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Considering Creep Parameters of Rock Mass to Evaluate the Necessity Thrust for Excavation in Squeezing Ground

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ORIGINAL ARTICLE

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ABSTRACT: There are a lot of complex problems involving a number of conflicting factors when planning a TBM drive in a squeezing ground. In this respect, numerical analyses represent a helpful decision aid. In this research, Beheshtabad water conveyance tunnel is introduced. Then, the geomechanical rock mass characteristics including time dependent parameters are determined for the 19th zone of Beheshtabad tunnel. Afterwards, the approaches to thrust evaluation and mitigation measures for thrust reduction are reviewed. Then the numerical simulation layout and the achieved results are investigated. According to these results, double and single shield Tunnel Boring Machines (TBM) might be utilized if 55 mm and 20 mm of over-boring in radius could be performed in the A&B and C geological units, respectively. Furthermore, over-boring quantity and shield length affect necessity thrust for excavation more than advance rate and the effectiveness of advance rate increment as a mitigation measure to thrust reduction is decreased by increasing the advance rate.

Keywords: Beheshtabad tunnel, Creep, TBM, Thrust, 3D numerical simulation

INTRODUCTION

Due to population growth, industry concentration, reduction of water quality and underground water level falling in the central part of Iran, water necessity is of great importance in this area. To supply the drinking, industrial and agricultural water necessities in the mentioned region, the Beheshtabad Water Conveyance Tunnel, whose length and lined diameter are 65 Km and 6 meters respectively, is under construction. This tunnel is planned to convey 1070 million cubic meter of water per year from Beheshtabad River to Zayanderod River.

In accordance with the surface and underground investigations, geophysics studies, laboratory tests and engineering geology mapping, the tunnel route has been broken up into 29 zones. As a result of weak geological condition and high overburden in the 19th zone, there is a high potential of squeezing in this region. The tunnel in this zone will be excavated by TBM, and due to machine type selection, calculation of the required thrust for excavation is crucial. So in this research, the essential thrust to overcome frictional resistance for a single or double shield TBM has been determined using 3D numerical simulation and the effectiveness of mitigation measures for thrust reduction such as over-boring quantity, shield length reduction and advance rate increment have been considered.

Shalabi (2005), based on the axisymmetric finite element modeling, considered the ground movement and contact pressure on the lining in the Stillwater tunnel in USA. In this study, the power law and hyperbolic creep models were applied and the differences between the results were investigated.

Farrokh et al. (2006), according to the filed data obtained in the Ghomroud Tunnel in Iran and the use of convergence-confinement method, introduced a new approach to determine the required thrust along different geological units. However, the close form solution only provides a rough estimate of the squeezing potential without any information about the rock pressure distribution in the longitudinal direction (Cantieni and Anagnostou, 2009).

Weng et al. (2010) developed a new anisotropic model which was a simple variable bulk and shear modulus to model time-dependent deformation of a tunnel in weak sandstone and compare the results of the numerical modeling with the Burger's model results and the measured insitu data.

Ramoni and Anagnostou (2010) carried out a parametric study using two dimensional axisymmetric modeling for a cylindrical tunnel through a homogeneous and isotropic ground subjected to hydrostatic insitu stress and presented dimensionless design monographs to predict the essential thrust for overcoming frictional resistance in squeezing ground condition. As a result of axisymmetric assumption, the over-boring was found to be the same around the circumference of the shield while the over-boring was executed more at the top of the shield. In addition, the parametric study did not include the time dependency parameters of the ground.

Bilgin and Algan (2012), using the TBM performance data in the Uluabat Tunnel, Turkey, and analyzing them, introduced a squeezing index and purposed the execution of some mitigating measures before TBM jamming according to this index.

To sum up, most of the research up to date has been focusing on the tunnel deformation through a squeezing ground and there is little research work on the determination of the necessity thrust for tunnel excavation. In addition, most researchers have focused on

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the 2D numerical modeling and there has been almost no study considering the effect of the TBM advance rate on the required thrust. So in this research, the required thrust for excavation has been investigated considering different over-borings and advance rates of TBM for the Beheshtabad Water Conveyance Tunnel. To do this end, at first the tunnels geometry and ground geotechnical parameters have been studied and the time-dependent rock mass parameters have been determined using laboratory creep tests. Then, a full 3D numerical simulation, different aspects of the tunnel boring such as asymmetry over-boring around the shield, advance rate, tunnel deformation before excavation and the force required to penetrate in the face and its supporting effect on the excavation face have been taken in to account. Finally, numerical results are utilized in order to evaluate the possibility of the mechanized excavation.

