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An overview of several techniques employed to overcome squeezing in mechanized tunnels; A case study

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Abstract. Excavation of long tunnels by shielded TBMs is a safe, fast, and efficient method of tunneling that mitigates many risks related to ground conditions. However, long-distance tunneling in great depth through adverse geological conditions brings about limitations in the application of TBMs. Among various harsh geological conditions, squeezing ground as a consequence of tunnel wall and face convergence could lead to cluttered blocking, shield jamming and in some cases failure in the support system. These issues or a combination of them could seriously hinder the performance of TBMs. The technique of excavation has a strong influence on the tunnel response when it is excavated under squeezing conditions. The Golab water conveyance tunnel was excavated by a double-shield TBM. This tunnel passes mainly through metamorphic weak rocks with up to 650 m overburden. These metamorphic rocks (Shales, Slates, Phyllites and Schists) together with some fault zones are incapable of sustaining high tangential stresses. Prediction of the convergence, estimation of the creeping effects and presenting strategies to overcome the squeezing ground are regarded as challenging tasks for the tunneling engineer. In this paper, the squeezing potential of the rock mass is investigated in specific regions by dint of numerical and analytical methods. Subsequently, several operational solutions which were conducted to counteract the challenges are explained in detail.

Keywords: squeezing; tunnel deformation; shield jamming; double shield TBM

1. Introduction

Despite significant progresses in the development of shielded tunnel boring machines (TBMs), the use of these machines through weak grounds and adverse geological conditions is still risky. The presence of the shield limits accesses to the tunnel walls in order to observe geological conditions and ground behaviors. Meanwhile, the excessive convergence of weak ground under high in situ stresses can impose high levels of load on the shield, which makes the machine susceptible to entrapment in weak rocks, especially under large overburden. It results in machine jamming and imposes high economic costs on tunneling companies (Farrokh and Rostami 2008).

Tunnel deformation in very weak rocks may cease during the construction period or remain over a long period of time (Taromi *et al.* 2017 and Eftekhari *et al.* 2014). These time-dependent deformations known as the squeezing phenomenon have been earlier studied by several scholars For example Lombardi and Panciera (1997), Wittke *et al.* (2007), Ramoni and Anagnostou (2007), Amberg (2009), Farrokh *et al.* (2008), Ramoni and Anagnostou (2010), Zhao *et al.* (2012), Hasanpour *et al.* (2012, 2014, 2015, 2017 and 2018), Sarafrazi *et al.* (2017) and Zhang and Zhou (2017) and conducted investigations on TBM tunneling using different methods. TBMs are particularly more vulnerable to squeezing conditions as a result of tunnel convergences being occurred with a remarkable magnitude at a short distance from the tunnel face and within a short period of time (Alvarez Grima *et al.* 2000). This condition could result in shield jamming, the necessity to re-excavate large areas and in the worst scenarios the abandonment of TBMs through the mountains (Eftekhari *et al.* 2018). Therefore, it is of crucial importance to initially investigate the squeezing potential. In the next stage, imposed ground pressure acting on the tunnel shield and support system in specific position needs to be evaluated (Wen-qi *et al.* 2013). In general, overburden of the tunnel is an essential factor for the squeezing phenomenon. In other words, the negative consequences of tunneling through weak rocks rise when the tunnel is excavated in a higher overburden (Aalianvari 2017). By increasing the proportion of long-distance and deep tunnels, the squeezing condition could possibly become more commonplace than in the past (Zhou *et al.* 2015).

Once the squeezing potential is assessed and predicated in specific sections of tunnel, operational measures such as lubricating the shield-ground intersection and overcutting are required to prevent shield jamming in very weak structures. In this regard, few studies have been conducted so far by which the theoretical aspects of squeezing phenomenon are connected to operational measures in mechanized excavation (Yang *et al.* 2015). Studies carried out within the frame of the Eureka Build project (2007), as well as investigations conducted by several universities (Graz, Rome) and some industrial companies (Lombardi Con., Herrenknecht Co., Robbins Co., Amberg Eng., BG Engineers and Ecole Polytechnique Federal de Lausanne) are among the most remarkable ones (Hassanpour *et al.* 2011).

