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CHOOSING TBM FOR TABRIZ SUBWAY USING MULTI CRITERIA METHOD

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Abstract. The world of underground engineering and construction has acquired a wide-ranging and high-level experience on tunnel construction with Tunnel Boring Machines (TBM) and nowadays remarkable progresses are traceable in the number of tunnels that are becoming longer, going deeper, and growing larger in diameter and in other words becoming more difficult to realize. Tabriz-one of the big cities in northern west of Iran has four subway lines which are under construction or investigation. The phase1 design of Tabriz urban railway line 2 (TURL2) has completely been done. Method statement of this line in the length of about 20 km and much interference due to tunneling in urban area dictates the application of TBM. Two kinds of TBM such as EPB (earth pressure balance) and SS (slurry shield) are usually used for urban areas. In this paper, the process of choosing TBM for TURL2 using MCA method (Multi Criteria Analysis) is expressed. Generally in this method some technical, economical and environmental parameters affected the TBM type are identified and taken into account by assigned weights related to the case study. Finally the results show that EPB-TBM will be more appropriate choice for TURL2 excavation.

Keywords: Mechanized tunneling, TBM, Tabriz subway, Multi Criteria Analysis, TURL2.

1. Introduction

Tabriz with 160 km^2 area and the population about 1,360,000 is one of crowded and important cities in north western Iran. According to traffic and transportation studies, 4 light urban railways with the length of 48 km (extendable to 72 km) are considered for this city (Fig. 1). General method statement of Tabriz Urban Railway Line 2 (TURL2) with 20 km in length expressed that the whole route will be excavated by two TBM. One of them starts from station A_{2-1} toward station G_2 and the other one starts from station N_2 toward station G_2. The excavation of the 2 TBMs is oriented in order to meet at the central point of the route in the center of city. Third part – station O_2 to S_2 – will be excavated by one of them which can finish its first duty. Two kinds of TBM such as EPB (earth pressure balance) and SS (slurry shield) are usually used for urban areas. Therefore choosing TBM between the two kinds such as EPB and SS based on important parameters affecting the machine operation including soil grain size, presence of boulders, hydrogeology condition, presence of cavities, and sticky material will be very important.

The subject of TBM selection has attracted much attention of many researchers recently (among others, Marinos *et al.* 1998, 2008, 2009; Shahriar *et al.* 2008; Erickson *et al.* 2008; Lehner and Hartmann 2007; Imaishi 2007; Lovat 2006; Diponio *et al.* 2007; Fan and Yu 2005; Anonymous 1995, 2005; Babendererde *et al.* 2004; Skelhorn 2005; Thewes and Burger 2004; Langmaack 2001, 2002; Nilsen *et al.* 2006; O'Carroll 2005; Chang *et al.* 2006; Bilgin *et al.* 2004; Shang *et al.* 2004; Farrokh and Rostami 2008; Dowden *et al.* 2001; Kalamaras *et al.* 2001; Marinos *et al.* 1998; Morris and Hansmire 1995; Xu *et al.* 1996; Sonmez and Ontepeli 2009). The investigations of Marinos *et al.* (2008) on applicable TBM for western extension of the Athens (both EPB or SS) and applicability of each type of TBM has been discussed using the available data obtained from an extensive site investigation. Shahriar *et al.* (2008), based on geotechnical risk minimization and a new approach analyzing decisions using decision tree selected a TBM for Nosoud water transfer tunnel (located in Iran) for problems such as encountering fault zones with running and water bearing gouge, tunnel walls instabilities in running or blocky grounds, hard and abrasive rock sections and convergent tunnel sections. Moreover, San Francisco Public Utilities Commission planned to replace 5 miles of pipeline under San Francisco Bay using a tunnel constructed by TBM. In order that the alignment supposed to pass under environmentally sensitive habitats through inter-bedded layers of sands and clays and buried bedrock ridge, Erickson *et al.* (2008), considering the geotechnical characterization and anticipated tunnelling conditions and various construction

