Studying the Effect of Tunnel Depth Variation on the Specific Energy of TBM, Case Study: Karaj–Tehran (Iran) Water Conveyance Tunnel

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Abstract The tunnel-boring machine **(**TBM) is a common piece of equipment used in tunneling projects. For planning a mechanical excavation project, prediction of TBM performance and the specification of design elements such as required forces are critical. The specific energy of excavation (SE), i.e. drilling energy consumption per unit volume of rock mass, is a crucial parameter for performance prediction of a TBM. In this study, the effect of variation of tunnel depth on SE by considering the post-failure behavior of rock mass was investigated. Several new relations between SE and tunnel depth are proposed according to the statistical analysis obtained from Karaj – Tehran Water Conveyance Tunnel real data. The results showed that there is a direct relation between both parameters and. Polynomial equations are proposed as the best expression of the correlation between these parameters.

Keywords: *forces; post failure behavior; specific energy; TBM; tunnel depth.*

1 Introduction

The specific energy of excavation (SE) is defined as the energy consumption required for drilling one unit volume of rock mass ($\frac{MJ}{m^3}$) [1]. The concept of SE has been presented for the first time by Teale [2] in the petroleum industry and is an index for evaluation of drilling processes and excavating results in rock masses. The SE can be determined by collecting data from the performance of a drilling machine or a TBM. Boyd[3] calculated the rate of penetration based ontheSE of a rock mass. The correlation of this parameter to the mechanical properties of rock mass makes it very attractive for researchers [4]. Some researchers, such as Murhead and Glossop [5] and Hustrulid [6], achieved a good correlation between this parameter and uniaxial compressive strength (UCS). Altindag [7] found that there is a meaningful relationship between SE and the fragility of arock mass. Bieniawski, *et al.*[8] established a correlation between rock mass excavability (RME) and SE. Acaroglu, *et al.* [9] proposed a

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method that uses a fuzzy logic procedure in the process of rock cutting to predict the specific energy requirements of constant cross-section disc cutters.

Atici & Ersoy [10] estimated the effect of brittleness and destruction energy on SE. Zhang, *et al.* [1] introduced a mechanical analysis of the shield excavating process into the nonlinear multiple regression of on-site data and achieved a diagnosis model of the specific energy. Wang, *et al.* [11] developed new SE equations with changes in disc cutter radius.

2 Concept of Specific Energy

As mentioned before, the specific energy (SE)is defined as the energy consumption required for drilling one unit volume of rock mass ($\frac{MJ}{m^3}$). Evaluation of the energy required for an excavation project can be done using the SE. TBM operation parameters dictate the required forces on disc cutters and these forces are determinant to the SE value [11]. SE is a function of two components, i.e. the rolling force (torque) and the axial force (thrust) of the disc cutter. When a TBM is in the operation, both the axial and the rolling force act on the machine during excavation [10].

The thrust (T) pushes the cutter head of the machine constantly into the rock mass and the torque (F) continuously rotates it to cut the rock mass. In fact, the required thrust is spent to generate micro fractures in the rock mass. In other words, the thrust force is related to the pre-failure section of the complete stress-strain curve of the rock mass. The post-failure behavior of the rock mass indicates the value of the required torque because it is spent to propagate micro fractures and to create macro fractures.

Teale [2] proposed the specific energy as the following expression:

$$SE = \left(\frac{F}{A}\right) + \left(\frac{2\pi}{A}\right)\left(\frac{NT}{u}\right) \tag{1}$$

where SE is the specific energy required for drilling ($\frac{MJ}{m^3}$), F is the total thrust (KN), A is the area of the drilling face (m^2), N is the rate of cutter head revolution (rps), T is the cutter head torque (KNm), and u is the average penetration rate (m/s).

Eq. (1) has two terms, the first representing the specific energy of the cutter head thrust from static loading, while the second part is the specific energy of rotation incurred by the rotating cutter head.

Hoek and Brown [12] proposed rock mass quality classification based on the geological strength index (GSI) and post-failure behavior as described below:

1. 70<GSI<90: very good quality rock masses with elastic brittle behavior
2. 50<GSI<65: averagely jointed rock masses with strain softening behavior
3. 40 <GSI<50: heavily jointed rock masses with strain softening behavior
4. GSI<30: very weak rock masses with perfectly plastic behavior and without dilation.

