Engineering geological studies used for redesigning and employing a hard rock TBM in soft rock formations of Chamshir water conveyance tunnel

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Abstract

The Chamshir water conveyance tunnel (CWCT) with a length of 7.4 km passes through soft marlstones and mudstones of the Aghajari formation and strong conglomerates and sandstones of the Bakhtiari formation, which are two main widespread formations in the Zagros simply folded zone in southwest Iran. This tunnel with a boring diameter of 5.3 m is excavated using a refurbished single shield TBM, initially designed to work in hard rock formations. This study focuses on engineering geological and geotechnical issues, which are important for checking the suitability of this machine and proposing required modifications for improving its performance in soft rock. The main objective of the investigation was to predict geological problems (clogging potential, swelling potential, abrasive ground, unstable tunnel face and probable water inflow) associated with TBM tunneling in the given ground conditions and to examine the ability of the selected TBM to overcome the anticipated challenges. Estimated tool wear in this project is also discussed using a new special prediction model, and the results are compared with actual disc cutter consumption in the excavated section of the tunnel. The actual observations and measurements in the first 1500 m of the tunnel indicate the validity of the assessments in the related engineering geological types. In addition, the study of machine specifications showed that the machine can excavate the tunnel by implementation of required modifications, especially the use of proper cutting tools and improvement in cutterhead design.

Keywords: *TBM Tunneling, TBM Selection, Geological Problem, Clogging, Tool Wear, TBM Performance.*

Introduction

Adverse geological conditions can increase construction time and cost, operational risks, safety issues, and environmental damages in mechanized tunneling projects. Anticipated geotechnical conditions, especially adverse conditions and geological problems along the alignment are critical to the selection of a new machine and the related components on the machine and its backup system, or the adjustment of technical specifications of a used machine to match the new conditions.

This paper presents the case study of the Chamshir water conveyance tunnel (CWCT) in Southwest Iran which is being excavated mainly through soft rocks using a used single shield machine. The main concern in this project was the suitability of the selected machine, which was initially designed for hard rock conditions, to meet the requirements for the special geological conditions of the project.

This paper will discuss the results of studies performed to identify engineering geological units and to measure the geomechanical properties of the formations along the tunnel alignment. Moreover, the additional efforts to identify geological problems will be discussed. The suitability of the selected TBM to offer a reasonable performance in the anticipated conditions will be checked using information gained from engineering geological studies. The evaluation of machine specifications for this project was based on the guidelines offered by the German Tunneling Committee or DAUB (Deutscher Ausschuss für unterirdisches Bauen) (DAUB, 2010). A brief description of the original TBM specifications and required modifications to fit the anticipated conditions along the project tunnel alignment will be presented. Also, tool wear predictions will be briefly described and compared with observations from completed sections of the tunnel.

Project description

The CWCT project is one component of the water management system in Southwest Iran. This tunnel with a length of approximately 7.4 km and boring diameter of 5.3 m has been designed to transfer 30 m^3/s of water from the Zohreh River to the Deylam plain, as shown in Fig. 1.

A used single shield TBM was procured and modified (based on the engineering geological settings of the Chamshir project) to excavate the total length of the tunnel from the Northern portal. Currently, about 1500 m of the tunnel has been excavated from this portal. The machine installs universal, 25cm-thick pre-cast concrete segments, in the tail shield as it advances.

TBM specifications

A used, single shield TBM (model S-124) manufactured by Herrenknecht, which had been designed for hard rock conditions, was procured by the contractor to excavate the tunnel. The original cutterhead, as shown in Fig. 2, featured 34 disc cutters, each 432 mm (17 inches) in diameter, with average spacing of 78mm (~3 inches). Disc cutters can be replaced by rippers depending on geologic materials encountered during tunnel excavation. Other main technical specifications for the TBM are summarized in Table 1.

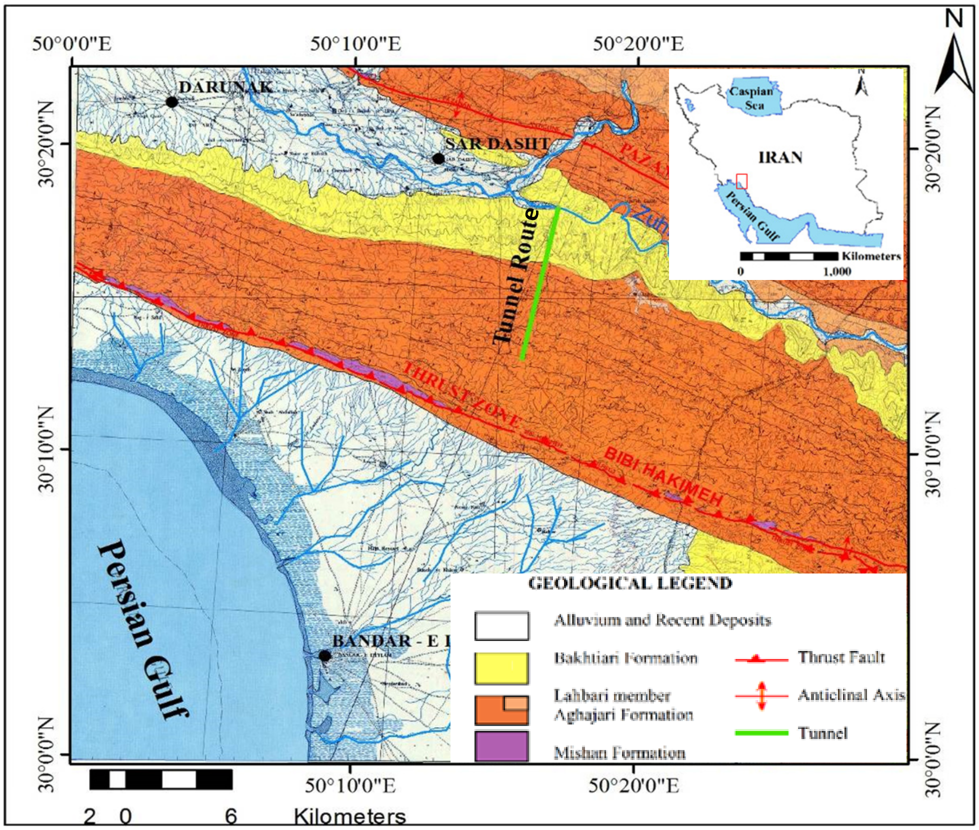
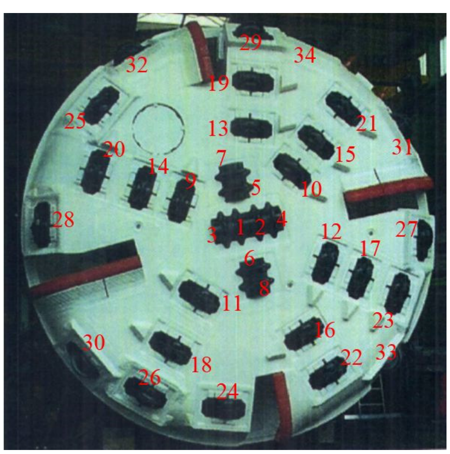
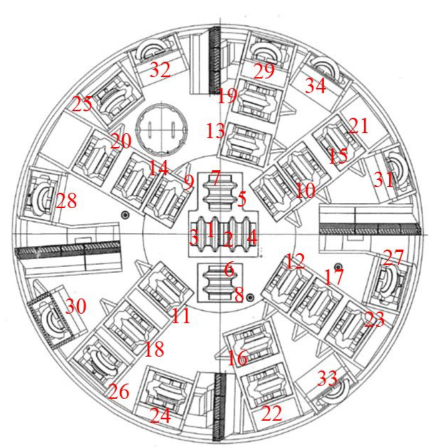


Figure 1. Geographical and geological map of the project site (based on 1:100000 geological map prepared by NIOC)



(a)



(b)

Figure 2. Picture (a) and drawing (b) of the original cutterhead (the numbers indicate cutter positions in cutterhead)

Table 1. Main specifications of TBM for CWCT project

Parameter	Value
Machine diameter	5.3 m
Number of disc cutters	34
Diameter of disc cutters	432 mm
Maximum operating cutterhead thrust	9350 kN
Cutterhead power	5 * 400 = 2000kW
Cutterhead speed	0 to 9 rpm
Cutterhead torque (nominal)	2500 kNm (6.5 rpm) 1500 kNm (9 rpm)
Thrust cylinder stroke	1,700 mm
Conveyor capacity (approx.)	300 m3/h
Cutterhead weight (approx.)	60 tons

As will be explained later, due to presence of soft rocks in extended reaches of the tunnel alignment, a modification of the machine was necessary to improve its performance. The most important modification was rearrangement of cutting tools on the cutterhead. In the new arrangement of cutting tools on the head, the mounting blocks for installing 10 additional rippers (112mm in width) were welded on the cutterhead. These rippers will be used when machine enters soft rock formations.