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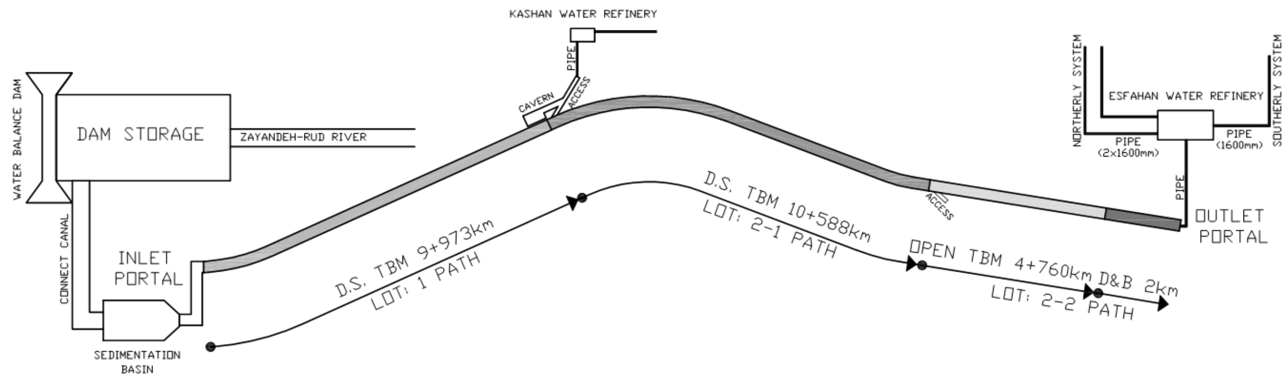

Fig. 1 Project overview of the Golab tunnel

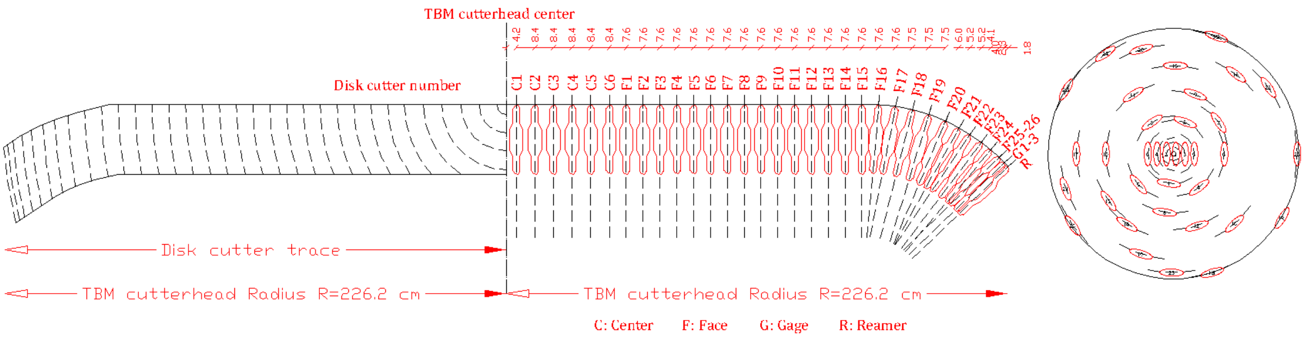

Fig. 2 Schematic diagram of D.S.TBM cutter head in the Golab W.C.T.

2. Project description

Golab water conveyance tunnel is the main component of a great project located in the western part of Isfahan province and in the downstream of the Zayanderud river dam near Hojatabad village. The overall length of the tunnel is approximately 27+321 km which was excavated in 3 main lots. The first lot (Lot 1) is around 9+973 km with an additional access tunnel with 1500 m length which was initially designed to provide drinking water from Zayanderud river water to Kashan City.

The remaining 17+348 km is intended to transfer the main proportion of water to Isfahan city for drinking water consumption (Eftekhari *et al.* 2018). The total flow rate of water is 23 m^3/s (Fig. 1)

Fig. 1 illustrates different lots of Golab water conveyance tunnel. As can be seen, Lot 1 and lot 2-1 with an overall length of 20+561 km and boring diameter of 4.525 m were both excavated using a double-shield TBM (TB 458 E/TS). Double-shield machines are capable of conducting simultaneous operations of excavation and segmental lining installation. However, shields with shorter lengths are more preferable in squeezing grounds.

The mechanized excavation of the tunnel in Lot 1 and Lot 2-1 commenced in June 2009 and was completed in September 2016 with an average progress of 400 m per month. During the excavation process, a number of TBM jamming incidences due to the harsh geological other theoretical features of squeezing issue and its deleterious effect on the TBM operation have been extensively covered in a number of other studies (Aalianvari *et al.* 2013). Conditions and technical-operational issues led to considerable delays. Nevertheless, 1125 m and 55 m were the monthly and daily progress records of excavation, respectively. Table 1 presents the tunnel and TBM main characteristics.

