be seen that the lower, middle and the upper value of selection criteria are given for the purposes of comparison. For example, when C1 and C2 are compared:

- On the average, C1 is weakly more important than C2 (represented by 3, medium value).
- But its importance level is between 2 and 4 (lower and upper values).

In addition, it should be noted that the matrix is filled considering Equation 3.

Table 3. Fuzzy comparison matrix of the main selection criteria

	C1 (Lower, Middle, Upper bounds)	**C2** (Lower, Middle, Upper bounds)	**C3** (Lower, Middle, Upper bounds)	**C4** (Lower, Middle, Upper bounds)	**C5** (Lower, Middle, Upper bounds)	**C6** (Lower, Middle, Upper bounds)
C1	1	(2,3,4)	(3,5,7)	(1/2,1,2)	(4,5,6)	(3,5,7)
C2		1	(4,5,6)	(1/2,1/3,1/4)	(2,3,4)	(4,5,6)
C3			1	(1/3,1/5,1/7)	(1/2,1,2)	(1/2,1,2)
C4				1	(3,5,7)	(4,5,6)
C5					1	(1,2,3)
C6						1

Then the matrix is used to find the priorities belonging to the main selection criteria using formulation 6. OPL Studio 3.7 optimization software is used for the solution. The priorities in Table 4 are obtained. In the solution, the value of λ which tells us the consistency level is 0.882. If λ is equal to 1, this shows us the results are 100 % consistent. The acceptable level of λ is usually said to be 0.7. Therefore, it can be said that the results are quite consistent and acceptable.

Tab. 4. Priorities of the main selection criteria (Example: Criteria C1 is 34.3% important).

Criteria	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Priority	0.3430	0.1470	0.0470	0.3370	0.0790	0.0470

The fuzzy comparison matrices of sub-criteria belonging to geology (C1), ground conditions (C2), tunnel properties (C3), machine technical properties (C5) and project properties (C6) are evaluated as depicted in Tables 4-5 (C1>C4>C2>C5>C3=C6). Since there exist no sub-criteria under geo-environmental hazard (C4), there is no fuzzy comparison matrix for C4.

5.1 Computing Priorities of Selection Criteria

Considering the fuzzy comparison matrices given in Section 3, the priorities of all sub-criteria are computed with formulation 6. The priorities and the level of consistency are given in Table 5 below. Looking at consistency values, it can be said that all computations are consistent.

Tab. 5. Priorities of all selection criteria (Example: Criteria C11 is 17 % important).

Selection Criteria		**Priority**	**Consistency Level**
C1 Geology	C11 Geologic failures	0.170	0.845
	C12 Topography	0.024	
	C13 Hydrogeology	0.050	
	C14 Formation type	0.100	
C3 Tunnel properties	C31 Length of tunnel	0.025	0.831
	C32 Tunnel geometry	0.009	
	C33 Depth of tunnel	0.006	
	C34 Type of tunnel support	0.006	
C4 Geo-environmental hazard/Risk assessment		0.337	1
C6 Project properties	C61 Project duration time	0.011	0.958
	C62 Cost	0.004	
	C63 Constructor reliability	0.031	
C2 Ground Conditions	C21 Mechanical properties	0.065	0.781
	C22 Physical properties	0.017	
	C23 Field experiments	0.012	
	C24 Face stability	0.012	
	C25 Soil classification system	0.029	
	C26 Ground settlement	0.012	
C5 Machines technical properties	C51 Power properties	0.037	0.86
	C52 Cutting head properties	0.013	
	C53 Weight of machine	0.004	
	C54 Shield type	0.009	
	C55 Reaction force	0.011	
	C56 Specific energy	0.005	

5.2 Computing Priorities of Alternative Machines

At the last step of the procedure, all alternative machines are rated over ten for their performance on each selection criterion. Similar to pairwise comparisons, important studies are used as a reference at this step (Kose et. al. 2007, Langmaack and Seven 2007, ITA 2000, Vardar and Bilgin 2007). The grades are given in Table 6. An example from the table is that machine M3 takes 8 points over 10 for C11 (geologic failures) whereas M4 takes 9 points and M7 takes 4 points. This shows that M7 is the best performing machine for C11 and M4 is the least performing machine for C11.

Tab. 6. Performance grades of each machine type according to each selection criterion. The grades are over 10. M_i represents machine i. C_j represents criterion j.

Cn	M1	M2	M3	M4	M5	M6	M7	M8	M9	Cn	M1	M2	M3	M4	M5	M6	M7	M8	M9
C11	5	6	8	9	6	6	4	4	6	**C31**	5	5	5	5	8	7	7	7	7
C12	6	5	9	9	4	5	4	4	3	**C32**	7	7	9	9	5	5	5	5	5
C13	7	6	10	9	4	5	3	2	2	**C33**	7	6	10	9	3	5	4	3	3
C14	7	5	10	9	4	4	3	2	2	**C34**	7	7	10	10	3	5	4	3	3
C21	7	6	9	10	4	5	3	2	2	**C4**	7	6	10	9	3	4	3	3	3
C22	6	5	10	9	3	4	2	2	2	**C51**	7	6	10	10	0	4	3	4	4
C23	6	4	10	9	3	4	3	3	3	**C52**	6	5	10	8	0	4	3	4	3
C24	7	6	10	9	3	5	2	2	2	**C53**	7	8	7	7	9	9	9	8	9
C25	8	6	10	10	4	5	4	5	5	**C54**	7	6	10	10	4	5	4	3	2
C26	8	6	10	10	3	5	3	3	3	**C55**	7	7	10	9	0	4	3	1	1
										C56	8	8	7	7	9	9	9	8	9
										C61	7	7	10	10	2	5	4	4	5
										C62	7	7	6	6	9	9	9	8	9
										C63	7	7	10	10	4	5	4	4	4