Geological settings

The area around the tunnel is located in the simply folded Zagros zone (SFZ) in Southwestern Iran. As shown in Fig. 1 and Table 2, the main stratigraphic units, which outcrop in the project area include mudstones, marlstones, sandstones and siltstones of the Aghajari Formation. In some synclines and lower parts of anticline limbs, the Aghajari Formation is covered by conglomerates and sandstones of the Bakhtiari Formation and Quaternary deposits.

This region includes very wide and gently folded parallel anticlines and synclines. The Bibi-Hakimeh anticline with a NW-SE trend, parallel to general trend of the SFZ, is the main structure in the project area which covers the total length of the Chamshir tunnel in its Northeastern limb. The geological cross section along the tunnel alignment is shown in Fig. 3.

Geological site investigations did not identify any important fault zone along the tunnel. The main fault around the project is the Bibi-Hakime reverse fault with the NW-SE trend and parallel to the axis of the anticline (Fig. 1).

Geotechnical investigations

As part of geotechnical site investigation, a series of exploratory boreholes were drilled along the tunnel alignment (see Fig. 3) to observe the rock mass characteristics at depth, measuring groundwater level, performing field tests and collecting samples for laboratory tests. Table 3 lists the 13 boreholes with a total length of 1017 m which were drilled during the site investigation phase. The most important field test was the Lugeon (Packer) test. This test was performed in all boreholes (except for boring T8) to determine permeability in varying depths around each the boreholes. Borehole T8 was selected for dilatometer testing and estimation of deformation modulus of host rock along the alignment.

Many samples were collected from boreholes and surface outcrops for rock mechanics testing to determine physical and mechanical characteristics of the different rock units (Table 4).

Engineering properties of the formations at the project site

Engineering geological studies are important for successful application of mechanized tunneling, particularly in soft rocks. Therefore, a detailed site characterization program was carried out in this study to collect required information to identify engineering geological units and quantify their engineering properties, to predict geological problems pertinent to TBM tunneling and to evaluate TBM specifications and potential alternative approaches to overcome adverse ground conditions.

Identification of engineering geological units

Field investigations and geotechnical reports prepared by Sabir (2014) show that the tunnel can be subdivided into six different engineering geological types (ET) with uniform characteristics related to TBM performance, tunnel stability, and groundwater inflow. These engineering geological types (ET), which are uniform in their physical state, are subdivisions within lithological types (LT). Each engineering geological type has distinctive geological and engineering properties (International Association of Engineering Geology or IAEG, 1976; Dearman, 1991). Fig. 3 shows the distribution of these units (lithological types and engineering geological types) along the tunnel. General characteristics of these engineering geological types are listed in Table 4. Pictures of the outcrops of engineering geological types are shown in Fig. 4 (a-d).

Intact rock properties

As mentioned earlier, many laboratory tests were performed on samples collected from boreholes and surface exposures, during the preconstruction phase (Table 3).

Table 2. Stratigraphic formations and identified engineering geological types along the tunnel alignment

Formation	Chainage (m)	Lithological types and their symbol		Eng. geological types and their symbol	
Quaternary deposits	At the Northern entrance	Al	Coarse grained alluvium	Cn-al	Cemented coarse grained alluvium, rounded particles
Bakhtiari (Plio - Pleistocene)	100-1700	Bk	Mainly conglomerate with interlayers of sandstone and siltstone	Cng1	Weak conglomerate
				Cng2	Thick-bedded, strong, well-cemented conglomerate
				Snd	Weak to moderately strong sandstone and siltstone
Aghajari (Upper Miocene to Pliocene)	1700-2550	Aj1	Mainly sandstone and siltstone beds with minor thin beds of mudstone	Snd	Weak to moderately strong sandstone and siltstone
	2550-3600	Aj2	Mainly mudstone with thin beds of weak sandstone and siltstone	Md	Weak Mudstone
				Snd	Thin beds of weak to medium strength sandstone and siltstone
	3600-7460	Aj3	Alternation of grey and red marls and mudstone with rare thin beds of weak sandstone and siltstone	Ml	Weak marlstone, joints are filled with gypsum
				Md	Weak mudstone

Table 3. List of drilled boreholes along the tunnel and performed field tests in each borehole

No	Borehole	Depth (m)	Coordinates (UTM)		Formations	Field tests	
			X	Y		Lugeon test	Dilatometer test
1	BH-9	110	430690	3349725	Bakhtiari - Aghajari	21	---
2	BH-10	80	430356	3348021	Aghajari	11	---
3	BH-11	120	430204	3346507	Aghajari	16	---
4	BH-12	45	429916	3345086	Aghajari	8	---
5	BH-13	90	430257	3351285	Aghajari	10	---
6	T1	20	431354	3352374	Quaternary deposits	---	---
7	T2	20	431360	3352299	Quaternary deposits	---	---
8	T3	40	431222	3351618	Bakhtiari	6	---
9	T4	125	431024	3350617	Bakhtiari	21	---
10	T5	85	430695	3348769	Aghajari	9	---
11	T6	75	430439	3347343	Aghajari	4	---
12	T7	120	430217	3346146	Aghajari	8	---
13	T8	87	430108	3345493	Aghajari	---	8

Table 4. List of laboratory tests performed on specimens taken from boreholes and surface exposures

Borehole	Physical test (density, porosity, water absorption, etc.)	Consistency limits	Sound velocity	Point load test	Brazilian test	Joint shear test	Uniaxial Compressive test	Triaxial test	Direct shear test	Swelling test	Petrographic analysis	XRF	Slake durability test	Cerchar test	LCPC test
BH-9	10		2	2	3	1	5		1	1	2				
BH-10	10	2	2	3	1		3	3		1	2				
BH-11	15	2	2	2	1		4	1	2	1	3	1			
BH-12	6	1	2				2	6	4		2				
BH-13	8			7		1					3				
T1	5														
T2	3						2								
T3	10	1	1	3		1	2		3		1	1	1		
T4	11		3	5	3	1	9				3		1		
T5	5	2	1	5	1		5	1			2	1	1		
T6	5	3	1	8	1		2	2			3		1		
T7	6	1	1	5			4	1			4				
T8	9	2	1	8	1		6				1	1	1		
Surface exposures	>20	5		>50			15			>10				10	10

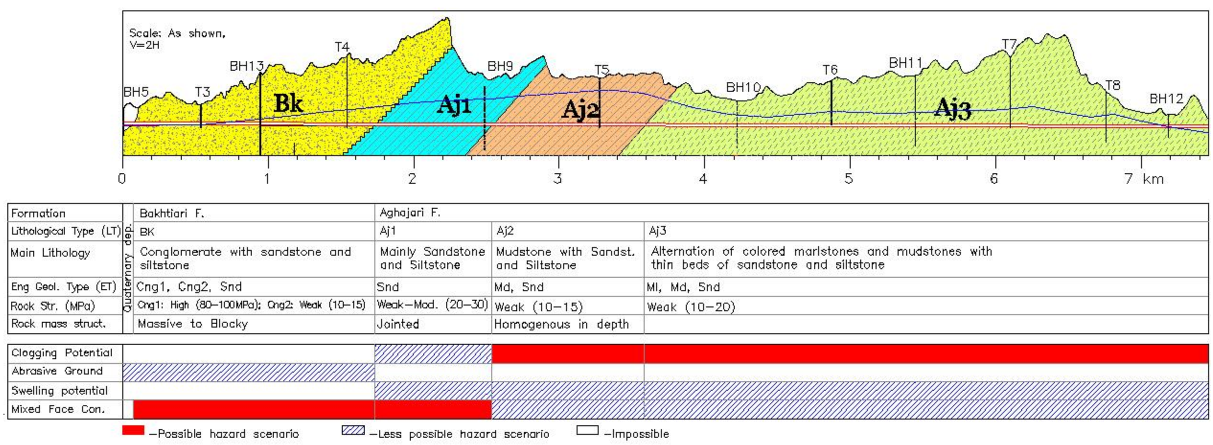


Figure 3. Geological profile of the tunnel and geological problems identified along the tunnel.

In addition, a series of simple onsite tests including point load and petrographic tests were performed on samples taken from muck during tunnel excavation. The results of the laboratory tests performed on engineering geological types are provided in Table 5.

Rock mass classification

In this study, geomechanical characteristics of the host rock mass were assessed using some empirical rock mass classification systems such as RQD, RMR, GSI and Q-system. The results of the rock mass classifications are summarized in Table 6.