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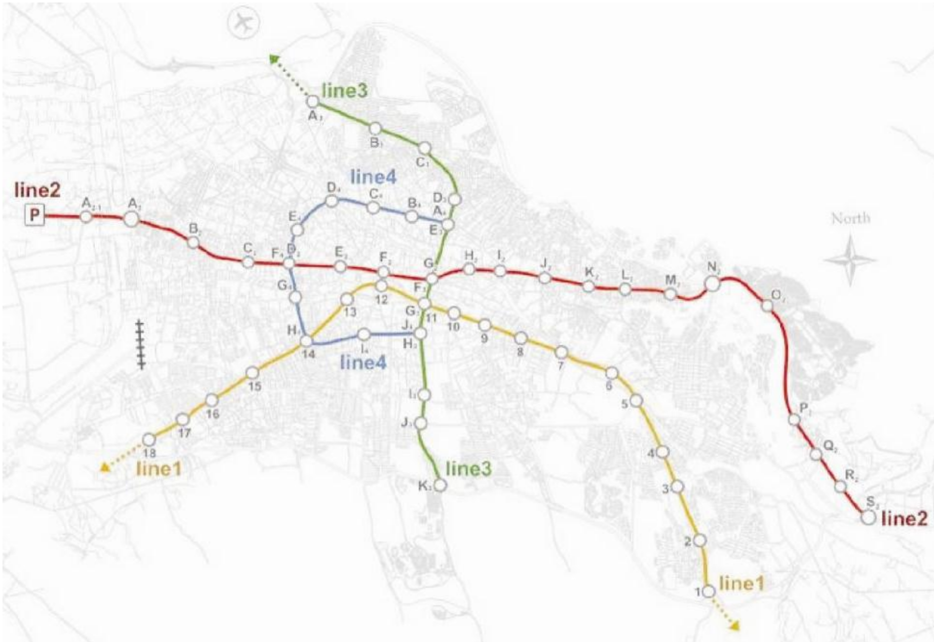

Fig. 1. Tabriz urban railways

methods finally select an EPB TBM described in detail. Also (Lehner and Hartmann 2007) applying fuzzy logic in selection of a tunnel boring machine showed that Fuzzy logic can be used to assist engineers in the process of making decisions, selecting from a range of options or classifying objects.

In this paper, after presenting affected criteria in TBM selection such as technical, economical and environmental objects, appropriate weight to each item is assigned according to engineering judgment. Then considering conditions like maximizing technical adequacy, minimizing excavation risk, costs, excavation duration and environmental impacts, MCA method (Multi Criteria Analysis) is used and finally applicable TBM for TURL2 is selected.

2. Geological geotechnical context

The TURL2 alignment can be subdivided in three sections:

1. Western extension: from the depot area to $A_{2\text{-}1}$ station about 2 km long (cut and cover method).
2. Main part: from station $A_{2\text{-}1}$ to O_2 about 12.5 km long (mechanized excavation method).
3. Eastern extension: from station O_2 to S_2 (final station) about 6.5 km long. (mechanized excavation method).

Geomorphology of the project region is formed under the effect of tectonic forces, faults, folds and erosion. The North Tabriz fault is located between North Mountains and Tabriz plain. There are many minor faults located at the southern part of the Tabriz city. Erosion and sedimentation are the main factors, affecting the outcrop of the region. Mehran River (Ghoorichay) is one of the most important rivers of the region, which is 200 to 300 meters apart from the investigated corridor, which meet the TURL2 between stations G_2 and H_2. General geological specifications of different parts of TURL2 are presented in Table 1.

