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ESTIMATION OF THE REQUIRED THRUST FOR TUNNEL EXCAVATION BY USING 3D NUMERICAL MODELING - A CASE STUDY OF THE BEHESHTABAD TUNNEL

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Abstract : *There are a lot of complex problems involving a number of conflicting factors when planning a TBM drive in squeezing ground. In this respect, numerical analyses represent a helpful decision aid. In the present paper, Beheshtabad water transmission tunnel is introduced, and mechanized full face and drill and blast excavation challenges in squeezing ground are investigated. Then the geomechanical rock mass parameters in the 19th zone are determined. In following, the approach to thrust evaluation and effective parameters on that is discussed, and the required thrust for penetration in the work face on the basis of advance rate, cutterhead geometry and compressive and tensile strength of the host rock is calculated. Then the numerical analysis pattern and the achieved results are investigated. According to these results, if three and ten cm overcutting were performed in the most and least favorable geotechnical condition respectively, double shield TBMs could be used in the 29030-31600 and the 34900-37490 Km of the tunnel. In the 31600-34900 Km, utilization of single and double shield TBMs is not possible, and decision on the usage of double and single shield TBMs in this section could be made if an exploration gallery were planned, and additional insitu tests were done for the determination of long term parameters of the host rock.*

KEYWORS: *Beheshtabad tunnel. Numerical analysis, Squeezing, TBM, Thrust*

1. INTRODUCTION

The requirement of water in the central part of Iran has increased because of Increasing of population, industry concentration, decreasing water quality and underground water level reduction in this area. To provide the water necessities for human, industrial and agricultural, the Beheshtabad water transmission tunnel which its length and lined Diameter is 65 Km and 6 meter respectively is under investigation. This tunnel is planned to transmission of 1070 million cubic meter of water from Beheshtabad River to Zayanderod River. The tunnel route from the tunnel inlet to the vicinity of the 17th Km is situated in Zagros thrust zone and after that to the tunnel outlet is located in Sanandaj-Sirjan zone and the main thrust of Zagros has separated these zones form each other.

In accordance with overground and underground investigations, geophysics studies, drilled boreholes and engineering geology mapping, the tunnel route is broken up to 29 zones. The high squeezing conditions in the 19th zone will take place according to high tunnel convergence, which is obtained by close form solution, because of high overburden and weak geotechnical conditions. The tunnel in this chainage will be excavated by TBM and for machine type selection, calculation of the required thrust for excavation is essential, so in this research, according to 3, 5 and 10 Cm over excavation in the 19th zone, the necessary thrust and appropriate method of excavation are determined.

2. EXCAVATION PROBLEMS IN SQUEEZING GROUND

Squeezing refers to the phenomenon of large time dependent deformation during tunnel excavation. It occurs mostly in week rocks with high deformability and a low strength, often in combination with a high overburden. In addition, there are considerable challenges for tunnel excavation if tunnel convergence exceeds 5 percent due to high squeezing conditions [1]. Various types of TBMs have different challenges in squeezing ground according to their thrust and existence or inexistence of the shield. Also drill and blast technique in contrast to mechanized full face excavation has flexibility in over-excavation quantity, but on the downside, the advance rate of this method is very slow.

Open TBMs have a short canopy or shield which supports the cutterhead. This type of canopy has an effective role in decreasing required thrust for excavation. Moreover, access to the face is easier and faster than single and double shield machines. On the other hand, impossibility of supplying sufficient thrust with gripers is a significant challenge which is encountered in squeezing ground. In these conditions, preconsolidation of the tunnel should be done before excavation and this consume a lot of money and time [2].

In single shield TBMs, The length of the shield is longer than open machines, so the possibility of blockage for these machines is more, but the advance rate of these machines is greater than open TBMs. In these machines, the required thrust for excavation is supplied by segment.

The length of double shield TBMs is longer than single shield ones, and the necessary thrust could be provided with tunnel wall or segments or both of them. By neglect the time effect, the longer the shield length, the greater the thrust for excavation, but the advance rate of double shield machine is greater than single shield one, and the greater advance rate, the less tunnel convergence, consequently the tunnel load which is applied on the shield of double shield machine is less, so the required thrust for excavation is less than single shield one. Because of great advance rate of double shield machines, the probability of blockage for these machines is less than single shield ones, but the occurrence of blockage means that more time and cost are needed for releasing in comparison with single shield machines.