MATERIAL AND METHODS

Geological survey

The 19th zone of the Beheshtabad Tunnel is extended from 29th to 37.5th Kilometers, covering three geological units. The first unit (A) consists of mylonitic limestone and the second one (B) includes mylonitic sandstone cemented with limestone. It is difficult to distinguish a boundary between these units. However, there are a lot of slaty cleavage, micro faults and micro folds in the second unit. The third unit (C) consists of sandy limestone, metamorphic sandstone, marly limestone and metamorphic shale. The overburden of the 19th zone is varied from 480 to 790 meters and the bored diameter is 7 meters by taking into account the segments thickness and back filling behind them, not including the over-boring. The longitudinal geological section of the 19th zone is presented in Figure 1. Furthermore, the intact geotechnical parameters of host rock in this zone have been determined on the basis of statistical analyses done on the laboratory tests. These tests have been carried out on the core samples obtained from three boreholes. The intact rock parameters of this zone and the utilized boreholes are presented in Table 1.

In order to determine the time dependent behavior of the rock mass, a time dependent model has to be used in the numerical simulation. The time dependent model utilized in the numerical simulation is the Burger-creep viscoplastic model (CVISC), which is a combination in the series of the Burger’s viscoelastic model and the Mohr-Coulomb model as a plastic flow rule. This model involves the visco-elasto-plastic deviatoric behavior, which is governed by Burgers' model and plastic flow rule, and an elasto-plastic volumetric behavior, which is driven by the liner elastic law and the same plastic flow rule.

The Mohr-Coulomb criterion parameters for the rock mass are calculated according to an approach presented by Hoek and Diederichs (2006). In this method, the three axial compressive tests are simulated and according to the Mohr circles, the friction angle and cohesion of the rock mass are determined. The least and most favorable rock mass parameters calculated on the basis of the intact rock parameters, overburden and GSI are presented in Table 2.

To determine the Burger's model parameters, creep test has been done on the ten samples and the average results of these tests are presented in Table 3. In this table, η_M and G_M are the Maxwell dynamic viscosity and shear modulus and η_K and G_K are the Kelvin dynamic viscosity and shear modulus, respectively. The Burger's model just reproduces the primary and secondary stages of creep and it does not include the tertiary stage. So, to determine the primary and secondary creep characteristics, the load applied on the samples is gradually increased up to the sixty percent of the sample uniaxail compressive strength. The creep test has been done for a period of 40 days.

Table 1. Intact geotechnical parameters of the host rock in the 19th zone

Unit	Beginning and ending of the unit in meters	UCS_i (MPa)	Poisson's ratio	E_i (Gpa)	m_i	Borehole
A and B	31600-34900	(10-30) Ave: 25	0.24	7	6	TB9B
C	34900-37490 & 29030-31600	(50-25) Ave: 45	0.22	11	7	BH9, TB9A

UCS_i: Unconfined Compressive Strength of Intact Rock, E_i: Elastic Modulus of Intact Rock
m_i: Constant of Hoek and Brown Failure Criterion

Table 2. Most and least favorable rock mass parameters in the 19th chainage

Unit	Geological Structure Index (GSI)	Cohesion (MPa)	Phi (Degree)	Poisson's ratio	E_m (MPa)
A and B	25-35	0.8	22	0.33	800
C(Least Favorable)	35	1.8	23	0.28	1250
C(Most Favorable)	45	1.8	26	0.28	2500

Table 3. Time dependent characteristics of the rock in the 19th zone

η_K (MN.day/m^2)	G_K (MPa)	η_M (MN.day/m^2)	G_M(MPa)
129025	42733	300926	3514

η_K and G_K: Kelvin Dynamic Viscosity and Shear Modulus
η_M and G_M: Maxwell Dynamic Viscosity and Shear Modulus