The aim of this work was to study the effect of variation of tunnel depth on the specific energy of a TBM by considering the post-failure behavior of rock mass based on real data from a water transfer tunnel in Iran.

3 Project Description and Geology

The Karaj-Tehran Water Conveyance Tunnel is one of the components of a water management system in Iran that was designed to transfer 16 m^3/s of water from the Amir-Kabir dam to Refinery No.6 in Tehran. The total length of the tunnel is 30 km and it is divided into two sections. Lot2, 14 km in length and 4.66 m in diameter,was excavated with a double shield TBM Herrenknecht, model S323. The basic specifications of the utilized TBM are shown in Table 1.

Table 1 Mechanical properties of double shield TBM Herrenknecht,model S323.

TBM type	Double Shield TBM
Total length	166m
Shield length	10.6m
TBM weight	750 ton
Shield weight	170 ton
Cutter head weight	45 ton
Number of disc cutters	31
Average spacing of disc cutters	75mm

The tunnel intersects a series of asymmetric faults and folded formations. The lithology of this area consists of a sequence of Karaj formations and a variety of pyroclastic rocks, often interbedded with sedimentary rock. The characteristic rock types in this section are gray tuff, siltstone, sandstone, monzodiorite and monzogabbro[13]. A section of the tunnel is shown in Figure 1.

In general, by excluding repeated units in different parts of the tunnel route, 20 engineering geological units were distinguished; their properties are listed in Table 2. The properties were obtained from in-situ and laboratory tests.

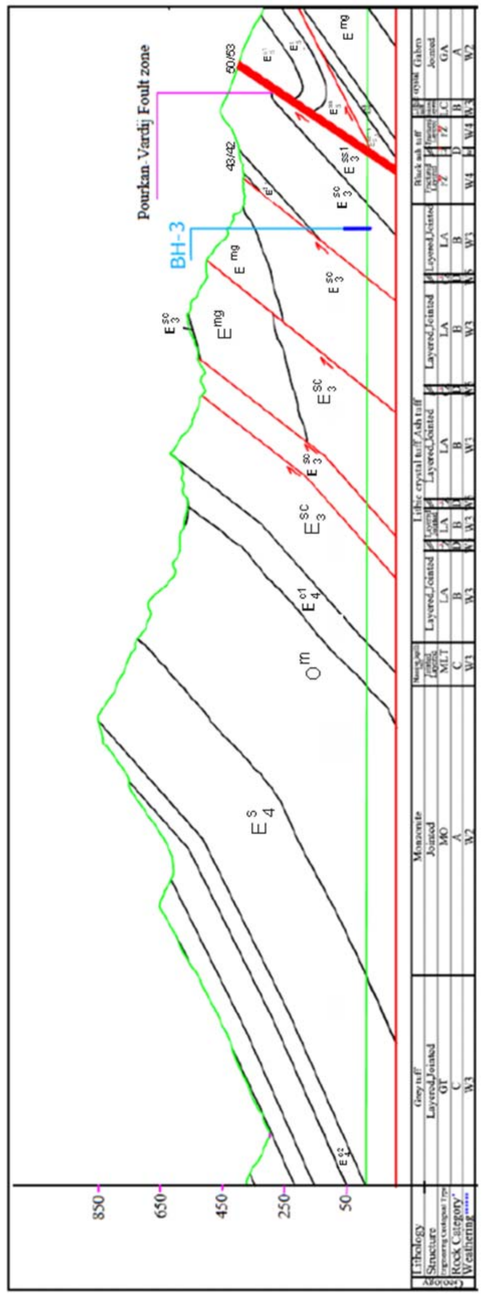

Figure 1 A section of Karaj–Tehran tunnel (Lot-2) .

Table 2 Engineering geological units along the tunnel route.