3. GEOLOGY

The 19th zone is extended from 29030 to 37490 Km which is including three geological units. The first unit consists of mylonitic limestone and the second unit includes mylonitic sandstone which is cemented with limestone. There are a lot of slaty cleavage, micro faults and micro folds in this unit. The third unit consists of sandy limestone, metamorphic sandstone, marly limestone and metamorphic shale. The overburden of the 19th zone is varied from 480 to 790 meters. The longitudinal geological section of this zone is presented in figure 1. Furthermore, the intact parameters of host rock in this zone are determined on the basis of statistical analyses on the laboratory tests which are done on the cores. These parameters are presented in table 1.

Table 1: Intact Parameters of host rock in 19th zone

Km	UCS_i(Mpa)	Nu	E_i (Gpa)	m_i	Borehole
34900-37490 & 29030-31600	(50-25) Ave: 45	0.22	11	7	BH9, TB9A
31600-34900	(10-30) Ave: 25	0.24	7	6	TB9B

Rock mass parameters, which are used for numerical modeling, are calculated on the basis of Hoek approach, GSI which is determined by engineering rock mass classification, and intact rock properties. The least and most favorable rock mass parameters are presented in table 2.

Table 2: Most favorable and least favorable of rock mass parameters of host rock in 19th zone

Km	GSI	Mpa Cohesion	Phi (Degree)	Nu	E_m (Mpa)
34900-37490 & 29030-31600	35-45	1.5-1.8	23-26	0.28	1250-2500
31600-34900	25-35	0.8	22	0.33	800

4. CALCULATION OF THE REQUIRED THRUST FOR EXCAVATION

Before evaluation of the required thrust for excavation, the following parameters should be determined:

I. Normal stress distribution around the shield
II. Length and diameter of the shield
III. Machine weight (W_{sh})
IV. The required thrust for penetration (A)
V. Friction coefficient between shield and ground (μ)

By integration of the normal stresses on the surface of the shield, the normal force (N) can be calculated, and the required thrust (T) could be estimated by equation 1. If numerical modeling involved the machine weight, it will affect the normal stress distribution around the shield so it could be omitted from equation 1.

$$T = \left(N + W_{Sh}\right) \times \mu + A \tag{1}$$

The required thrust for penetration equals to the addition of the normal forces on the disc cutters. These normal forces could be evaluated according to pressure distribution around the disc cutters and the surface of the contact area between the disc cutters and the face. Rostami for evaluation of pressure around the disc cutters has purposed equation 2, on the assumption that pressure distribution around the disc cutters is uniform [3].