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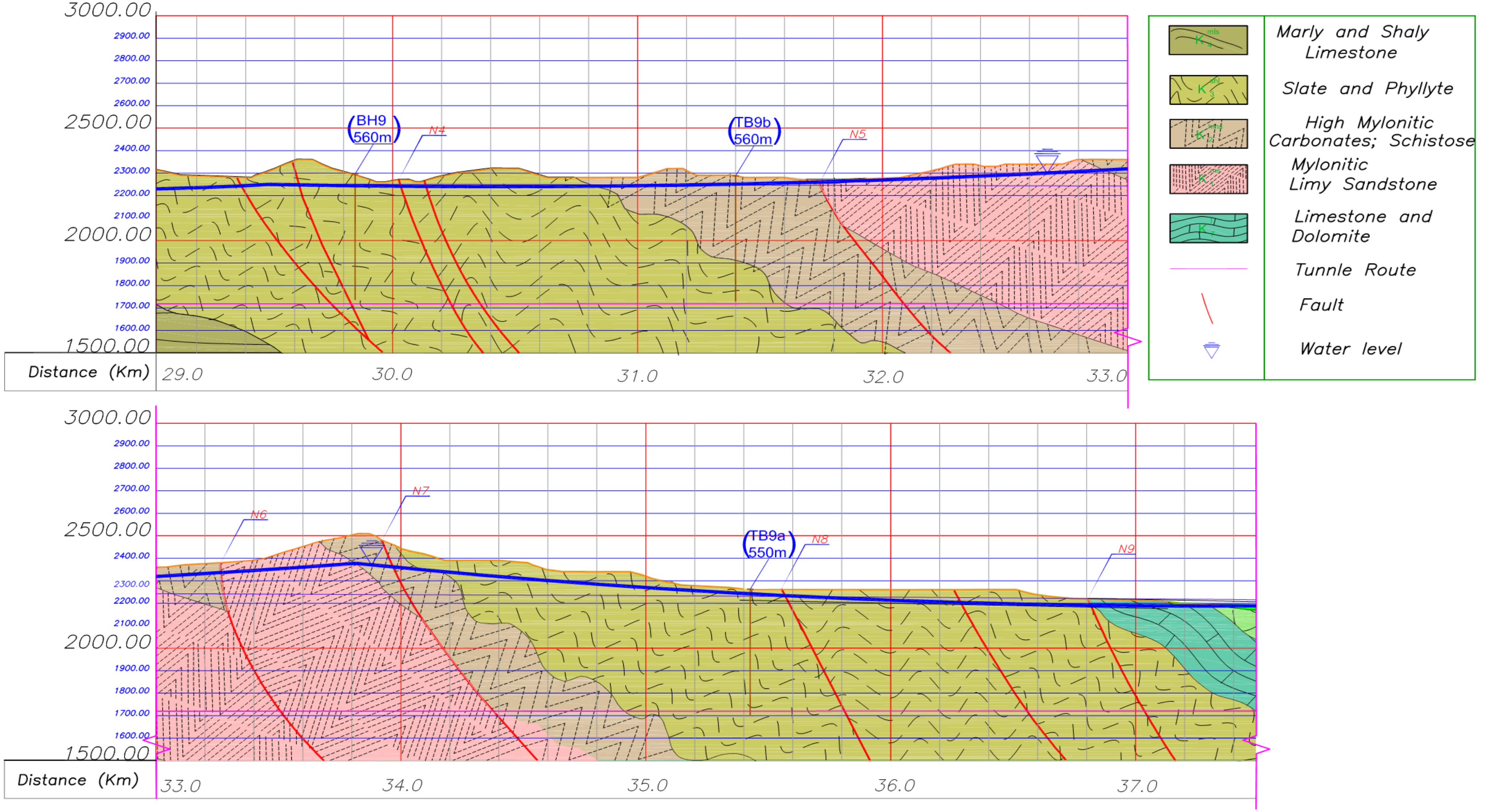

Figure 1. Longitudinal geological section of the 19th zone

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The necessity thrust

Thrust calculation: The necessity thrust to overcome the frictional resistance could be determined by equation 1: $$T = (N + W_{Sh}) \times \mu \quad (1)$$

Where N is the normal force on the shield skin, W_{sh} is the machine weight and μ is the friction coefficient between the shield and ground. The normal force could be calculated by integration of the normal stresses on the outer surface of the shield. Moreover, if the numerical modeling included the machine weight, it would affect the normal stress distribution around the shield. So the machine weight has to leave out of the equation 1. Normal stress distribution on the periphery of the outer shield skin is a function of geotechnical characteristics of the rock mass, shield geometry, advance rate and over-boring quantity.

When the machine is advancing, the frictional coefficient is called dynamic. On the other hand, when the machine is blocked, the frictional coefficient is called static and it is more than the dynamic one. In this research, according to the literature survey (Gehring 1996), the dynamic and static frictional coefficients were assumed to be 0.25 and 0.4, respectively.

Thrust reduction approaches: A common procedure for thrust reduction in a squeezing ground is over-boring. Since it allows an increment in the tunnel convergence, the stress releases more and the normal stress on the shield is decreased. The amount of over-boring for the mechanized full face excavation is limited up to about 15 cm in radius technically. In addition, this over-boring could be performed in a limited length. The over-boring is usually done by using extendable cutters on the periphery of the cutterhead that could be extended mechanically or hydraulically. Furthermore, the cutterhead should be located in the centerline of the tunnel. It can be easily handled by open TBMs; for shielded TBMs, lifting the centerline of the cutterhead is necessary. In addition, for all types of TBMs, repositioning of the mucking bucket is needed (Ramoni and Anagnostou 2006).