Table 1. Geological specifications of different parts of the route

Zone	Main geological/geotechnical features
From western part to station L_2 (mid line of main part)	Quaternary deposit (Variable permeability + grain size distribution)
From station L_2 to O_2	Bed Rock (Marlstone + Siltstone + Sandstone)
From station O_2 to P_2 (mid line of eastern part)	Quaternary deposit (Variable permeability + grain size distribution)
From station P_2 to S_2 (end of eastern part)	Bed Rock (Marlstone + Siltstone + Sandstone)

3. Effective factors of TURL2 mechanized excavation

The only two suitable TBM for TURL2 construction are EPB an SS TBM's due to urban area with ancient/important building, underground interferences, critical geotechnical and hydrogeological conditions. General comparison between EPB and SS types of TBM are presented in Table 2. Mechanized excavation of TURL2 tunnel is influenced by geotechnical and environmental items explained as below:

3.1. Grain size distribution

Grading test results of TURL2 in main and extension parts are entirely piled up in Figs. 2, 3, 4 and 5 respectively. According the displayed grain size distributions, both the TBM type machines appear applicable with maybe some preference for the Slurry.

Table 2. General comparison between SS and EPB types of TBM

Items	SS	EPB
Grain size distribution	Fine sand, sand, gravel	Clay, silt, fine sand, sand
Presence of boulders	Use stone crusher	Remove boulders by hand
Sticky behavior	Add polymers to slurry	Cutter head opening design
Face pressure management	By bentonite slurry pressure	By excavated material pressure
Face stability	Controlled by the "liquid" slurry	Controlled by "dense" slurry pressure like a paste
Surface settlement	Face support pressure + grout behind segments	Face support pressure + grout behind segments
Mucking	Pumped out	Extracted by screw conveyor
Working Cycle Efficiency	Muck-out by pumps (continuous)	Muck-out by train (not continuous)
Maintenance	Chamber entrance possibility from air cushion	Difficulty for chamber entrance
Environment	Ease to separate soil from liquid by separation plant	Muck can be too liquid and difficult for transport to disposal areas
Ease of operation and tolerance to operator experience	Need high experience	Relatively lower risk level
Costs	Higher cost because of separation plant	Operational costs increasing for ground conditioning necessities