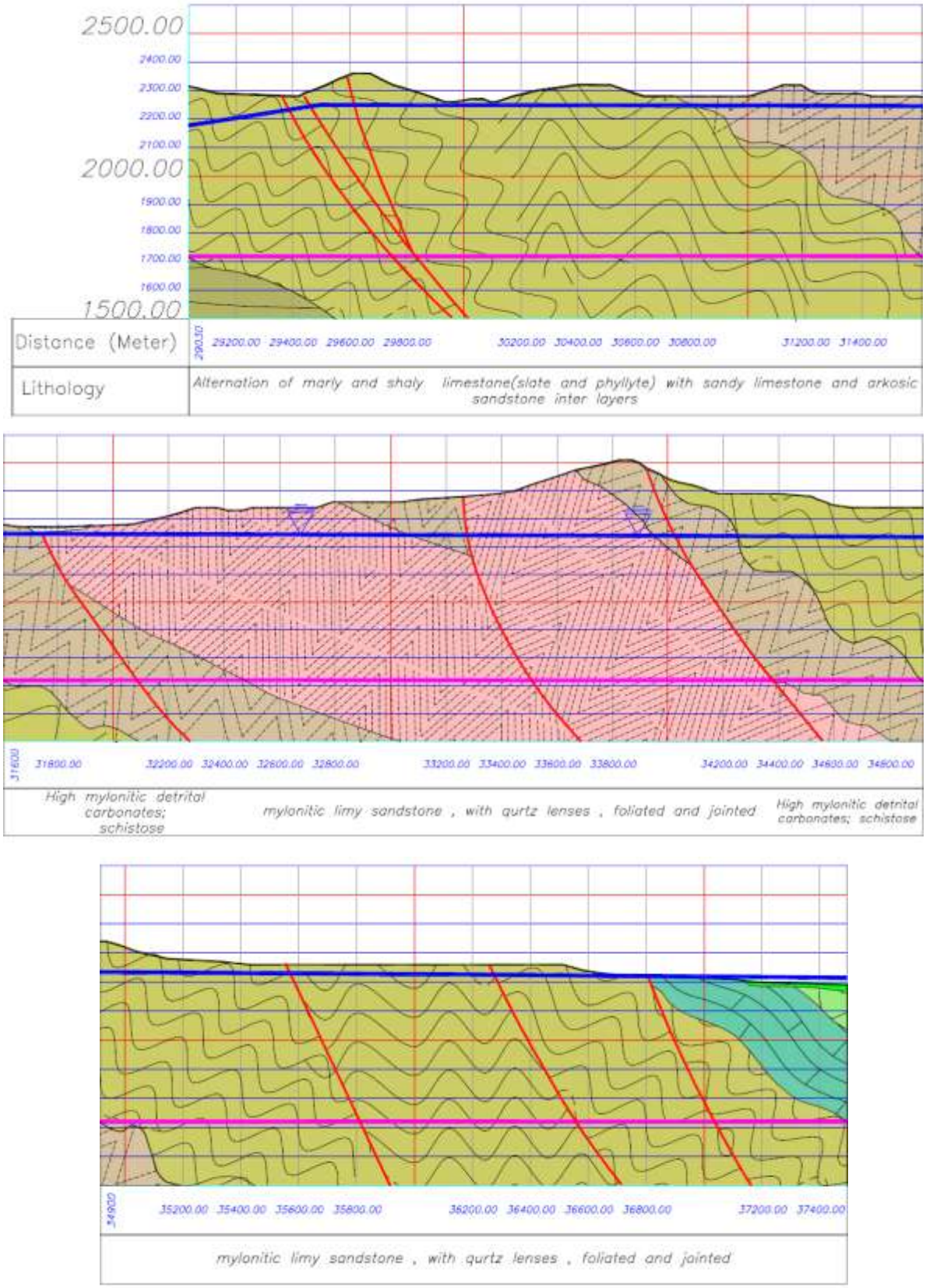

Fig. 1: Longitudinal geological section of the 19th zone

$$P = 2.12\sqrt[3]{\left(S \times \sigma_c^2 \times \sigma_t\right) / \left(\varphi\sqrt{Rt}\right)} \tag{2}$$

$$\varphi = Cos^{-1}\left(\left(R - P_n\right)/R\right) \tag{3}$$

Where σ_c and σ_t are the compressive and tensile strength of rock
φ is the angle of the cutter disc contact with the face which is determined by equation 3
R and t are diameter and thickness of disc cutter
S and P are spacing of disc cutters and pressure on them respectively
P_n is disc cutter penetration in the face per round of the cutterhead

On the basis of poor geological conditions, machine characteristics and tunnel section, advance rate and utilization factor of the machine are determined 300 meters per month and 20 percent. According to rotational speed of the cutterhead (12 RPM), disc cutter penetration in the face per round of the cutterhead is 5 mm. the necessary thrust for penetration in the face could be calculated by equation 4, on the assumption that pressure distribution around disc cutter is uniform.

$$Thrust_{penetration} = N \times P \times R \times \varphi \times t \times Cos(\varphi/2) \tag{4}$$

Where N is the number of disc cutters

According to the laboratory test results, the compressive and tensile strength of the tunnel host rock in this zone are 20 and 2 Mpa respectively. If the number of disc cutters and disc cutter diameter and thickness were assumed 50, 17 inch and 1 inch respectively, the required thrust for penetration would be 3 MN.

Based upon researches have been done, when the machine is advancing, the friction coefficient which is named dynamic friction coefficient could be assumed 0.25, but when the machine is blocked, the friction coefficient which is named static friction coefficient could be supposed 0.4 [4]. The usage of Bentonite between shield and ground could reduce the friction coefficient up to 50 percent. In this research the excavated tunnel diameter is 7 meters, and the single shield and double shield length are assumed 8 and 13 meters consistent with the catalogue of manufactured TBMs.

Normal stress distribution around the shield is a function of geotechnical characteristics of rock mass, advance rate and over-cutting quantity. Usage of over-cutting is a common procedure in squeezing ground for thrust reduction because it allows both tunnel convergence and stress release to increase; consequently, the required tunnel support and the necessary thrust for excavation will decrease.