Eng.Geo.Unit	Sign	GSIPeak	σ_{ci}(MPa)	σ_{cm} (MPa)	E_{rm}(GPa)
Diorite	DIO	65-75	100-200	61.7	15
Gabbro	GA	60-70	100-200	57.4	12.5
Lithic Crystal Tuff	LCT	40-50	50-100	15.2	5
Ash and Lithic Tuff	AL	35-45	50-100	13.7	4
Lithic and Lapili Tuff	LL	60-70	50-100	32.6	7.5
Lapili Tuff	LT	50-60	50-100	16.2	5
Gabbro Rubble	BG	55-65	50-75	17.1	7.5
Thick Lithic Tuff	LC	50-60	100-150	31.2	7.5
Lithic and Ash Tuff	LA	55-65	50-100	20.8	7.5
Massive Lipili Tuff	MLT	50-60	50-100	26.3	5
Monzonite	MO	70-80	100-200	69.3	15
Gray Tuff	GT	50-60	50-100	16.6	5
Lithic Lapili Tuff	LLT	65-75	100-150	43.5	10
Ash Tuff	AT	35-45	50-100	8.8	2.5
Cream Tuff	CT	70-80	100-150	44.5	10
Gray Lithic Tuff	GLT	45-55	50-100	22.5	5
Green and Cream Tuff	TU	45-55	100-150	24.7	7.5
Ash Lithic Tuff	ALT	40-50	50-100	9.9	4
Fractured Zone	FZ	30-40	---	8.1	2.5
Crushed Zone	CZ	20-30	---	6.3	1.5

GSI: Geological Strength Index, σ_{ci}: uniaxial compressive strength of intact rock, σ_{cm}: uniaxial compressive strength of rock mass, E_{rm}: deformation modulus of rock mass.

4 Estimation of Specific Energy

The main purpose of this section is to evaluate specific energy changes to depth of tunnel for each engineering geological unit of the tunnel route. For this reason actual data from the 10,114 sections in the tunnel route were collected and analyzed, including thrust, torque, rotation speed, average rate of advance, and tunnel depth. Then, the SE of excavation for each unit at a certain depth was calculated using Eq. (1).

For simplifying the calculation due to the large number of data, the SE, thrust and cutter head torque values of each unit were averaged at regular depth intervals. The results are given in Figures 2 to 7.

It can be concluded from these figures that the torque, thrust and specific energy have a direct relation with the depths of the rock and the correlation between these parameters is best expressed using a polynomial equation as given in Table 3.

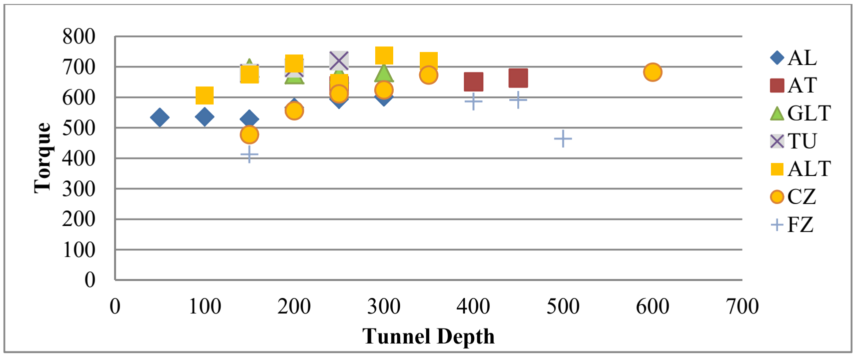

Figure 2 Relation between tunnel depth and cutter head torque for low to moderate units (50>GSI>25).

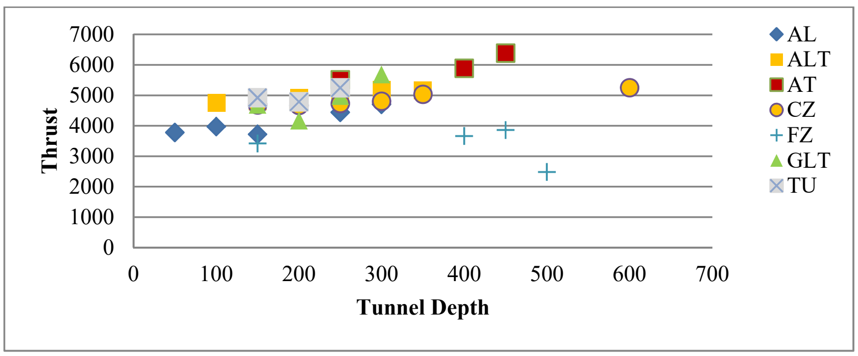

Figure 3 Relation between tunnel depth and thrust for low to moderate units (50>GSI>25).