It must be noted that despite the presence of some joints in mudstones and marlstones (Ml and Md) observed in surface outcrops, the role of these discontinuities in defining the behavior of the rock mass can be ignored at depth, especially below the water table. This means that the behavior of these rock masses is not structurally controlled by these joints. As a result, the use of rock mass classification systems such as Q, RMR, etc. for predicting behavior of these engineering geological types is unreliable.

Table 5. Physical and mechanical properties of the engineering geological types

Eng. geological type	UCS (MPa)	Brazilian tensile strength (MPa)	Modulus of elasticity, E (GPa)	Dry unit weight, (kg/cm3)	Porosity (%)
Cng 1	12	0.5	1.3	2.4	24
Cng 2	90	-	25	2.4	24
Snd	25	1.9	2.6	2.12	23
Ml	20	1.5	1.5	2.1	17
Md	12	2.11	1.2	2.15	23.4

Table 6. Rock mass properties of the engineering geological types

Eng. geological type	Discontinuity condition	RQD (%)	GSI	RMR	Q
Cng 1	Good	95-100	65-70	50-55	8.25
Cng 2	Good	95-100	65-70	55-60	8.25
Snd	Fair	75-90	45-50	35-40	6.19-7.43

RQD: Rock Quality Designation; GSI: Geological Strength Index; RMR: Rock Mass Rating; Q: Barton's Q System

a) Conglomerate (Cng2)
b) View of conglomerate particles (Cng1)
c) Mudstone (Md)
d) Marlstone (Ml)

Figure 4. Pictures of different engineering geological types

Consequently, in this study, these classification systems were not used to classify two engineering geological types of Ml and Md.

Rock mass permeability

Fig. 5 shows the Lugeon values obtained from packer tests in the exploration boreholes which indicate that the permeability of rock mass in engineering geological types Ml and Md (effectively almost the total length of the tunnel in the Aghajari formation) is usually very low (Lu<1). Thus, it can be concluded that the groundwater flow through Aghajari formation and into the tunnel would be very low. The tests performed in boreholes drilled in the conglomerates and sandstones of Cng1, Cng2 and Snd types (Bakhtiari formation) show higher Lugeon values and higher groundwater inflow into the tunnel can be expected.

Rock mass boreability and excavatability

Boreability is the term commonly used to express the ease or difficulty of chipping the rock with a tunnel boring machine. It is the most important parameter for prediction of TBM performance (Gong & Zhao, 2009), selection of machine type, and determination of the machine specifications (Hassanpour *et al.,* 2011, 2015).

In this research, the boreability classification proposed by Hassanpour *et al.* (2011, 2015), presented in Fig. 6 (right graph) and Table 7, was utilized to determine boreability of identified engineering geological types. As shown, in this classification, the field penetration index (FPI), which has been related to rock mass properties (UCS and RQD), is the main criterion for categorizing rock mass boreability.

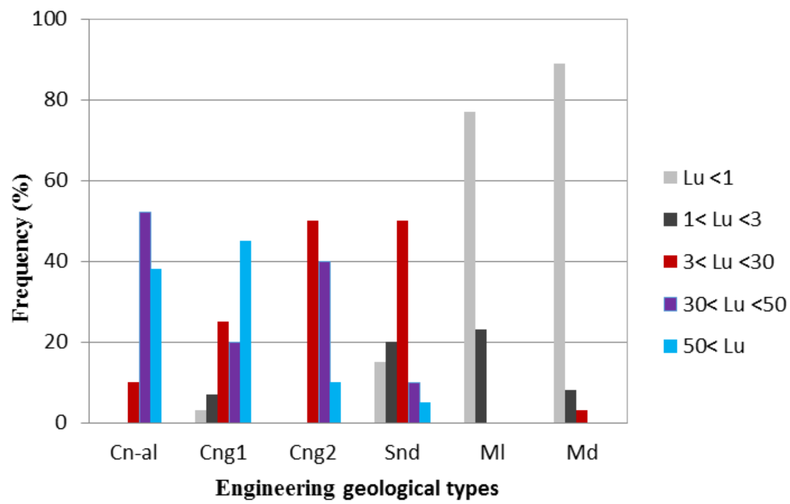


Figure 5. Variations of Lugeon values for various engineering geological types

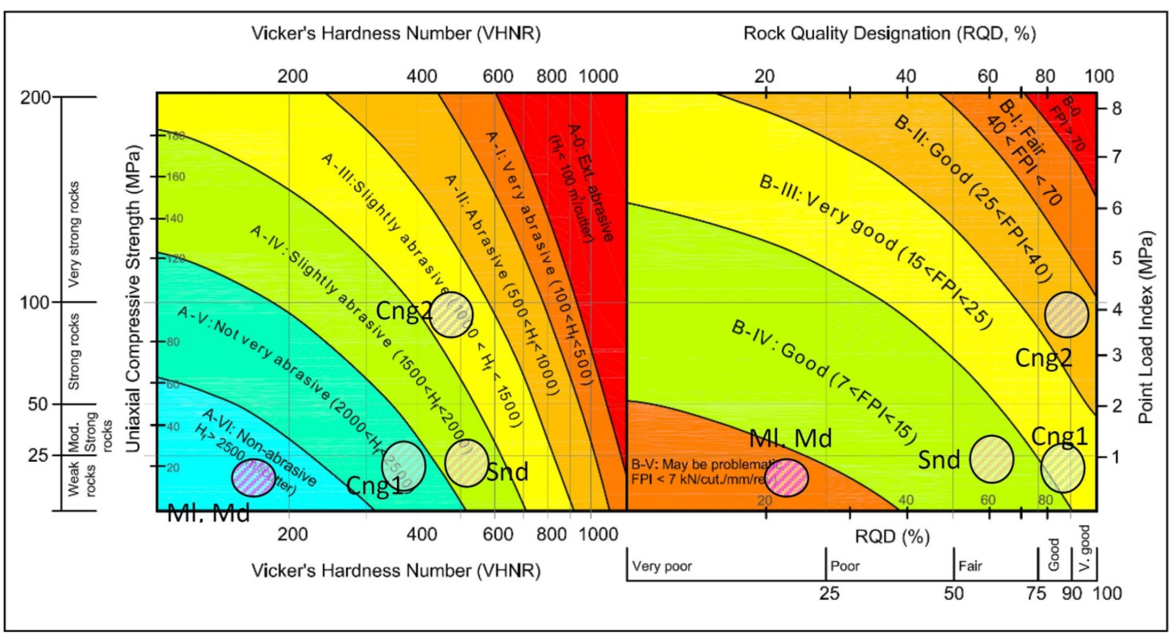


Figure 6. General cutter life and boreability prediction chart (Hassanpour *et al.,* 2015) and range of boreablilty and abrasivity of engineering geological types in the CWCT project

Table 7. Summary of ground conditions for various Boreability classes (Hassanpour *et al.,* 2011, 2015)

Boreability Class	**FPI range (kN/mm/rev)**	**Rock mass boreability**	**Stability condition**	**TBM Excavatability (Relative difficulty of ground for TBM use)**	**Example**
B-0	>70	Tough	Completely stable	Tough, difficult boring	Very strong and massive intrusive and metamorphic rocks
B-I	40-70	Fair-tough	Stable	Fair	Strong igneous and metamorphic rocks
B-II	25-40	Good-fair	Minor instabilities	Good	Blocky and jointed Tuffs, Limestones
B-III	15-25	good	Only local structural instabilities	Very good, easy boring, potential support problems	Alternations of Sandstones, limestones and Shales
B-IV	7-15	Very good	Some major instabilities	Good, easy boring, potential support problems	Flysch type sediments, most low strength rocks and jointed rock masses
B-V	<7	Excellent	Collapse, gripper problems, squeezing, clogging, etc.	May be Problematic, shielded tunneling	Highly foliated and schistose metamorphic rocks, Shale, Marlstone, Mudstone, thick fault zones

FPI is a composite parameter and is defined using TBM performance and operating parameters:

$$FPI = \frac{F_n}{P} = \frac{60\ F_n\ RPM}{1000\ ROP} \quad (1)$$

Where F_n is average cutter load (kN/cutter), P is penetration (mm/revolution), ROP is the rate of penetration (m/h), and RPM is cutterhead speed (revolution per minute).

In fact, in a given project, rock mass properties have direct influence on boring difficulty of ground by TBMs and consequently on FPI values. Usually stronger and less fractured rock masses are more difficult for cutting by disk cutters and boring by TBM, and require use of higher thrusts to achieve a certain level of penetration. Therefore higher values of FPI are usually recorded in strong and massive rock masses like massive intrusive sills, dikes, and thick quartzitic veins (typically greater than 70 kN/cutter/mm/rev). On the other hand, in poor quality rock masses such as mud-rocks (marlstone, mudstone, shale, siltstone), there is no need to apply high thrust values for reasonable penetration and therefore FPI values are small and typically less than 10 kN/cutter/mm/rev. So, FPI can be a good index for categorizing rock mass boreability. In the study done by Hassanpour *et al.* (2011), based on actual FPI values measured in many tunnel sections, six rock mass boreability classes, from most difficult for boring or B-0 class (Tough) to easiest for boring or B-V class (Excellent) were defined (Table 7).