After grading all machines the weighted sum of all grades are found by multiplying the priorities of each selection criterion (from Table 5) and the corresponding grade of the machine (from Table 6). Equation (6) gives the computation for machine M1. All other final scores are computed in the same manner and given in Table 7.

$$[5\ 6\ 7\ 7\ 7\ 6\ 6\ 7\ 8\ 8\ 5\ 7\ 7\ 7] \times \begin{bmatrix} 0.17 \\ 0.024 \\ 0.05 \\ 0.1 \\ 0.065 \\ 0.017 \\ 0.012 \\ 0.012 \\ 0.029 \\ 0.012 \\ 0.025 \\ 0.009 \\ 0.006 \\ 0.006 \\ 0.337 \\ 0.037 \\ 0.013 \\ 0.004 \\ 0.009 \\ 0.011 \\ 0.005 \\ 0.011 \\ 0.004 \\ 0.031 \end{bmatrix} = 6.6 \qquad (6)$$

Tab. 7. Final grades of each machine.

Machine	M1	M2	M3	M4	M5	M6	M7	M8	M9
Rate	6.6	5.9	9.4	9.1	3.8	4.7	3.5	3.3	3.6

As seen from Table 7, the highest score belongs to machine M3. M3 is recommended to the decision maker for the tunnel under study. The second highest score belongs to M4 and it is very close to M3. Therefore, this machine can also be used for this tunnel. However, all other machines have very low scores compared to these two. This shows us that they are not suitable for this tunnel at all.

6. Discussion and Recommendations

Multicriteria decision making methods are very useful in selecting production techniques and machines. Fuzzy AHP (FAHP) is a suitable method for multi-criteria decision making problems where the comparisons between selection criteria are vague. By FAHP decision errors in evaluating decision criteria can be decreased. This methodology is strongly advised to be used in tunnel projects since it is both fast and inexpensive. In this study FAHP is used to evaluate the selection criteria of a tunnel boring machine for soft ground conditions. Among a number of criteria pairwise comparisons are made by stating lower and upper bound. Then priorities to each criterion are assigned and the final scores of each alternative machine are computed. The excavation machine to be used is determined according to the final scores of each machine.

Among the selection criteria, geology (C1:34 %), and geo-environmental hazard/Risk assessment (C4:33.7 %) are found to be the most important factors affecting the selection of tunneling machine. Other criteria are found to be ground conditions (C2:14.7 %), machines technical properties (C5:7.9 %), tunnel properties (C3:4.7 %) and project properties (C6:4.7 %), respectively.

When we consider only the sub-criteria, the most important one is found to be geologic failures (C11:17 %), formation type (C14:10 %), mechanical properties (C21:6.5 %), hydrogeology (C13:5.0 %), respectively. Among geologic failures, especially faults are important. The crossing of fault zones in TBM tunnelling represents in general a problematic event. It may cause blockage of the TBM head and hence slows down the progress rate and causes delay in time schedule.

In this research, a sample application of FAHP on selection of excavation machine in the Izmir subway tunnel is given. EPB TBM allows soft, wet, or unstable ground to be tunnelled with a high speed and safety which was previously not possible. It limits ground settlement and produces a smooth tunnel wall. This significantly reduces the cost of lining the tunnel, and makes it suitable to use in heavily urbanized areas. Therefore, EPB TBM is selected for the tunnel project.

Tunneling is a sector with severe uncertainty conditions. In order to minimize uncertainty, FAHP which is an effective multi-criteria decision making tool is employed in this study. The results are very promising. Therefore, this methodology can also be used in future tunnel projects. The selection criteria and the pairwise comparisons can easily be adjusted according to the specific tunnel conditions and the most suitable excavation machine can be selected for the tunnel. Furthermore, the study results are thought to be helpful in selecting the machine type for the other tunnels which will soon be started in Turkey.

7. Conclusion

Tunnelling projects have very costly initial investments. Therefore, selecting a wrong type of machine would be very costly to the firm as well as causing the delay of the project. There are many different factors affecting the type of machine to be used. For this reason, employing a quantitative method to select the excavation machine rather than an intuitive method would decrease errors and lead to correct decisions.

As a result of the study, EPBM (M3) was found to be the most suitable machine for the tunnel under study. Slurry type machine (M4) turned out to be the closest alternative. Also, M1 and M2 type machines achieved acceptable scores. However, all other alternative machines achieved very low scores and should not be employed in the case under study at all. M3 and M4 type machines are very advantageous for Konak-Basmane line compared to all other machines. Fast tunnel extraction and decreasing geo-environmental risks (minimum ground settlement and protecting tunnel walls) would decrease tunnel costs. Considering the field studies and the decision making criteria, selecting machine type M3 is consistent with the results of the study.

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