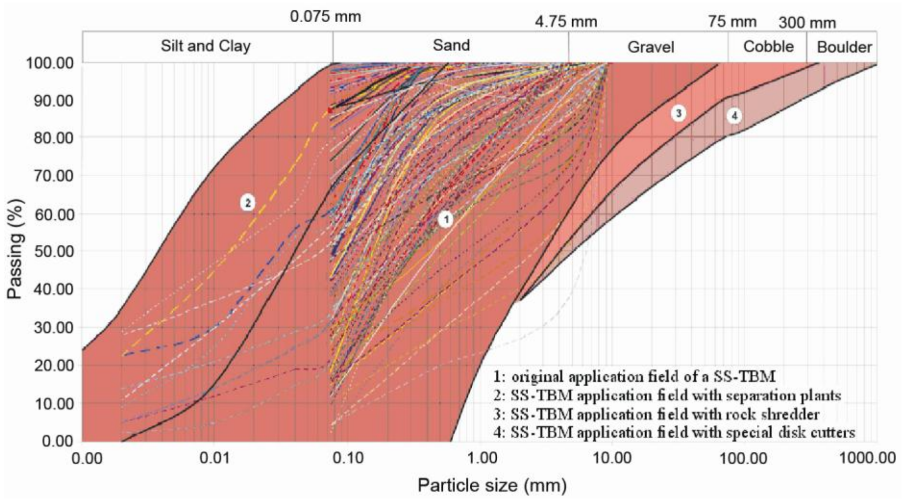

Fig. 2. Grading test results of main part soil on field of SS-TBM

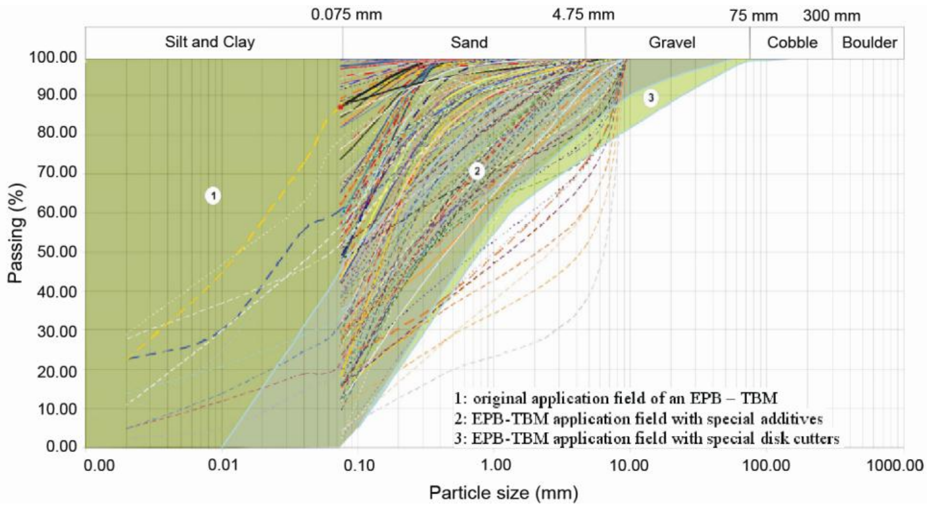

Fig. 3. Grading test results of main part soil on field of EPB-TBM

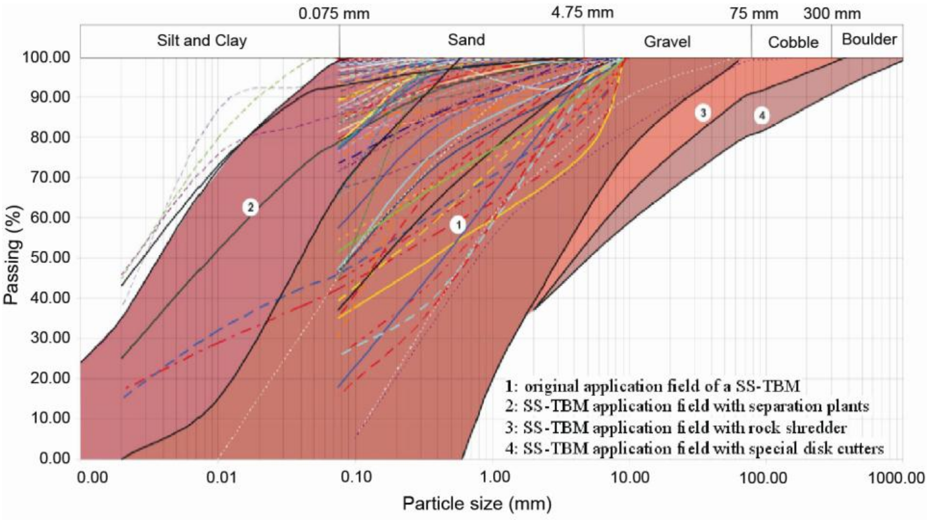

Fig. 4. Grading test results of extension part soil on field of SS-TBM

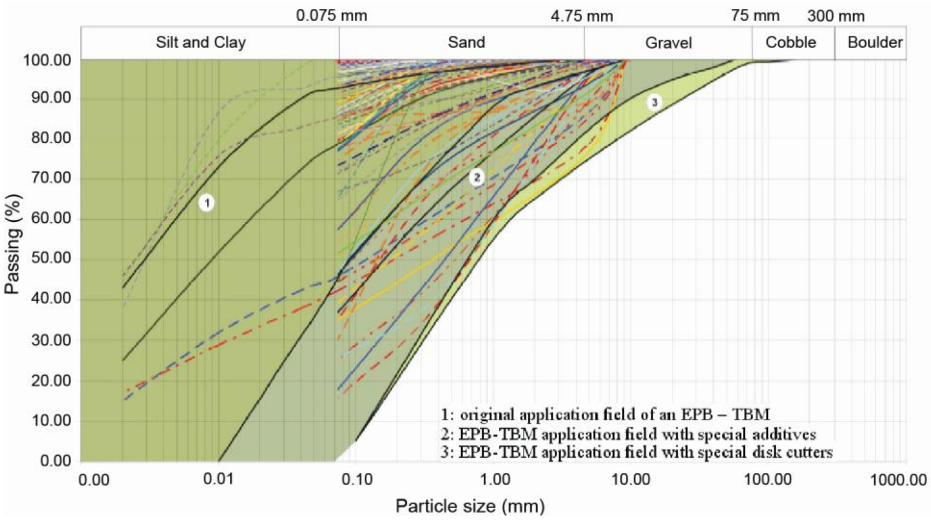

Fig. 5. Grading test results of extension part soil on field of EPB-TBM

3.2. The presence of boulders

Historically, boulders are a frequent source of problems in soft ground tunneling. During tunnel construction, breaking and removing boulders manually as obstructions cause delays to the project. A tunnel boring machine (TBM) maintenance can also cause delays. Managing these problems is difficult since normal soil investigation techniques do not accurately predict the presence or frequency of boulders. This has lead to considerable number of claims for extra costs and delays during the construction of soft ground tunneling projects. These issues are exacerbated in pressurized face tunneling systems where there is limited access to the TBM cutter-head for obstruction removal and/or cutter-head maintenance (Diponio *et al.* 2007; Dowden *et al*. 2001). Mechanized tunnel excavation of Tabriz subway line 1 (TURL1) was started with low advance rate due to the presence of boulders not passing through the screw conveyor (Fig. 6)

Fig. 6. Some boulders given during TURL1 mechanized excavation

causing stop of the excavation and requires extra maintenance of the cutting tools. During excavation of TURL1, usually the settlement is zero but it had sudden collapse due to the problems listed above. Due to the presence of Sahand volcanic mountain, the Mehran River has brought along its bed some big boulders (more shallow) and some smaller ones (deeper). The complementary geotechnical investigations on the route of