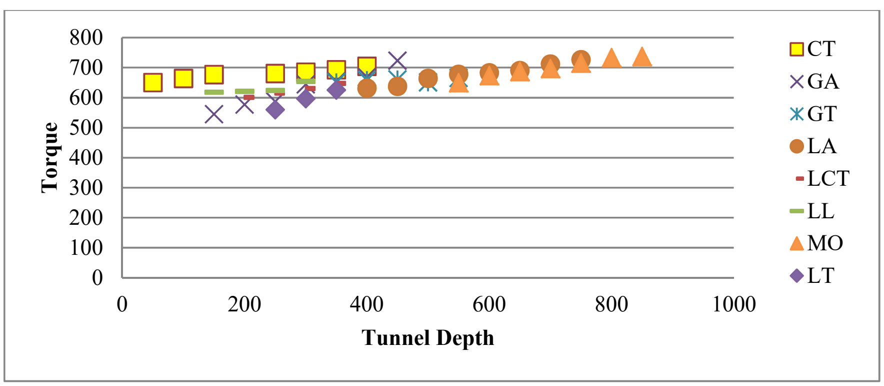

Figure 4 Relation between tunnel depth and cutter head torque for good units (75>GSI>50).

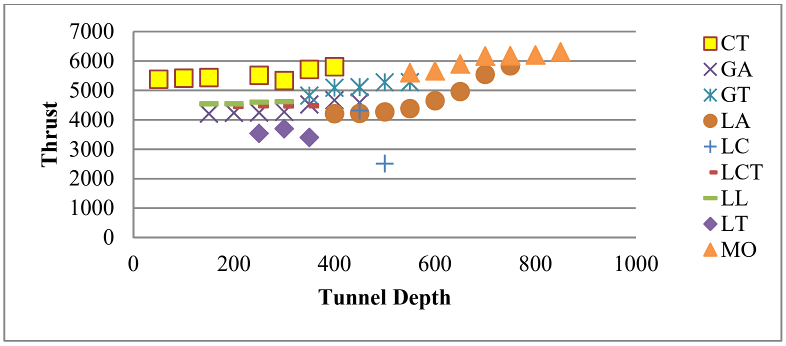

Figure 5 Relation between tunnel depth and thrust for good units (75>GSI>50).

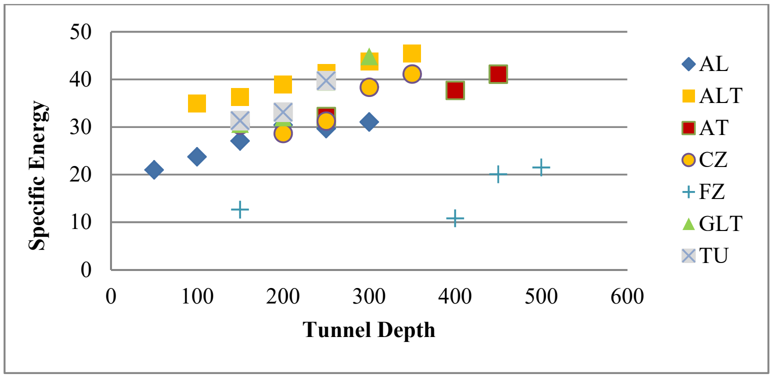

Figure 6 Relation between tunnel depth and specific energy for low to moderate units (50>GSI>25).

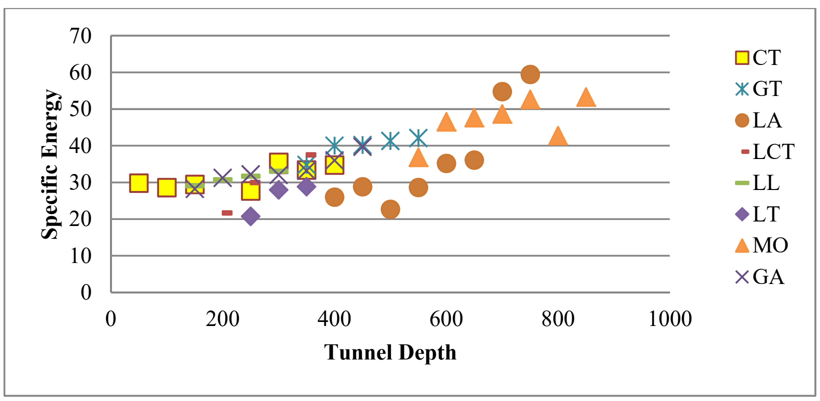

Figure 7 Relation between tunnel depth and specific energy for good units (75>GSI>50).