Another mitigating measure to reduce the required thrust for excavation is increasing the advance rate. Although there have been cases of intense and rapid development of ground deformation close to the work face, experiences show that tunnel deformation usually takes place over a period of hours, days or month (Ramoni and Anagnostou 2007). So, due to an increment in the advance rate, the duration of the excavation reduce and as a result of that, the tunnel deformation and the normal force on the shield skin are decreased.

In addition, the application of a conical shield could reduce the required thrust. In this way, the shield diameter is decreased along the shield. The application of some mitigating measures such as Bentonite between the outer shield skin and ground could reduce the frictional coefficient and as a consequence, the necessity thrust would be up to 50 percent.

RESULTS AND DISCUSSION

Numerical Simulation

Numerical simulation is an appropriate method to determine the normal stress distribution around the shield. In a long distance away from the work face, the plane strain condition could be used. However, to evaluate the full face boring machines thrust, since the machine is near the face, it affects deformation and stress distribution around the shield, so the plane strain condition is not valid and 3D numerical modeling should be used.

In the numerical simulation, the finite deference approach has been used and some effective aspects on the thrust requirement such as the deformation before the work face, advance rates and asymmetric over-boring periphery of the shield have been considered.

Tunnel deformation before the work face

The over-boring is carried out in the numerical simulation via an enlargement in the tunnel diameter at the top portion of the tunnel according to reality, implying that the TBM slides on the floor and the tunnel radius enlargement is at the top. Since the tunnel deformation begins before the work face (Panet 1993, Unlu and Gercek 2003), when the over-boring is performed at the work face, a portion of the tunnel deformation took place, with its amount being dependent on the tunnel geometry, geotechnical parameters of the rock mass and advance rate. So, the quantity of this deformation was calculated according to the mentioned effective parameters and considered in the numerical simulation.

The pressure on the working face

The pressure on the face ,which is applied by the cutterhead for excavation, confines the working face and decreases the tunnel deformation and as a consequence, reduces the necessity thrust to overcome the frictional resistant. If the applied pressure on the face be less than reality, the required thrust calculated via numerical simulation is overestimated. So, determination of the pressure applied on the face is essential for the accurate evaluation of the necessity thrust.

To determine the pressure on the face, the normal force required to penetrate in the face has to be evaluated, consistent with the penetration rate. On the basis of poor geological conditions, machine characteristics and tunnel section, the disc cutter penetration in the face has been estimated to be 5 mm per cutterhead revolution. On the assumption that the pressure distribution around the disc cutter is uniform, the pressure on the working face is 75 KPa (Rostami and Ozdemir 1993).

Boundary condition

A schematic layout of the finite difference model and boundary conditions is presented in Figure 2. To minimize the boundary effects, the dimensions of the finite difference model in the X, Y and Z directions are considered 80, 120 and 120 meters respectively. In addition, to consider the interaction between the shield, cutterhead and surrounding ground, the interface element has been used between them and the nearby ground. The size of the finite difference mesh around the shield is assumed 50 cm with a gradually increment toward the boundaries.

The creep model used in the numerical simulation to model the time dependent deformation of the rock mass was CVISC model. As mentioned before, this model is a combination of the Mohr-Coulomb criterion and the Burger's creep model in series. The Mohr-Coulomb model parameters for the least and most favorable geotechnical condition are presented in Table 2 and the average value of the Burger's model parameters is shown in Table 3.

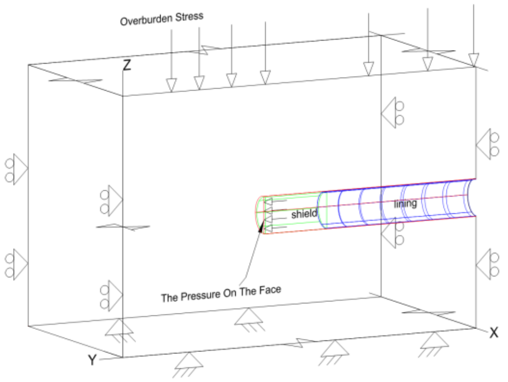

Figure 2. The schematic layout of finite difference model and boundary condition

Numerical simulation results

The required thrust to overcome the frictional resistance was calculated according to the normal forces applied on the shield skin, as determined by numerical simulation and the friction coefficient between the shield skin and ground in the 19th zone, which was assumed to be 0.25. This calculation was carried out for the most and least favorable geotechnical condition, showing 20, 30, 40 and 55 millimeters of over-boring and different rates of tunnel boring.