TURL2 have confirmed the presence of boulders both between stations F_2 and G_2 and in the eastern part whilst boulder depth estimating is difficult. It is possible to use a stone crusher that can destroy boulder with diameter up to 80–90 cm inside a SS. An EPB machine with excavation diameter of approx.10 m can be equipped with a screw conveyor with diameter around 1 m. In this case the maximum dimension of the boulders extractable inside the muck is about 30–40 cm.

3.3. The permeability of the ground and the water pressure

In general it is possible to say that the permeability values are compatible with the usage both TBM's type because the instant pressure produced by such phenomena can be managed by both TBMs. In EPB TBMs a risk can be water inflow into the screw conveyor. Hence it is necessary to have an adequate pressure at the face and a water resistant closing gate. Fig. 7, shows the Permeability test results done in TURL2 geotechnical investigation.

3.4. The sticky behavior

When a TBM excavates through zones with high percentage of clays and silts "sticky behavior" occurs which can highly reduce the TBM progress and in some cases even cause a complete stop of the advancement of the tunnel. A simple and efficient method exists for assessing the stickiness of the ground to be excavated, based on the natural water content (W_n), plastic limit (W_P) and plasticity index (I_p). The ground should have a sticky behavior if $W_n/W_p \geq 1.0$ and $I_p \geq 0.25$.

Generally, sticky behavior may strongly influence the cutter head configuration (opening ratio percent), mucking path from the plenum to the first conveyor belt and also torque amount to be supplied to the cutter head (in EBP). Hazard of clogging in muck circulation is so dangerous that the plenum should be designed to ease the movement of muck from its upper part to its lower part (Thewes and Burger 2004).