If the method of tunnel excavation were drill and blast technique, the over-cutting could be done in an unlimited length and quantity, but for mechanized full face excavation the quantity of over-cutting is limited to 15 cm in radius. In addition, this over-cutting could be performed in a limited length. Over-cutting usually is done by using extendable cutters on the periphery of the cutterhead which could be extended mechanically or hydraulically. The mechanical ones have less length limitation in comparison with the hydraulic ones. In addition, for over-cutting the cutterhead should be located in the centerline of the tunnel. It can be easily handled by open TBMs; for shielded TBMs, lifting of the centerline of the cutterhead is necessary. Furthermore, for all type of TBMs repositioning of the mucking bucket is needed [5]. Another way to thrust reduction is usage of a conical shield. In this way the upper limit for shield diameter reduction is 6 cm which is done in numerical analysis.

5. NUMERICAL MODELLING

Numerical modeling is an appropriate method to determine the normal stress distribution around the shield. In long distance away from the work face, the plane strain condition could be used, but for evaluation of the full face boring machine thrust, because the machine is near the face, it affects deformation and stress distribution around the shield, so the plane strain condition is not true, and 3D numerical modeling should be used.

Although there have been cases of intense and rapid development of ground deformation close to the work face, experiences show that usually tunnel deformation takes place over a period of days, weeks or months. This time dependent deformation is called creep. Because determination of time dependent rock mass parameters is expensive and time consuming, usually in numerical modeling the effect of time on deformation is neglected, therefore the normal forces which are calculated by numerical modeling are the ultimate ones, and the estimated thrust is conservative [6].

If numerical modeling includes time effect, the critical standstill duration could be calculated according to the creep parameters of the rock mass and the over-cutting quantity. If the standstill duration of the machine were more than the critical standstill duration, the machine thrust will not sufficient to overcome friction force

between shied skin and ground and the machine will be blocked. However, the conditions prevailing at the beginning of a standstill will depend on the advance rate during the previous TBM operation. The higher the advance rate, the lower the total required thrust force will be during excavation, therefore the more time must elapse during a standstill in order that the required thrust reaches the available one[7].

The distance between the cuter head and the tunnel face in the numerical modeling is evaluated accordance to compatibility of the friction force around the shield with the normal force on the cuter head and the advance direction. This compatibility is achieved by making a lot of numerical models and analysis their results.

6. NUMERICAL MODELING RESULTS

6.1. The 29030-31600 and the 34900-37490 Km

In numerical modeling, three, five and ten cm overcutting in radius and two class of geotechnical parameters, most and least favorable, which are presented in table 2 are considered. The single and double shield length is 8 and 13 meters respectively and by using conical shield, its diameter is reduced by 6 cm.

The results of numerical modeling are presented in table 3. The upper limit of available thrust force for a double shield machine, which its diameter is 7 meters, is about 60 to 70 MN. Consequently, the shielded machine could be used in sections which the geotechnical parameters are the least if 10 cm over-cutting were done. This amount of over-cutting could be performed in a limited length, and were the length of these sections more than 200 to 300 meters, application of shielded machine will be risky. The variation of necessary thrust for excavation vs. shield length for the least favorable geotechnical condition is presented in the figure 2. In this graph, the right vertical axis is related to 10 cm over-cutting and the left one is belonged to 3 and 5 cm over-cuttings.

Table 3: the required thrust for excavation in the 29030-31600 and the 34900-37490 Km

Nu	E_m (Mpa)	C (Mpa)	Phi (Degree)	over cutting (cm)	Thrust (MN)	
					Double Shield	Single Shield
0.28	2500	1.8	26	3	8	8
				5	3.7	3.4
				10	3.7	3.4
	1250	1.5	23	3	423	273
				5	183	111
				10	19	18