To consider the effect of TBM advance rates on the necessity thrust, according to Figure 3, the TBM length was divided to a few parts and the stress distribution was calculated along each part, consistent with the TBM advance rate. As an example, if the TBM advance rate was 1 m/hr, the stress distribution around the first part of the shield would be investigated after one hour; around the second part, after two hours, around the third part, after three hours and so on (Figure 3).

Figure 4 shows the tunnel deformation at the crown against the creep time for different distances from the face. According to this graph, a substantial portion of tunnel deformation took place rapidly in a short period and this portion was increased by getting distance from the working face. Moreover, the elastic, primary and secondary creep portion of deformation was visible in the graph.

The necessity dynamic thrust for the first and second geological unit along the shield length has been presented in Figures 5 and 6 for 40 and 55 millimeters of over-boring in radius, respectively. As shown in these graphs, as a large part of tunnel deformation took place rapidly in this geological condition, an increment in advance rate from 1 to 3 m/hr just reduced the required thrust 3 percent while fifteen millimeter tunnel radius enlargement could reduce the necessity thrust up to 85 percent. In addition, decreasing the shield length played a major role in the thrust reduction. For example, one meter reduction in the shield length could reduce the required thrust up to 20 MN and 5 MN when the over-boring was 40 and 55 mm respectively, which was about 14 percent. In accordance with the available thrust for single and double shield machines, execution of 55 millimeters of over-boring in this geological unit is inevitable.

While the over-boring is 55 millimeters and the creep time varies from 0.25 hour to 10 hours, radial deformation around the tunnel was calculated in the first and second geological units at different distances from the face as presented in Figure 7. The radial deformation and the distance from face are in meter.

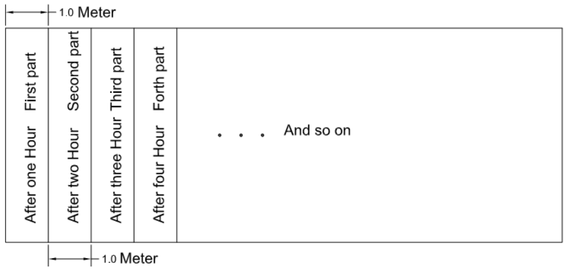

Figure 3. Thrust calculation scheme when the TBM advance rate is 1 m/hr

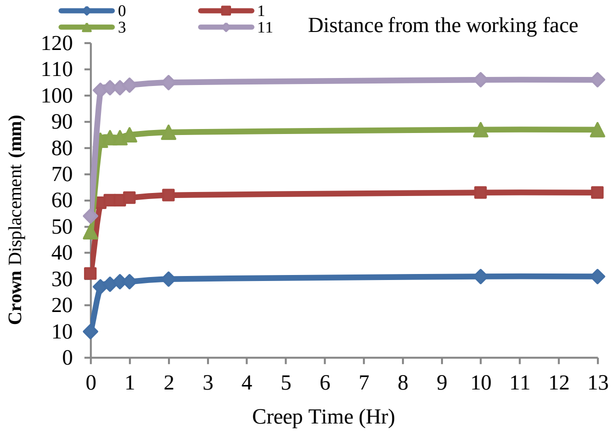

Figure 4. Elastic, primary and secondary creep portion of tunnel deformation at the crown

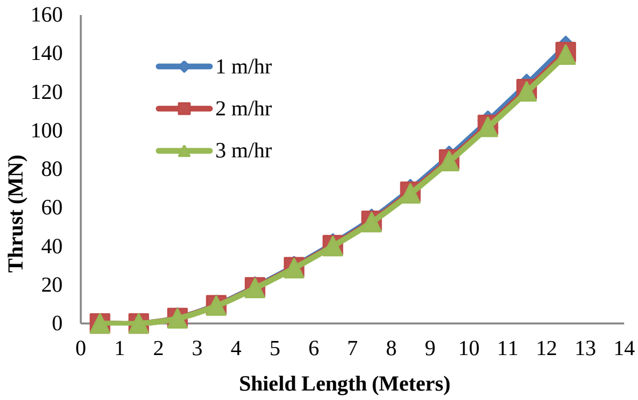

Figure 5. The required thrust to overcome frictional resistance in the A&B geological units for different rates of advance rate when the over-boring is 4 centimeters