Table 7 also presents general ground stability conditions of different rock mass boreability classes. As shown, stability conditions in different classes vary from completely stable to problematic and unstable grounds. Tunnel wall instabilities have negative impacts on utilization factor of the machine and operational parameters during excavation of the tunnel. In general, more competent and stronger rocks indicated in classes B-0 and B-I coincide with higher utilization rate due to minimal ground support requirement and related stoppages and downtimes. On the opposite side of the scale, in the rock masses with very good to excellent boreability (B-IV and B-V classes), although the instantaneous penetration rate can be very high, but due to instability problems and some machine limitations, the TBM may suffer from lower utilization resulting in lower daily advance rates (Hassanpour *et al.,* 2011). Considering combined effect of boreability and tunnel stability, the parameter of TBM excavatability can be defined. Although the best boreability is expected to achieve in poor rock masses or B-IV and B-V classes, the best excavatability is achieved in B-III class where rock mass is fractured enough to ease chipping process and has enough stability to prevent large face and wall collapses.

Table 8 shows results of boreability classification of engineering geological types identified along the tunnel. As shown almost all of the tunnel alignment is classified as good to excellent boreability and the TBM is not expected to require high thrust to bore these formations.

Table 8. Boreability and TBM excavatability classification of engineering geological types

Eng. geological type	UCS (Mpa)	RQD (%)	FPI (kN/c/mm/rev)	Boreability class	Boreability description	TBM excavatability
Cng1	12	95	15-20	B-III	Good	
Cng2	90	95	25-30	B-II	Good-Fair	
Snd	35	80	7-15	B-IV	Very good	
Ml	20	-	3-7	B-V	Excellent	May be problematic
Md	12	-	3-7	B-V	Excellent	

However due to clogging potential and other related problems, particularly in two engineering geological types of Md and Ml, achieving high advance rates is doubtful.

Abrasiveness of rock formations

The term "abrasiveness" describes the potential of a rock or soil to cause wear on a tool (Plinninger & Restner, 2008). Three laboratory tests are usually utilized for characterizing the abrasiveness of rocks and soils including the Cerchar test (Cerchar, 1986), the LCPC test (Thuro & Käsling, 2009) and the NTNU test (Bruland, 1998; Macias, 2016).

The Cerchar test is based on scratching a fresh surface of the rock specimen with a steel pin with defined geometry and quality under a static load of 70 N. The CAI (Cerchar Abrasivity Index) is then calculated from the measured diameter of the worn steel testing pin (Plinninger & Restner, 2008).

In the LCPC test, the weight loss of a steel impeller with defined geometry and hardness is measured after 5 minutes of rotation at 4500 rpm in a 500 g specimen of soil or crushed rock (grain size: 4-6.3 mm). The LAC (LCPC Abrasivity Coefficient) value is then calculated from the weight loss of the impeller (grams) divided by specimen weight (ton) (Plinninger & Restner, 2008).

In addition to these tests, some of the most frequently used abrasivity indices include the Vicker's Hardness Number (VHNR) (Bruland, 1998), the Equivalent Quartz Content (EQC) (Thuro, 1997) and the Abrasiveness Index (ABI) (Hassanpour *et al.,* 2014, Hassanpour, 2018). These abrasivity indices are typically obtained using petrographic and strength parameters.

VHNR for a rock type is found by calculating the weighted average of the Vickers hardness of each mineral (VHN) to a compound Vickers hardness for the rock type (Bruland, 1998). Equivalent quartz content (EQC) can be determined by multiplying the percentage of minerals present in the rock by relative Rosiwal abrasiveness values as suggested by Eq. (2) (Thuro, 1997).

$$EQC = \sum_{i=1}^{n} A_i \cdot R_i \tag{2}$$

where EQC is the equivalent quartz content, A_i is mineral amount (volume %), R_i is the relative Rosiwal abrasiveness and n is the number of minerals in rock. Ri can be calculated by Rosiwal number of i_{th} mineral divided by Rosiwal number of quartz (R_{quartz}=1).

ABI or Abrasiveness Index is a new index for assessing rock abrasiveness (Hassanpour *et al.,* 2014). This index is derived by combining the two important parameters of VHNR and rock compressive strength (UCS) as follow:

$$ABI = VHNR \cdot \left(\frac{UCS}{100}\right) \tag{3}$$

In this study, the abrasiveness of engineering geological types along the tunnel alignment was determined using different methods and the results are summarized in Table 9.

The two engineering geological types Md and Ml are mainly formed by clay minerals, hence, they can be classified as non-abrasive rocks. On the other hand, abrasivity of conglomerates is very dependent on the petrography of aggregates and type and strength of their cement. Therefore, a number of LCPC and Cerchar tests were performed on samples taken from outcrops and muck to obtain the abrasiveness of conglomerate units (Cng1 and Cng2). However, no additional laboratory tests were needed in determining the abrasivity of marlstone and mudstone units.

The above mentioned abrasivity indices are the essential input parameters for the tool wear prediction models and are used to estimate cutter life and number of cutter changes in the project in the following sections.

The results of abrasivity tests (Table 9) indicate that engineering geological types along the tunnel alignment present low wear potential.

Consistency of clayey materials

Consistency and plasticity of soft sedimentary rocks, containing clay minerals, are the main parameters influencing the machine performance during tunnel excavation. As will be explained later, clogging and tunnel face stability are two major problems in mechanized tunneling, which are directly controlled by consistency of clay mineral constituent of soft rocks.

In this study, a number of consistency limits tests (including liquid limit or WL and plastic limit or WP) were performed on samples taken from boreholes and surface exposures of the two engineering geological types Md and Ml, and the results are presented in Table 10. As can be seen in this table, all the specimens have liquid limit (WL) between 35 and 40% and can be classified as “intermediate class” as suggested by Bell (2000). Also, an alternative classification proposed by IAEG (1979) is used to evaluate consistency of the clay rich rocks and results are provided in Table 11.

Table 9. Summary results of laboratory and geotechnical indices to determine rock abrasivity

Eng. geological type	Minerals			EQC	VHNR	ABI	Cerchar test		LCPC test	
	Calcite	Clay mineral	Quartz				CAI, Cerchar Abrasivity Index	Description	LAC (g/t)	Description
Cng1	90	3	7	14.075	333	40	1.5	Considerably abrasive	90	Slightly abrasive
Cng2	80	2	18	21.625	435	391	2	Abrasive	150	Low abrasiveness
Snd	87	3	10	13.952	290	101	1.3	Moderately abrasive	-	-
Ml	70	20	10	13.400	130	26	0.9	Little abrasive	-	-
Md	20	70	10	13.400	116	14	0.8	Little abrasive	-	-

EQC: Equivalent Quartz Content; VHNR: Vicker’s Hardness Number; ABI: Abrasivity Index; LAC: LCPC Abrasivity Coefficient

Table 10. Summary results of consistency limits obtained from the laboratory tests

Sample No.	Eng. geological type	Natural water content (W_n), (%)	Liquid Limit (WL), (%)	Plastic Limit (WP), (%)	Plasticity index (PI), (%)	Consistency Index, I_c	
						Value (%)	Description
1	Ml	18	41	22	19	1.21	Very stiff to Hard
2	Ml	17	38	24	14	1.50	
3	Ml	16	36	23	13	1.54	
4	Ml	18	42	21	19	1.26	
5	Ml	19	39	20	19	1.05	
6	Ml	17	38	24	14	1.50	
7	Ml	18	37	22	15	1.27	
8	Ml	17	39	23	16	1.38	
9	Ml	18	43	24	19	1.32	
10	Md	16	39	24	15	1.53	
11	Md	17	38	22	16	1.31	
12	Md	19	39	22	17	1.18	
13	Md	18	40	24	16	1.38	
14	Snd (siltstone)	12	23	NP	-		
15	Snd (siltstone)	14	25	NP	-		

Table 11. Classification of clayey materials according to consistency characteristics

Liquid Limit (%)		Plasticity index (%)		Consistency index, Ic (Bell, 2000)	
< 35	Lean/Silty	< 7	Non-plastic to slightly plastic	Ic > 1	very stiff to hard
35-50	Intermediate	7-17	Moderately plastic	0.75 < Ic < 1	Stiff
50-90	Fat-Very fat	17-35	Highly plastic	0.5 < Ic < 0.75	Firm
> 90	Extra fat	> 35	Extremely plastic	0.25 < Ic < 0.5	Soft
				0 < Ic < 0.25	Very soft
				Ic < 0	Liquid

The plasticity index (PI=WL-WP) of the majority of specimens was classified as moderately plastic (7<PI<17). Meanwhile, highly plastic specimens (17<PI<35) were also encountered during testing.