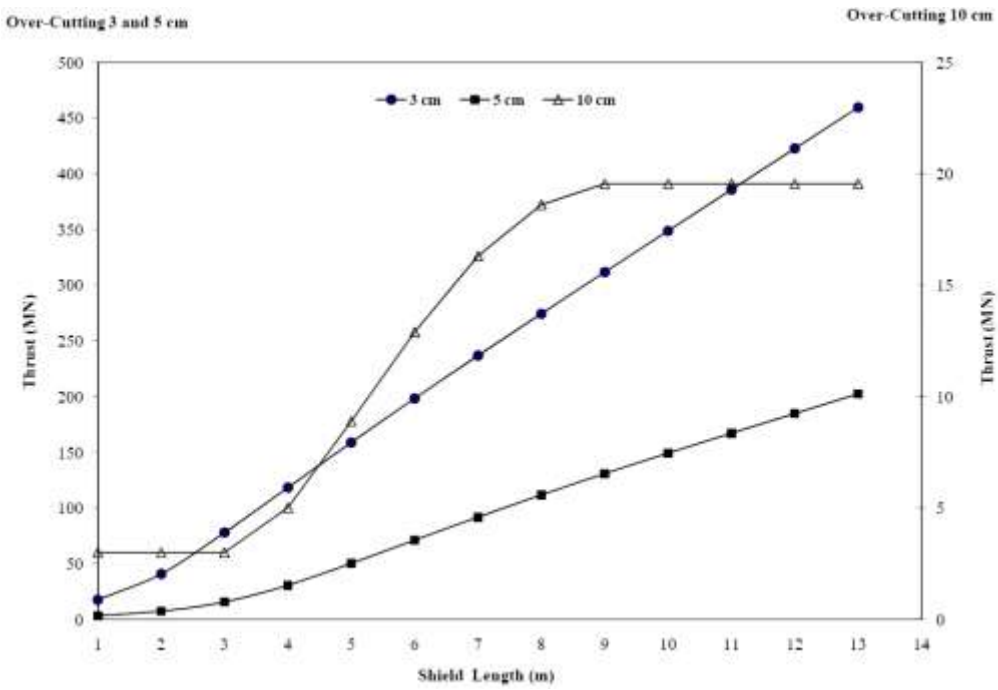

Fig. 2: Thrust variation vs. tunnel length for the least favorable geotechnical parameters in the 29030-31600 and the 34900-37490 Km

In sections which the geotechnical parameters are the most favorable, the upper limit of required thrust for excavation is 8 MN which is easily available for the single and double shield machines, so 3 cm of over-cutting is adequate in these sections and performing 5 and 10 cm over-cutting is not necessary. If 3 cm over-cutting were not done, the required thrust for a conical double shield machine will be 400 MN. Consequently, shielded machine could not be used without 3 cm over-cutting.

6.1. The 31600-34900 Km

The results of numerical modeling in this section are presented in table 4. According to these results, shielded machines could not be used even if 10 cm over-cutting were done, and Preconsolidation of the tunnel is essential for excavation in this section. Because the upper limit of thrust is calculated in this research, decision on the usage of double and single shield TBMs in this section could be made if time dependent rock mass parameters were included in the numerical modeling, so the exact thrust could be calculated considering the time effect. Determination of time dependent rock mass parameters could be done in an exploration gallery with executing additional insitu tests.

7. CONCLUSION

In the 29030-31600 and the 34900-37490 Km, execution of 10 cm over-cutting is necessary to application of shielded machines for the least favorable geotechnical parameters. In addition, the length of these sections should not be more than 300 meters because of technical problems. Furthermore, as a result of higher advance rate of double shield TBMs, application of these machines is more preferable than single shield ones in this zone.

Performing tree cm over-cutting is sufficient in the 29030-31600 and the 34900-37490 Km for sections which the geotechnical parameters are the most favorable. This quantity of over-cutting could be done in the entire zone without technical limitations.

In the 19th zone, to accurate decision on the usage of shielded machines and determination of shield type an exploration gallery should be excavated and additional insitu tests were done in this gallery.

Table 4: the required thrust for excavation in the 31600-34900 Km

Nu	E_m (Mpa)	C (Mpa)	Phi (Degree)	over cutting (cm)	Thrust (MN)	
					Double Shield	Single Shield
				3	729	383
0.33	800	0.8	22	5	641	332
				10	547	330

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Mr. Mahdevari graduated in mining engineering from the University of Tehran in 2001. He obtained a M.Sc. degree in rock mechanics at Tehran University in 2004. From 2002 to 2004 he worked for ministry of road and transportation, specializing in design and stability analysis of underground excavations and slopes. From 2004 up to now he has been lecturer and researcher at Isfahan University of technology, where he specialises in numerical analysis of underground excavation. From 2005 up to now he joined Zayandab Company as tunnel design Chief Engineer. His interested research field are flow analysis, back analysis and numerical modeling.

Mrs. Ayati graduated in Geology from the University of Isfahan (Iran) in 2001. She obtained a Ph.D in Petrology at the University of Isfahan from 2004 to 2009. The title of her thesis is "Neogene magmatism of northeast of Arak and related hydrothermal alteration (Cu-Au index of Dalli, Central province of Iran).her interested research field is petrology of igneous rocks, alteration and Cu porphyry mineralization. She worked as a laboratory technician (Mineralogy and petrology) in Isfahan University of technology for 2 years and now she works for Payamenoor University of Shahrekord (Chahar mahal Bakhtiari Province, Iran) from 2009 as an associated professor.

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