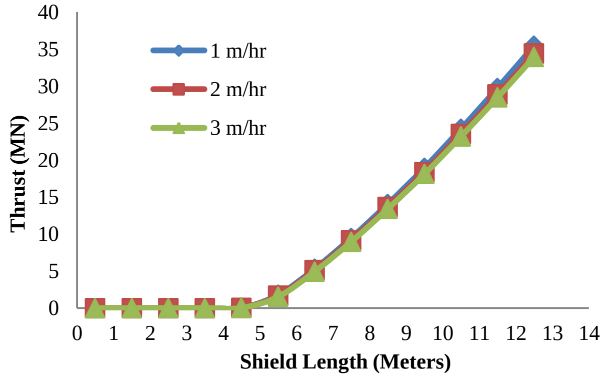

Figure 6. The required thrust to overcome frictional resistance in the A&B geological units for different rates of advance rate when the over-boring is 55 millimeters

According to Figure 7, the radial deformation at the top portion of the tunnel is more than bottom portion. It is because the over-boring around the shield is asymmetric and the radial deformation at the bottom portion of the tunnel has been restricted by the shield weight. Moreover, most tunnel deformation took place in the distance of 4 meters from working face when the creep time was less than 0.25 hour. In addition, the sum of deformation at the crown and floor of the tunnel was equal to over-boring amount plus tunnel deformation before the working face.

When the over-boring was 20 and 30 mm, radial displacements for the third geological unit have been depicted in Figure 8. To calculate the radial displacement in this figure, the least favorable geological parameters in the third geological unit were used. According to this figure, when the over-boring was 20 mm, the radial deformation around the tunnel was asymmetric and the total deformation was restricted by the shield. Moreover, when the distance of face was 1 meter, while the creep time was increased up to 10 hours, the tunnel deformation at floor tended to decrease. The reason is when the creep time was one hour, the TBM was on the floor and the tunnel deformation at top portion was less than over-boring. So the floor deformation was restricted just by the shield weight. On the other hand, when the creep time was increased, the tunnel deformation at the crown was more than over-boring. Therefore, the floor deformation was restricted by the TBM weight and the pressure applied on the shield skin at the top portion of the tunnel; as consequence of that, the floor displacement was decreased by creep time increment.