The consistency index (I_C) is a very important parameter in soft ground tunneling and is defined as:

$$I_C = \frac{WL - W_n}{WL - WP} \tag{4}$$

Where W_n is the natural water content of the specimen. According to laboratory tests performed on undisturbed specimens taken from core boxes of Md and Ml units, W_n is in the range of 15-20%.

As shown in Table 10, almost all of the specimens have a consistency index I_C of over 1 and can be classified as "Very stiff to Hard" according to Bell (2000) classification (Table 11).

Geological problems

One of the main objectives of engineering geological studies in mechanized tunneling projects is the identification of geological problems that may be encountered during the construction phase._The type and extent of these geological problems directly influence machine selection and its specifications. In general, predicting the engineering geological problems (such as squeezing grounds, water ingress, raveling, clogging, gas emission, etc.) before commencing the project, can minimize the risk of extended delays or long stoppages in operation.

In this particular case, the most likely geological problems include groundwater inflow, stickiness and clogging, instability of tunnel face, and ground swelling behavior. The potential for encountering these problems and the effects on TBM selection will be described in the following sections.

Groundwater inflow

The project area is very arid with low annual precipitation. Hydrogeological field investigations also show that there are no significant groundwater resources in the area. Measurements of the groundwater level in drilled boreholes show that the groundwater depth is in the range of 30-60 m (10-20 ft). Since the tunnel alignment is below this depth, almost the total length of tunnel will be constructed below the groundwater table. The head of water above the tunnel can be approximated within the range of 0-50 m (0-16 ft). On the other hand, there is no geological formation in the area that is potentially suitable for forming an aquifer. Almost 75% of tunnel length will be excavated in the Aghajari formation, which lithologically consists of impervious marlstones and mudstones. The Bakhtiari formation (or BK lithological type) can potentially create an aquifer, but due to low annual precipitation and lack of groundwater recharge by surface waters, it is not expected to contain a substantial amount of water.

So, it can be concluded that no major water inflow is expected in the tunnel, although most of the tunnel alignment is below groundwater table. Only minor drippings in Bakhtiari conglomerates is expected.

Stability of tunnel face

According to the DAUB recommendations (DAUB 2010), stability of the tunnel face is an important factor for selecting the proper machine type. If the face is stable, e.g. in stiff clay with high consistency and sufficient cohesion or in solid rock, open face shield machines can be used. In such conditions there is no need to support the face by applying pressure. Since the TBM that was selected for this project is an open shield machine, without the ability to apply face pressure, the tunnel face must be stable, otherwise the machine can not function properly.

The stability of face in soils and clayey rocks can be assessed using the consistency index. As shown in Table 11, if the natural water content (W_n) is greater than the liquid limit (WL) and $I_C < 0$, the material behaves like a liquid. On the other end of the spectrum, when plasticity index (PI) is high or/and water content is low, consistency index is high and the material is in a semi-solid state and is classified as very stiff to hard. The face is stable and there is no need to support the face by applying pressure, only when $I_C > 1$ and the ground is impervious.

The two engineering geological types Md and Ml were laboratory-tested for the consistency index due to their high clay mineral content and, thus, susceptibility to face instability. As shown in Table 10, all of the measured consistency indices are categorized in the very stiff to hard class, and it is anticipated that the face will be stable in most sections in these two engineering geological types. It is probable that in few tunnel sections where Ml and Md engineering geological types are adjacent to thick water bearing sandstone layers the water content of these two units increase considerably. In these very infrequent tunnel sections the water content may increase and I_C reduce to critical condition.

Clogging potential in clayey rocks

Clays with pronounced plasticity and sedimentary rocks containing clay minerals, such as mudstones and marlstones, have proved particularly susceptible to stickiness (Maidl *et al.,* 2014). These materials have a potential for clogging, which can significantly impact tunneling. Clogging reduces the advance rate by causing the need for time-consuming manual cleaning of the cutting tools, buckets, cutting chamber, and conveyors. Stickiness always occurs in combination with water, which can be the natural water with open and earth pressure balance machines, or process water (support slurry, soil conditioning, cutterhead water spray for dust suppression in hard rock tunneling, etc). To prevent delays related to sticky clays, appropriate selection of the TBM and additional equipment on the machine should be taken into consideration (Maidl *et al.,* 2014, Tarigh Azali *et al.,* 2012).

Recent studies on stickiness and clogging phenomena include the work completed by GEODATA-Torino (1995), Thewes & Burger (2004), Martinotto & Langmaack (2007), Sass & Burbaum (2008), Feinendegen *et al.* (2010), Hollmann & Thewes (2013) and Alberto-Hernandez *et al.* (2018). In this study, the potential for clogging is analyzed based on the most recent approach by Hollmann & Thewes (2013), in which a simplified diagram is offered to evaluate the clogging potential for all types of tunneling machines (Fig. 7). This diagram is based on a combined evaluation of water content (W_n) and liquid and plastic limits, to assess the clay material behavior. In this diagram the clogging potential of materials has been categorized into five different classes. In addition, the diagram includes the classification of clayey materials based on their consistency index (red lines).

To evaluate clogging potential along the Chamshir tunnel, the results of liquid and plastic limits and natural water content (Table 10) are plotted in Fig. 7. As shown, most of the specimens of Md and Ml units are categorized as very stiff and hard with no potential for clogging. However, a small increase in water content during the tunneling process can change the material behavior to a critical condition.

In addition to Hollman & Thewes' approach, the "Cone pull-out apparatus" was also used to predict clogging potential. This laboratory apparatus, initially introduced by Sass & Burbaum (2008) and Feinendegen *et al.* (2010), has been fabricated at the University of Tehran (Fig. 8a).

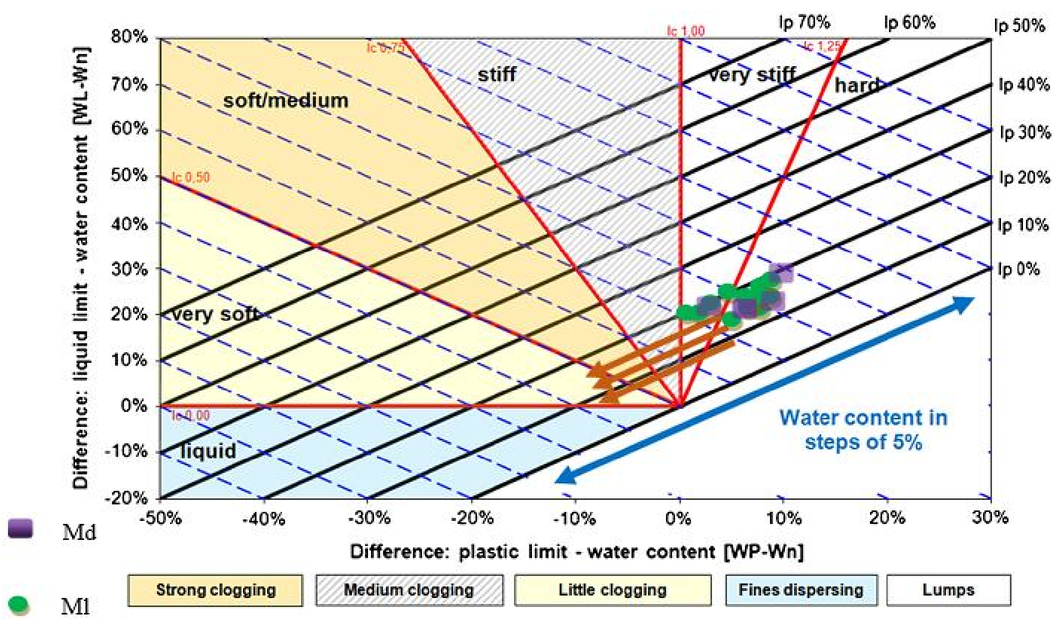


Figure 7. Classification diagram for critical consistency changes regarding clogging and dispersing (Hollman & Thewes, 2013) with samples from the CWCT project.

Figure 8. a) Cone pull-out apparatus at the University of Tehran and b) a picture of a sample during test

In this new laboratory test the sample material is compacted in a standard proctor device. The test method consists of pushing a special cone (Fig. 8b) into the prepared specimen at a rate of 20 mm/min. After 3 minutes of adherence time, the cone is pulled out with a velocity of 5mm/min. At the end of each test, the mass of adhering material per cone surface area (in g/m^2) is determined by weighing and recorded as output parameter.