Thus, the openings in the centre part of the chamber shall be bigger than in the external part because in the central part of the plenum the speed is the lowest. The experiences show that a cutter-head clogging start in this central part where the tangential speed of the cutter-head is rather low and consequently the excavated material is relatively slow and results initiation of front cutter-head clogging which increases until complete blockage of advance. A wider open center design also limits the wear on the cutter-head structure and increasing the flow of the material and these phenomena increase cutter-head torque and required thrust and eventually put severe limits on the TBM advance rate. For appropriate design of cutter-head, injection of additives to the front or in the cutter chamber should be implemented wherever necessary.

3.5. The risk of gas

According to geotechnical investigations, CO_2 has been encountered near station M_2 which is very risky for the safety of the personnel working inside the tunnel. Hence flameproof machinery and an adequate air monitoring system will be necessary for both 2 TBMs.

3.6. Required space for separation plants

The SS requires an area to install of at least 10.000 m^2 which is not available in Tabriz. So, this subject will be a negative score for SS TBM.

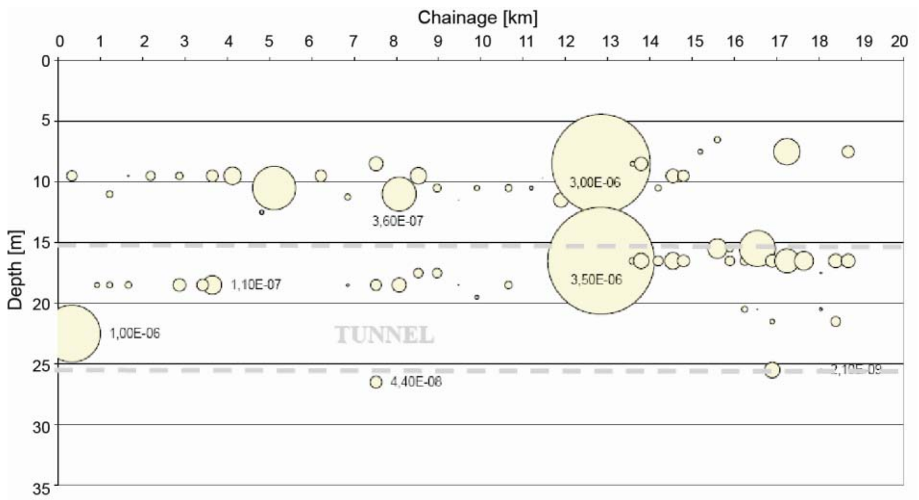

Fig. 7. Permeability test results done in TURL2 geotechnical investigation

3.7. The closed face TBM's type experience in Iran

Actually in Iran there are 8 TBMs with face support and all of them are EPB. It must be considered that foreign personnel is difficulty available in Iran for this reason also considering the complexity of conditioning slurry it is necessary to consider properly the lack of experience as a major item to choice. The correct choice of machine without the correct management and operating controls is as bad as choosing the wrong type of machine for the project (BTS/ICE 2005).

3.8. The suitable TBM's costs

From cost point of view, the cost of SS and EPB types of TBM including TBM, Back-up system and auxiliary equipments is 22 and 17 million Euro respectively.

4. MCA (Multi Criteria Analysis) concept

The comparative evaluation of alternative scenarios on the basis of different criteria requires special tools that allow the comparison of different subject inside a unique system. The MCA method is suitable to solve this kind of feature and to provide a scheme where different themes (the criteria) shall be taken into account simultaneously (Guglielmetti *et al.* 2008).

This method allows the direct comparison between alternatives using a numerical index. MCA method allows calculating a performance index for each alternative. Each column of the performance matrix (criteria) can be transformed in a utility scale (u_j) varying from 0 to 1 where 0 represents the worst performance and 1 represents the best performance.

The utility (U), or rating, of each alternative (x) is calculated as the sum of the values coming form each criteria normalized to its weight (P_i):

$$U_x = \sum_{i,j}^{n} u_j * P_i . \quad (1)$$

The weights allow defining the relative importance of each factor compared to the others.

$$\sum_{i}^{n} P_i = 1. \quad (2)$$

Based on expressed important items the weight of each criterion is presented in Table 3.