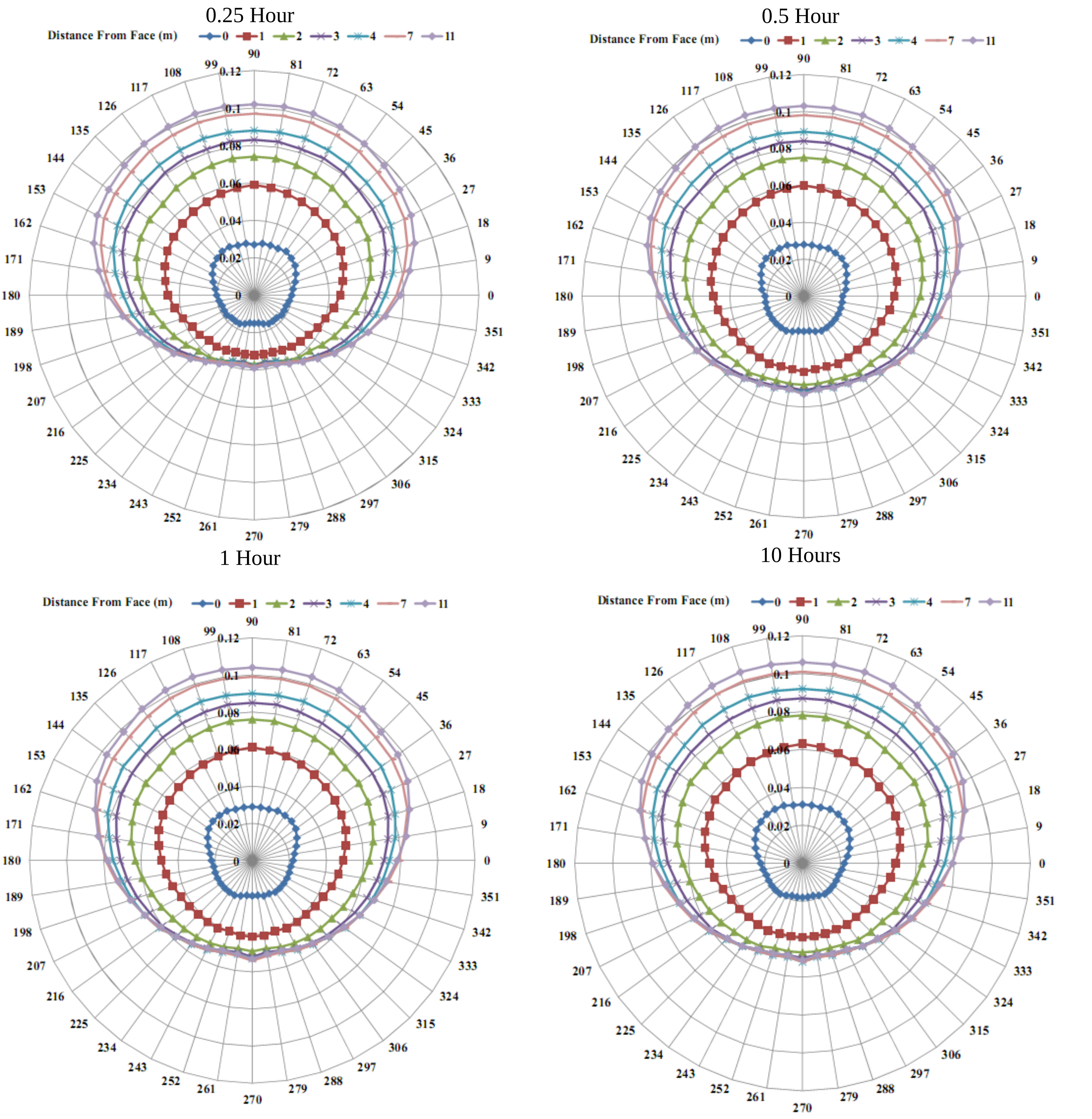

Figure 7. Radial displacement around the tunnel in the A&B geological units when the over-boring is 55 mm and creep time varies from 0.25 to 10 hours

The redial deformation around the tunnel tended to be more symmetric while the over-boring was increased up to 30 mm (Figure 8b). In addition, when the distance of face was increased, the tunnel deformation was increased at the crown and floor of the tunnel simultaneously. As a result of over-boring increment, the tunnel deformation at the crown was less than over-boring and the floor deformation was restricted just by the TBM weight.