A series of tests were performed on marlstone (Ml) and mudstone (Md) samples taken from surface outcrops. To evaluate the influence of water content and consistency index on clogging potential, specimens were tested in different water contents. Figure 9 provides a plot of measured adherence versus the consistency index. The classification from Feinendegen *et al.* (2010) is also provided in Fig. 9 (left side of graph). As shown, maximum adherence for Ml and Md engineering geological types is in the range of 450-520 gr/m^2 when Ic=0.4-0.5. According to the classification proposed by Feinendegen *et al.* (2010), Ml and Md types have low clogging potential in conditions of natural water content. However, an increase of 10-15% water content during tunneling process can lead to a critical condition of clogging for these units. This expected behavior is in agreement with Hollman & Thewes diagram (Fig. 7).

Therefore, it must be kept in mind that water content is critical to sticky behavior of the material to be mined and clogging potential, and special measures required to minimize added water to the TBM tunneling process.

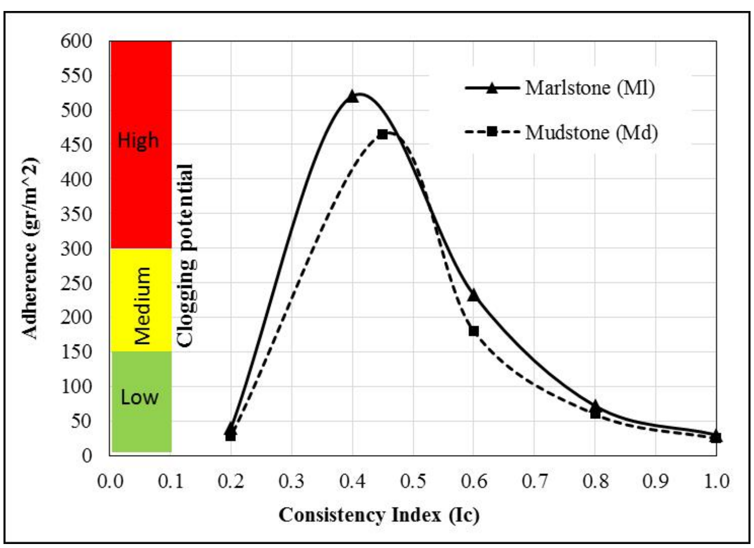


Figure 9. Variations of Adherence with consistency index of tested materials

Swelling behavior of clayey rocks

Swelling potential is also one of the items considered in selecting suitable machine in TBM tunneling. Rocks containing clay minerals such as Ml and Md units have the potential to undergo volume changes when they are subject to changes in water content. If volume increase is restrained or prevented, very high swell pressures may develop against the shield.

To check swelling behavior of the mudstone and marlstone units (Md and Ml), a series of samples were taken from boreholes and exposures and their swelling pressure, swelling strain and free swelling indices were measured in the laboratory using Oedometer and free swelling tests. Both rock powder and undisturbed rock samples were used to determine swelling behavior of rocks using International Society of Rock Mechanics (ISRM) suggested methods (ISRM, 2007) and Norwegian National Group of ISRM (NBG) recommendations (NBG, 2000).

NBG defines swelling pressure below 0.1 MPa as low, 0.1 - 0.3 MPa as moderate, 0.3 - 0.75 MPa as high and above 0.75 MPa as very high based on oedometer test on rock powder specimens (NBG, 2000). NBG also defines free swelling index (Fs) below 100% as low, 100% - 140% as moderate, 140% - 200% as high and above 200% as very high (NBG, 2000).

Table 12 lists the results of performed tests. As shown, most of the tested samples show low potential for swelling. Only a few specimens (3 out of 13 samples) show moderate potential for swelling. Hence, swelling can be an issue only in limited reaches of tunnel and must be prevented by reducing the exposure of the formations to additional water during the tunneling operations.

Checking the suitability of selected machine

As stated before, the TBM model S-124 manufactured by Herrenknecht was not originally designed for geological conditions of the Chamshir project and had to be examined for its suitability for this project. This TBM is a single shield machine with open face (without support) and is categorized in SM-V1 class, according to the DAUB classification (DAUB, 2010).

According to the DAUB guidelines, if the face is stable, e.g. in stiff clay, or in solid rock, open face shield machines (or SM-V1) can be used. Single shield TBMs are suitable for rock formations that are highly jointed and prone to rockfall and can excavate rock with a cutterhead fitted with disc cutters, with no need to pressurize the face.

In this study, the DAUB (2010) guidelines were considered for evaluating the machine and its suitability for anticipated ground conditions along the alignment including the soft and hard rock formations, respectively. Table 13 presents areas of application and selection criteria for single shield (SM-V1) machine. As can be seen, the application area of the machine must be evaluated using different geological and geotechnical parameters including:

1) Soft ground: Percent fines, permeability, consistency index, density, support pressure (tunnel face stability), swelling behavior, abrasiveness (LCPC index).

2) Rock: UCS, RQD, RMR, water inflow, abrasiveness, swelling behavior, support pressure (tunnel face stability).

Table 12. Summary results of swelling tests

No.	Sample location	Eng. geological type	Sample type / Standard	Swelling strain (%) (Oedometer test)	Swelling pressure (MPa) (Oedometer test)	Fs or Free swelling index (%)	Swelling Potential
1	BH10	Ml	Undisturbed / ISRM	0.35	0.006	---	Low
2	BH11			1.55	0.031	---	Low
3	Surface exposures		Rock powder / NBG	---	0.031	80	Low
4				---	0.218	130	Moderate
5				---	0.092	90	Low
6				---	0.086	65	Low
7				---	0.155	125	Moderate
8				---	0.048	90	Low
9	BH9	Md	Undisturbed / ISRM	2.06	0.085	---	Low
10	Surface exposures		Rock powder / NBG	---	0.084	75	Low
11				---	0.128	115	Moderate
12				---	0.066	85	Low
13				---	0.059	80	Low

Table 13. Areas of application and selection criteria for single shield (SM-V1) machine (DAUB, 2010)

Geotechnical values	**Shield Machine with full-face and without support (SM-V1)**				
Soft ground					
Fine grain fraction (< 0,06 mm)	<5%	5-15%	15-40%	>40%	
	-	-	0	+	
Permeability, k (m/s)	V. H. Permeable > 10^{-2}	Str. Perm. 10^{-2} to 10^{-4}	Preamble 10^{-4} to 10^{-6}	Sl. Perm. < 10^{-6}	
	-	-	0	+	
Consistency Index (Ic)	Pasty 0-0.5	Soft 0.5-0.75	Stiff 0.75-1.0	Semi-Solid 1.0-1.25	Hard 1.25-1.5
	-	-	0	+	+
Density	Dense	Fairly Dense	Loose		
	+	0	-		
Supporting pressure (bar)	0	0-1	1-2	2-3	3-4
	+	-	-	-	-
Swelling behavior	None	Little	Fair	High	
	+	+	0	-	
Abrasiveness (LCPC index LAC (g/t))	Very Low 0-500	Low 500-1000	Medium 1000-1500	High 1500-2000	Very High > 2000
	+	+	+	+	0
Breakability LCPC index BR (%)	Very Low 0-25	Low 25-50	Medium 50-75	High 75-100	Very High > 100
	+	+	+	+	0
Hard rock					
UCS (MPa)	0 - 5 / 5 - 25	25 - 50	50 - 100	100 - 250	> 250
	0 / 0	+	+	0	0
RQD (%)	very poor 0 - 25	poor 25 - 50	fair 50 - 75	good 75 - 90	excellent 90 - 100
	o	+	+	0	0
RMR	very poor < 20	poor 21 - 40	fair 41 - 60	good 61 - 80	very good 81 - 100
	0	+	+	0	0
Water inflow per 10 m tunnel (l/min)					
	+	+	+	0	-
Abrasiveness (CAI)	not very abrasive 0.3 – 0.5	slightly abrasive 0.5 - 1	abrasive 1 - 2	very abrasive 2 - 4	extremely abrasive 4 - 6
	+	+	+	0	0
Swelling behavior	none	poor	fair	high	
	+	+	0	-	
Supporting pressure (bar)	0	0 - 1	1 - 2	2 - 3	3 - 4
	+	-	-	-	-

+ Main field of application, o Application possible, - Application critical

In Table 13, the cells with a symbol "+" denote ranges, in which this type of machine has shown a successful track record without many additional measures being required. The use of a tunneling machine in the fields marked dark grey with a symbol "0" may require special measures, but the feasibility of their applicability has been demonstrated. The achievable advance rates and cost-effectiveness may be reduced in comparison to the main application areas. The use of a tunneling machine in the fields marked light grey with a symbol "–" will probably require considerable additional measures or modification of the ground, otherwise difficulties should be expected. The achievable advance rates and cost-effectiveness will be considerably reduced compared to the core area.