5. Comparison between EPB and SS using MCA method

Most important objects in MCA comparison method are:

- To maximize the technical adequacy (reduction of construction time);
- To minimize the costs;
- To minimize the environmental impact.

The line with varying length and relative weights is reported in Table 4.

Table 3. The weights assigned to each criterion based on Tabriz condition

Sub-Goals	Criteria	Weight
Technical Adequacy (affecting construction time)	Grain size distribution	0.15
	Presence of boulder	0.4
	Presence of cavity	0.2
	Sticky material	0.05
	Hydrogeological condition	0.15
	Water inrush	0.05
Costs	Cost for TBM furniture and assembly	0.4
	Cost of excavation of each part	0.6
Environmental Impact	Land occupancy	0.5
	Muck disposal	0.25
	Aquifer protection	0.25

Table 4. The length and relative weights of each part of TURL2

Sub-Goals	Criteria	Geotechnical condition	Distance (m)	Weight (%)
Main Part	Station A_{2-1} to G_2	Soils	7040	39
	Station G_2 to O_2	Soil with boulder	6485	36
Extension Part	Station O_2 to P_2	Soil with boulder	3070	17
	Station P_2 to S_2	Rock	1420	8

The grain size distribution appears to be most suitable for a SS TBM. Only in the eastern part in the final zone of excavation through marlstone an EPB TBM is preferable. Generally EPB TBM is adaptable to the route by means of some additives.

The risk of boulders is predictable from the G2 station up to the start of the marlstone in the eastern part and a SS TBM is much preferable in this condition to an EPB TBM.

The presence of cavities is a risk especially dealing with the centre of the city where usually exist wells or manholes for ancient sewerage lines. These structures shall be very dangerous for a SS TBM because if such a TBM encounters them during excavation it may cause a loss of pressure at the face with risk of high settlements and/or collapses affecting the surroundings structures. Moreover loss of slurry inside wells may exit of it to the surface or cause groundwater pollution.

The sticky behavior is a hazard along the line that can cause low advance rate and SS TBM is a bit preferable for this hazard. Anyway the difference between these two systems in these conditions is almost negligible. For an EPB the eventual occurrence of water inrush cannot be excluded if the excavation chamber is not full of saturated material with consequent risk of stoppage of the advancement and even safety problems for the workers. The overall comparison of the two alternatives with respects to the different criteria is summarized in Table 5.

Table 5. Overall comparison of the two alternatives

	Station $A_{2\text{-}1}$ to G_2		Station G_2 to O_2		Station O_2 to P_2		Station O_2 to N_2		Overall Ratings	
	Weight = 0.39		Weight = 0.36		Weight = 0.17		Weight = 0.08			
	EPB	SS	EPB	SS	EPB	SS	EPB	SS	EPB	SS
Grain Size Distribution	0.8	1	0.8	1	0.8	1	1	0.8	0.82	0.98
Presence of Boulders	1	1	0.2	1	0.2	1	1	1	0.58	1
Presence of Cavities	1	0.5	1	0.5	1	1	1	1	1	0.63
Sticky Behavior	0.8	1	0.8	1	0.8	1	0.8	1	0.8	1
Hydrogeological condition	0.8	1	0.8	1	0.8	1	1	1	0.82	1
Water inrush	1	1	0.8	1	1	1	0.8	1	0.91	1

Table 6. Final making decision about EPB or SS for TURL2 mechanized excavation

Sub-goals↓ Alternatives →	EPB	SS
Technical adequacy (T)	0.763	0.923
Costs (C)	1	0.792
Environmental Impact (E)	1	0.675