Table 3 Relations between torque, thrust and specific energy and tunnel depth for each layer of tunnel route.

	Torque	Thrust	Specific Energy
AL	$T = 0.001h^2 - 0.114h + 533.5$	$Th = 0.003h^2 + 2.814h + 3594.$	$SE = -0.000h^2 + 0.098h + 16.15$
AT	$T = 0.000h^2 - 0.436h + 697.3$	$Th = 0.037h^2 - 21.78h + 8624.$	$SE = 0.000h^2 - 0.067h + 39.00$
GLT	$T = 0.002h^2 - 1.288h + 828.1$	$Th = 0.122h^2 - 47.66h + 9007.$	$SE = 0.000h^2 - 0.078h + 32.98$
TU	$T = 0.000h^2 + 0.048h + 649.9$	$Th = 0.119h^2 - 44.59h + 8919.$	$SE = 0.001h^2 - 0.303h + 55.10$
ALT	$T = -0.001h^2 + 1.076h + 528.4$	$Th = -0.003h^2 + 3.641h + 4388.$	$SE = 7E\text{-}06h^2 + 0.040h + 30.53$
CZ	$T = -0.002h^2 + 1.917h + 242.7$	$Th = -0.000h^2 + 1.750h + 4377.$	$SE = 0.000h^2 - 0.132h + 40.72$
FZ	$T = -0.005h^2 + 4.010h - 57.29$	$Th = -0.041h^2 + 25.09h + 586.1$	$SE = 0.000h^2 - 0.158h + 29.85$
CT	$T = -7E\text{-}05h^2 + 0.162h + 646.3$	$Th = 0.006h^2 - 1.764h + 5504.$	$SE = 8E\text{-}05h^2 - 0.016h + 29.98$
DIO	$T = 1.487h + 167.1$	$Th= 3.840h + 3292.$	$SE = 0.015h + 24.05$
GA	$T = 0.000h^2 + 0.457h + 473.9$	$Th = 0.003h^2 - 0.155h + 4141.$	$SE = 7E\text{-}05h^2 - 0.012h + 29.53$
GT	$T = 4E\text{-}05h^2 + 0.005h + 646.8$	$Th = -0.010h^2 + 11.89h + 2005.$	$SE = -0.000h^2 + 0.237h - 19.76$
LA	$T = -2E\text{-}05h^2 + 0.291h + 518.2$	$Th = 0.017h^2 - 14.92h + 7435.$	$SE = 0.000h^2 - 0.412h + 121.2$
LC	$T = 3.126h - 967$	$T = -36.12h + 20575$	$SE = 0.020h + 3.864$
LCT	$T = 0.000h^2 + 0.164h + 557.3$	$Th = -0.001h^2 + 1.128h + 4302.$	$SE = -0.000h^2 + 0.307h - 24.45$
LL	$T = 0.002h^2 - 0.961h + 703.8$	$Th = 0.001h^2 - 0.279h + 4540.$	$SE = -2E\text{-}05h^2 + 0.035h + 24.34$
LT	$T = -0.001h^2 + 1.606h + 257.9$	$Th = -0.090h^2 + 52.70h - 3998.$	$SE = -0.001h^2 + 0.844h - 110.8$
MLT	$T = 0.767h + 60.12$	$Th = 8.828h - 1546.$	$SE = 0.093h - 30.19$
BG	$T = 1.660h - 115.1$		$SE = 0.165h - 29.21$
MO	$T = -0.000h^2 + 0.689h + 357.5$	$Th = -0.006h^2 + 11.49h + 1177.$	$SE = -0.000h^2 + 0.333h - 79.39$

5 Conclusions

This study investigated the effects of depth and quality of rock mass on thrust, torque and specific energy in Karaj–Tehran Water Conveyance Tunnel TBM drilling. The following results were obtained:

1. The increase of the tunnel's depth is associated with the increases in required thrust, torque and specific energy. The associated relationships are best expressed using a polynomial equation.
2. The thrust increase rate of the low to moderate quality layers (50>GSI>25) is higher than that of the good layers (75>GSI>50).
3. The torque increase rate of the good quality layers (75>GSI>50) is higher than that of the low and moderate layers (50>GSI>25).

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