The results of the assessment of the CWCT machine for use in this project with given ground conditions are presented in Table 14. The conclusion is that, while the TBM may require some additional measures in some of the engineering geological types, the machine is acceptable for application to this project and conditions.

Table 14. Assessment of proposed TBM for CWCT project based on DAUB guidelines

Tunnel Boring Machines	**Shield Machine with full-face and without support (SM-V1)**				
Soft ground					
Eng. Geological types	**Cng-1**	**Cng-2**	**Snd**	**Md**	**Ml**
Fine grain fraction (< 0,06 mm)				+	+
Permeability k (m/s)				+	+
Consistency (Ic)				+	+
Density				+	+
Supporting pressure (bar)				+	+
Swelling behavior				0	0
Abrasiveness LCPC-index ABR (g/t)				+	+
Breakability LCPC-index BR (%)				+	+
Hard rock					
UCS (MPa)	0	+	0		
RQD (%)	0	0	0		
RMR	+	0	+		
Water inflow per 10 m tunnel (l/min)	+	+	+		
Abrasiveness (CAI)	0	0	+		
Swelling behavior	+	+	+		
Supporting pressure (bar)	+	+	+		

+ Main field of application, **o** Application possible, - Application critical

Recommended modifications on TBM specifications

As explained before, the selected TBM can complete the project, after some modifications and adjustments to match the machine specifications with the special geological conditions of the Chamshir tunnel alignment. One important item was the adjustments for boring in soft rocks. Although, the original cutterhead can be used to excavate the conglomerate units of the Bakhtiari Formation (BK unit), modifying the type, number and arrangement of the cutting tools was essential to achieve a reasonable performance in the Aghajari formation (Md and Ml units).

The two engineering geological types, Md and Ml, were categorized as class B-V in the boreability chart (Fig. 6 and Table 8). As shown in Table 7, rocks categorized as B-V class, due to their poor quality cause many problems during tunneling process. In addition to stability conditions, when these high clay-content types of rocks, are saturated (below the groundwater table), they no longer behave as brittle rocks and completion of the boring process or chipping is difficult by using disc cutters.

In the cutting process of a hard rock TBM, the very high contact pressure exerted by the disc cutter, generates cracks in the rock right in front of the cutter. These cracks generate a chip releasing the rock. This process is more efficient if the rock is brittle and the penetration rate is high. On the other hand, in soft ground TBM a combination of rotating disc cutters, scraper and ripper tools are installed on the TBM cutterhead. Generally, the disc cutters are designed to apply a high thrust force (approximately 250 kN per disc) in to rock mass, inducing tensile failures and chipping from rock, while ripper tools are ripping cohesive soft material like mudstone and marlstone.

As mentioned earlier, the original cutterhead shown in Fig. 2 had 34 disc cutters (452 mm or 17 inch in diameter), with average spacing of 78mm (~3 inches). In the modified cutterhead (for tunneling in Md and Ml soft rocks), in addition to replacing disc cutters by rippers at some positions, 10 extra blocks (Fig. 10 a, b) were installed for mounting of rippers with 112mm width. This reduced the average spacing of cutting tools to 60mm (2.4 inches). Analyzing various cutterhead arrangements and their effects on the boring process is beyond the scope of this paper, but a quick review indicates that the proposed modification can improve the boring operation.

(a) (b)

Figure 10. a) The position of new rippers on the cutterhead face; b) Closer view of welded blocks for installing new rippers

In addition to the adjustment of cutting tools to improve the boring process in soft rock, the clogging potential in these sections must be controlled by suitable remedial measures. As noted in section 7-3, although most of the specimens taken from two engineering geological types of Md and Ml were categorized as very stiff and hard with no potential for clogging, a small increase in water content during the tunneling process can change the material behavior to a critical condition. So, the most important measure to control this phenomenon includes reducing the amount of water used in the tunneling process. In addition, conditioning of the muck by adding suitable anti-clogging foams can be a solution for clayey rocks with clogging potential. So, the decision was made to equip the TBM with a foam generator and foam injection system.

In this study, FPI values (Table 8) have also been used to evaluate machine specifications (particularly cutterhead thrust). As shown in Table 8, the maximum FPI values of 25-30 kN/cutter/mm/rev is expected in the Cng2 unit as this is the strongest rock unit identified along the tunnel alignment. If the minimum penetration (P) of 7-8 mm/rev is required to reach a reasonable penetration rate (ROP) of 1.8-2 m/h at RPM=3.5-4, then the estimated cutter force (F_n), according to Eq. 5 (derived from Eq. 1), will be in the range of 200-220 kN/cutter, which is in the upper range of cutter load capacity. By considering number of disc cutters (N_{TBM}=34) and approximately 1000 kN thrust required to overcome skin friction (T_f), maximum required thrust (according to Eq. 6) will be T_h = 34 × 220 + 1000 = 8480 kN, which is in the range of machine capacity (please refer to Table 1). Therefore, there is no need to increase the thrust capacity of the TBM.

$$F_n = P \cdot FPI = \frac{1000\ FPI\ .\ ROP}{60\ RPM} \tag{5}$$

$$T_h = F_n \cdot N_{TBM} + T_f \tag{6}$$

Cutting tool wear

One of the main cost items in mechanized tunneling projects in rock and soil is the cost of changing of damaged or worn cutting tools. In addition, cutting tool change is a time consuming operation which can have a negative influence on TBM performance. An estimation of tool wear and number of required cutting tool changes during a project is essential to the estimated project cost.

Hassanpour (2018) and Hassanpour *et al.* (2014, 2015) offered a model that uses VHNR and UCS as the main geological parameters for prediction of cutter life. This simple model is presented in Fig. 6. The prediction chart was created based on the following empirical equation and can be used to estimate cutter life and cutter consumption in the project:

$$H_f\,(m^3/cutter) = -2.544\,VHNR - 8.331\,UCS + 3288.248 \tag{7}$$

and

$$W_f\,(cutter/m) = \frac{\pi D^2}{4 H_f} \tag{8}$$

Where H_f is cutter life in m3/cutter, W_f is cutter consumption in cutter/m (Bruland, 1998, Macias 2016) and D is tunnel diameter.

As shown in the tool wear prediction chart (Fig.

6), rock units can be categorized in seven different abrasivity classes (A-0 to A-VI) based on their characteristics and anticipated cutter life. These classes, which are named A-0 to A-VI, are defined in Table 15.

Table 16 summarizes the results of calculation of two parameters of H_f and W_f in different engineering geological types identified along the Chamshir tunnel. By multiplying W_f and L_{sec} (tunnel section length), the total required number of disc cutters in each section can be estimated. So, it is anticipated that a total number of about 64 disc cutters will be required for completion of Chamshir project, not including miscellaneous events and special cases which might impact tool wear. The estimate is based on the assumption that the cutter life is not significantly impacted by the installation of rippers.

As of the date of submission of this manuscript about 1500m of tunnel length has been excavated through the conglomerates of Cng1 and Cng2 types. Based on monthly site reports, during excavation of this section, no disc cutter has been changed. Reports also show that the wear of disc cutters is in the range of 6-11mm, shown in Fig. 11.

Table 15. Summary of ground conditions for various abrasivity classes

Abrasivity Class	H_f range (m^3/cutter)	Rock mass abrasivity	Example
A-0	< 100	Extremely abrasive, High cutter wear	Very strong quartzitic veins, intrusive and metamorphic rocks with high quartz contents
A-I	100 -500	Very abrasive	Strong to very strong granites and gneisses
A-II	500 -1000	Abrasive	Strong siliceous tuffs and quartz sandstones
A-III	1000 -1500	Moderately abrasive	Moderately strong to strong well-cemented sandstones
A-IV	1500 -2000	Slightly abrasive	Shales, strong limestones and dolomites
A-V	2000 -2500	Not very abrasive	Moderately strong limetones, dolomites
A-VI	>2500	Non-abrasive, almost no cutter wear	Marls, Mudstones, Weak limestones

Table 16. Results of estimation of cutter life, cutter consumption and total number of disc cutters required for completing each section of tunnel

Eng. Geological type	Section length (km)	VHNR	UCS (MPa)	Abrasivity class	ABI	H_f (m^3/c)	W_f (c/m)	Required no of disc cutters	Construction phase
Cng1	1045	333	12	A-V	40	2341.1	0.0094	10	Excavated
Cng2	450	435	90	A-III	391	1431.8	0.0154	7	
Snd	750	290	35	A-V	101	2258.9	0.0098	7	Under excavation
Ml	3095	130	20	A-VI	26	2790.9	0.0079	24	
Md	2120	116	12	A-VI	14	2893.2	0.0076	16	
								64	