Table 7. Sensitivity analysis final making decision about EPB or SS

Scenario	EPB	SS
T = 0.33; C = 0.33; E = 0.33	0.921	0.797
T = 0.50; C = 0.25; E = 0.25	0.882	0.828
T = 0.25; C = 0.50; E = 0.25	0.941	0.796
T = 0.25; C = 0.25; E = 0.50	0.941	0.766
T = 1.00; C = 0.00; E = 0.00	0.763	0.923
T = 0.00; C = 1.00; E = 0.00	1	0.792
T = 0.00; C = 0.00; E = 1.00	1	0.675

Based on Table 6, it is obvious that EBP TBM will be more appropriate than SS TBM for TURL2 excavation. The rating of the main goal "Best choice of the TBM" is evidently related to the weight assigned to each sub-goal. Considering the subjectivity of such estimation, a sensitivity analysis has been performed considering different scenarios of assignments. In Table 7, the results of the multi-criteria analysis according the different scenarios are summarized, including also for completeness the case of absolute preference for each sub-goal already shown in Table 6. According to the Table 7, only one scenario suggests using SS TBM whereas we consider only technical aspect. It proves that considering all aspects including C and E it is appropriate to choose EPB TBM.

6. Conclusion

Choosing TBM process for Tabriz Urban Railway Line 2 (TURL2) using multi criteria analysis (MCA) is expressed in this paper. Generally it is possible to say that in the excavation through soft soils in urban areas the TBM should be chosen between EPB TBM and SS Using multi criteria analysis (MCA) method. It is identified that technical, economical and environmental criteria affect the TBM type. Site investigation and other line of Tabriz experiences show that the most important parameters affecting TBM type will be grain size distribution, presence of boulder, permeability and water pressure, soil sticky behavior, risk of gas, required space for separation plants. Based on significance of each criterion, a specified weight is assigned. From technical point of view the experience from TURL1 in presence of boulders affirms that boulders in Tabriz are the most important problem for mechanized excavation. For this reason the use of a SS TBM seams to be preferable. On the other hand SS presents some general disadvantages such as necessity of experienced team, major spaces for separation plants, major consumes and purchasing costs.

In any case technical specification is valuable both for EPB and SS TBMs but it is very important that the manufacturer should propose machine which can operate in presence of boulders without continuous prolonged stoppages and/or having face instabilities that may cause damage to the surroundings. Therefore EPB TBM plus some additives is more appropriate for TURL2 excavation.

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TABRIZO METRO TGM PARINKIMAS TAIKANT DAUGIATIKSLĮ SPRENDIMŲ PRIĖMIMO METODĄ

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Santrauka

Požeminė inžinerija ir statyba labai išplito bei įgijo aukšto lygmens patirtį tunelių statyboje ėmus naudoti tunelių gręžimo mašinas (TGM). Šis statybos būdas taikytas statant daug tunelių, kurie vis ilgėja, gilėja ir platėja pagal skersmenį, t. y. statyba realizuojama sunkiau. Tabrize – viename iš didžiausių šiaurės vakarų Irano miestų – yra keturios statomos arba planuojamos statyti metro linijos. Tabrizo miesto geležinkelio 2-os linijos (TMG2L) pirmoji projektavimo fazė yra baigta. Jos ilgis – 20 km, daug jos atkarpų eina po žeme. Požeminėms atkarpoms pastatyti gali būti naudojamos dviejų tipų TGM. Tai žemės slėginės pusiausvyros mašina (ŽSPM) arba suspensijos skydo mašinos (SSM). Šiame straipsnyje nagrinėjamas TGM pasirinkimas tarp ŽSPM ir SSM taikant daugiatikslį sprendimų priėmimo metodą (DSPM). Šiam metodui pritaikyti apibrėžiami tam tikri techniniai, ekonominiai ir aplinkos rodikliai, darantys įtaką TGM tipui. Rodikliams priskiriami svoriai. DSPM taikymo rezultatai parodė, kad ŽSPM yra tinkamesnė TMG2L kasti.

Reikšminiai žodžiai: mechanizuotas tunelio kasimas, TGM, Tabrizo metro, daugiatikslis sprendimų priėmimas, TMG2L.

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