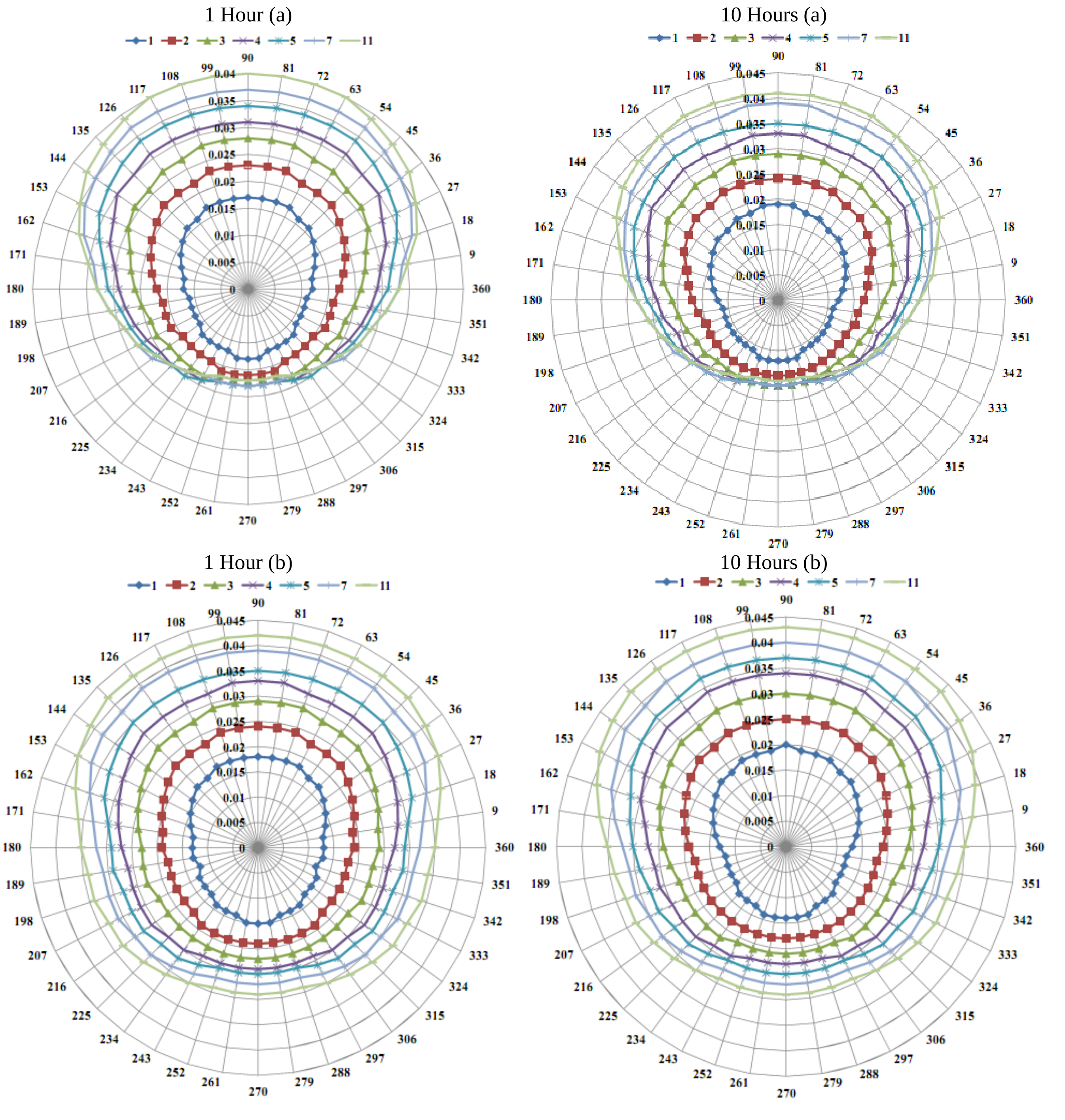

Figure 8. Radial displacement around the tunnel in the C geological unit, a: when the over-boring is 20 mm, b: when the over-boring is 30 mm

The dynamic thrust necessity to overcome frictional resistance in the third geological unit was considered for least and most favorable geotechnical parameters. For the least geotechnical parameters, in case the over-boring was 30 mm and there were the most favorable geotechnical parameters, the tunnel deformation was less than over-boring values, so the required thrust was just more than frictional resistance due to the TBM weight.

The required thrust to overcome frictional resistance for the least favorable geotechnical parameters and 20 mm of over-boring in the third geological unit has been calculated and presented in Figure 9 along the shield length. According to this graph, when 20 mm of over-boring in radius was performed in this unit, the maximum thrust for a double shield TBM whose length was 13 meters would be less than 60 MN.

Advance rate increment could reduce the necessity thrust more effectively when the shield length was increased. The reason is in the sections close to the tunnel face the supporting effect of the face controls the tunnel deformation more than creep parameters. Furthermore, the relation between thrust reduction and advance rate increment was nonlinear. As an example, when the advance rate was increased from 1 to 2 meters per hour, the thrust reduction was 5 percent, but when it was increased from 2 to 3 meters per hour, the thrust was decreased by just 2 percent.

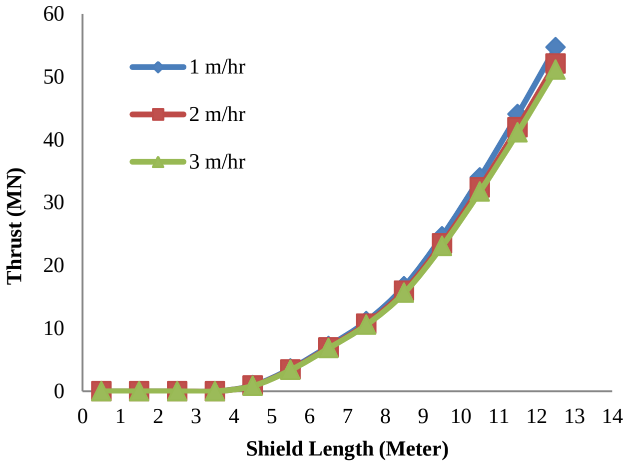

Figure 9. The required thrust to overcome frictional resistance in the C geological units for different rates of advance rate and least favorable geological parameters when the over-boring is 20 millimeters

CONCLUSION

The thrust available for single and double shield TBMs was adequate for excavation in the A&B and C geological units when 55 and 20 millimeters of over-boring could be done in these unit, respectively.

According to the mentioned geological parameters for the 19th zone and numerical simulation results, over-boring quantity and shield length affected the necessity thrust more than the rate of excavation.

As most tunnel deformation took place rapidly after excavation in a small period in accordance with the geological condition of the 19th zone, advance rate increment had a minor effect on the thrust reduction.

According to numerical simulation results, the effectiveness of advance rate increment on thrust reduction was decreased when advance rate was increased.

The tunnel deformation around the shield skin was asymmetric especially when the tunnel deformation at the floor was restricted by the TBM weight and the pressure was applied on the shield at the top portion of the tunnel.

The tunnel deformation was more symmetric when the over-boring was increased.

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