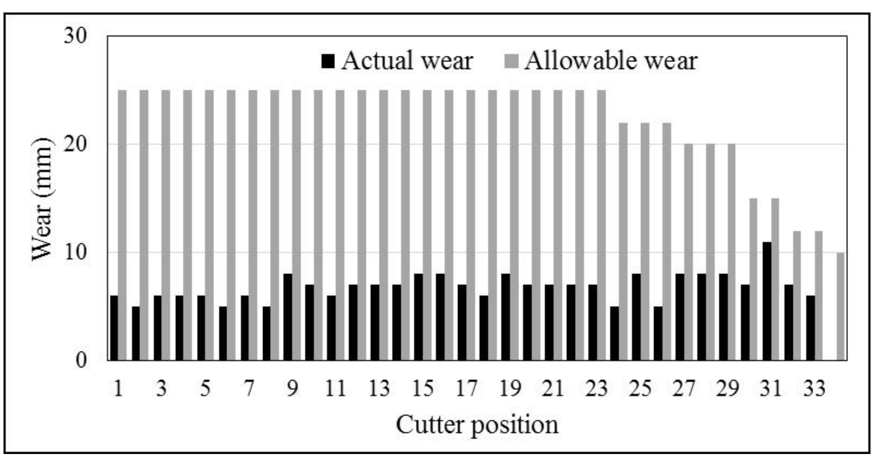


Figure 11. Actual wear of disc cutters in excavated length of tunnel (about 1500m)

By comparing actual wear of disc cutters with the allowable wear of disc cutter in Fig. 11, it can be concluded that about 35-40% of disc cutter rings have been consumed during excavation of 1500m of tunnel length. Considering the total number of disc cutters on the cutterhead (N_{TBM}=34), it can be concluded that the measured wear in the first 1500 m of tunneling to be equivalent to:

Equivalent worn disc cutters= (0.35-0.40) × (N_{TBM}) = (0.35-0.40) × (34) = 11.9-13.6 ≈ 12-14

Which is close to the predicted 17 discs anticipated to be changed in this section of the tunnel (Table 16).

Conclusions

The TBM selected for this particular project has to pass through hard and soft rock formations. Accordingly, geological investigations were focused on data collection to assist in the prediction of behavior of high clay-content materials and related geological problems during TBM excavation. In normal conditions, abrasivity of clay bearing soft rocks is low and their boreability is favorable. However, secondary phenomena such as instability at the face, mixed face conditions, and stickiness of clay minerals can reduce the machine performance and increase wear of cutting tools. The assessment of geological problems associated with soft rocks, including clay stickiness, will be the most critical issue. Results of laboratory tests performed to evaluate stickiness of the geological formations indicated that different units present along the tunnel alignment have little to medium clogging potential at natural moisture content. Increasing water content in these units during the operation can lead to critical conditions and severe clogging. Special measures such as controlling added water during the tunneling process and applying additives such as anti-clogging foams, should be considered to reduce the clogging and associated downtime.

Another objective of this study was to examine the suitability of the procured TBM for the project and an evaluation of possible modifications that could reduce excessive downtimes. The study of machine specifications and its potential to successfully excavate different engineering geological units showed that the machine can excavate the tunnel by careful consideration of the water contents of the various formations and implementation of required modifications, especially the use of proper cutting tools and improvement in cutterhead design (by installing 10 extra rippers). The actual observations and measurements in the first 1500 m of the tunnel indicate the validity of the assessments (water inflow, clogging, degree of cutter wear, etc.) in the related engineering geological types.

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References

Alberto-Hernandez, Y., Kang, C., Yi, Y., Bayat, A., 2018. Clogging potential of tunnel boring machine (TBM): a review. International Journal of Geotechnical Engineering, 12 (3): 316-323

Bell, F., G., 2000. Engineering properties of soils and rocks. 4th ed. Oxford: Blackwell Science

Bruland, A., 1998. Hard rock tunnel boring, vols. 1-10, Ph. D. thesis. Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Cerchar (Centre d'Études et des Recherches des Charbonages de France), 1986. The Cerchar Abrasiveness Index. Center of Study and Research of the French Coal Industry, Verneul.

Dearman, W., R., 1991. Engineering Geological Mapping. Oxford, Butterworth-Heinemann Ltd.

DAUB (Deutscher Ausschuss für unterirdisches Bauen), 2010. Empfehlungen zur Auswahl von Tunnelvortriebsmaschinen. Available online at www.daub-ita.de/uploads/media/gtcrec14.pdf

Feinendegen, M., Ziegler, M., Spagnoli, G., Fernández-Steeger, T., Stanjek, H., 2010. A new laboratory test to evaluate the problem of clogging in mechanical tunnel driving with EPB-shields. In: Proc. EUROCK 2010, Lausanne, Switzerland, Taylor & Francis Group, London

GEODATA S.p.A., 1995. Report: Review of alternative construction methods and feasibility of proposed methods for constructing Attiko Metro Extension of Line 3 to Egaleo, Attiko Metro S.A., 191-193

Gong, Q. M., Zhao, J., 2009. Development of a rock mass characteristics model for TBM penetration rate prediction, International Journal of Rock Mechanics and Mining Sciences, 46 (1): 8–18

Hassanpour, J., 2018. Development of an empirical model to estimate disc cutter wear for sedimentary and low to medium grade metamorphic rocks. Tunneling and Underground Space Technology, 75: 90–99

Hassanpour, J., Rostami, J., Zhao, J., Tarigh-Azali, S., 2015. TBM performance and disc cutter wear prediction based on ten years experience of TBM tunneling in Iran. Geomechanics and Tunnelling, 8: 239–247

Hassanpour, J., Rostami, J., Tarigh-Azali, S., Zhao, J., 2014. Introduction of an empirical TBM cutter wear prediction model for pyroclastic and mafic igneous rocks; a case history of Karaj water conveyance tunnel, Iran. Tunneling and Underground Space Technology, 43: 222–231

Hassanpour, J., Rostami, J., Zhao, J., 2011. A new hard rock TBM performance prediction model for project planning. Tunneling and Underground Space Technology, 26: 595–603

Hollmann, F. S., Thewes, M., 2013. Assessment method for clay clogging and disintegration of fines in mechanized tunneling. Tunnelling and Underground Space Technology, 37: 96–106

IAEG, 1976. Engineering geological maps: a guide to their preparation. UNESCO Press, Paris

IAEG, 1979. Classification of rocks and soils for engineering geological mapping part I: Rock and soil materials. Report of the Commission of Engineering Geological Mapping of the International Association of Engineering Geology, Bulletin of Engineering Geology and the Environment, 19 (1): 364–371

ISRM, 2007. The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006. Edited by: R. Ulusay and J.A. Hudson, Compilation arranged by the ISRM Turkish National Group, Ankara, Turkey

Macias, F. J., 2016. Hard rock tunnel boring: performance prediction and cutter life assessments. PhD thesis, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Maidl, B., Thewes, M., Maidl, U., 2014. Handbook of Tunnel Engineering II: Basics and Additional Services for Design and Construction. Wiley-VCH Verlag GmbH, D-69451 Weinheim, Germany

Martinotto, A., Langmaack, L., 2007. Toulouse Metro Lot 2: soil conditioning in difficult ground conditions. In: Barták, J., Hrdina, I., Romancov, G., Zlámal, J. (Eds.), ITA-AITES World Tunnel Congress (WTC), Prague, Czech Republic, 1211–1216

Norwegian Group for Rock Mechanics (NBG), 2000. Engineering Geology and Rock Engineering, Handbook No. 2. Oslo, Norway, 192

Plinninger, R. J., Restner, U., 2008. Abrasiveness testing, quo vadis? - a commented overview of abrasiveness testing methods. Geomechanics and Tunneling, 1 (1): 61–70

Sabir Dam & Water Works Construction Company, 2014. Engineering geological report of Chamshir tunnel, unpublished report

Sass, I., Burbaum, U., 2008. A method for assessing adhesion of clays to tunneling machines. Bulletin of Engineering Geology and the Environment, 68 (1): 27–34

Tarigh-Azali, S., Ghafoori, M., Lashkaripour, G., Hassanpour, J., 2013. Engineering geological investigations of mechanized tunneling in soft ground: A case study, East–West lot of line 7, Tehran Metro, Iran. Engineering Geology, 166: 170–185

Thewes, M., Burger, W., 2004. Clogging risks for TBM drives in clay. Tunnels & Tunneling International, 28–31

Thuro, K., Käsling, H., 2009. Classification of the abrasiveness of soil and rock. Geomechanics and Tunneling, 2 (2): 179–188

Thuro, K., 1997. Prediction of drillability in hard rock tunnelling by drilling and blasting. - In: Golser, J., Hinkel, W.J., Schubert, W. (eds.): World Tunnel Congress 1997, Vienna, Austria. Proceedings. Tunnels for People. Tunnels für Menschen. Rotterdam, Brookfield (Balkema), 1: 103–108