Table 1 Tunnel and double shield machine characteristics

Specifications TBM		Tunnel Characteristic	
Machine type	Telescopic shield TB 458 E/TS	Tunnel length	20+561 m
Maximum thrust	18000kN	Environment during drilling	0.444
Maximum torque device	802 kN.m	Diameter tunnel excavation	23.12
Power	1120 kW	Finished diameter tunnel	0.251
Rotational speed	0-12 RPM	Slope tunnel	-0.1%
Stroke	0.65 cm	Tunnel section	Circular
Number of Disc Cutter	36	Concrete cover	Hexagonal segment
Maximum design load on each disc cutter	500 kN	Lithology	Metamorphic, Igneous & Sedimentary
Maximum working load on each disc cutter	230 kN	Volume of Conveyance water	23 m^3
Max cutting measured at the tail shield	145 mm		

Additionally, the cutter head is consisted of 36 disc cutters with diameters of 432 mm (17 inches) which was initially designed for hard rock conditions (See the cutter head profile in Fig. 2). The profile includes 1 reamer cutter, 3 Gauge cutters, 6 Center cutters and 26 face cutters

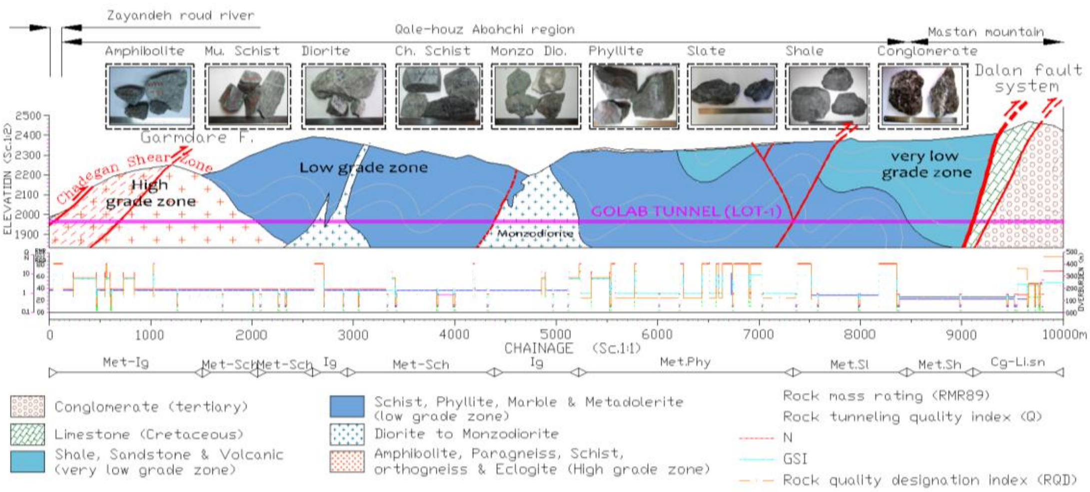

Fig. 3 The geological and rock mass classification profile along the Golab tunnel alignment

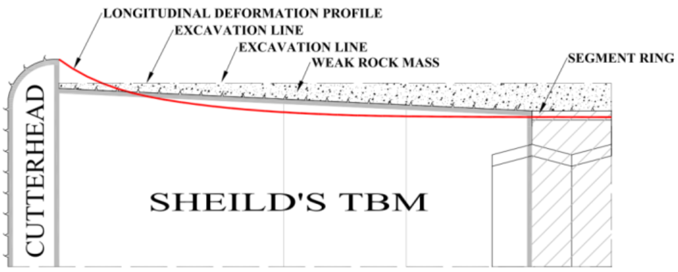

Fig. 4 Schematic section TBM with deformation curve

(Eftekhari and Bakhshandeh Amnieh, 2016).

Regarding Golab tunnel lot 2-1, the same TBM was inevitably utilized without considerable geological hazards except for a single region with squeezing risks. Moreover, the first section of Lot 2-2 with a length of 4+760 km and boring diameter of 4.9 m was excavated by an open TBM.

This tunnel started excavation in March 2013 and was completed in January 2015. The average progress rate of the tunnel was 225 m per month. The remaining 2 km tunnel at the end was excavated by drilling and blasting method with an average progress rate of 80-90 m per month.

The main emphasis in this research is placed on the harsh squeezing conditions, taken place in Golab tunnel Lot 1.

3. Geology setting

From the geological aspect, the tunnel path is situated in the northeastern part of the Sanandaj-Sirjan zone. Outcropped units in this region contain Jurassic metamorphic deposits, igneous rocks and upper cretaceous sedimentary to Paleocene rocks. The stratigraphy and geology after Permian period are affected by events related to Neotethys (Aalianvariet *et al.* 2017). Six types of lithology including amphibolite, schist, Phyllite and Slate (low grade zone), Shale and Sandstone (very low grade zone), metamorphic limestone and igneous rocks are encounteredin the tunnel path.

The geological and morphological evidences in the tunnel path can be classified into three main divisions (See Fig. 3). The first section in the beginning part of the tunnel contains Basin margin, which was affected by medium to high-grade metamorphism. The outcrops of the second region in the middle part of the tunnel with a hill shape topography are located in Ghalehhouz-Abachi. This region is influenced by low grade metamorphism and moderate deformation. The third division with a high-elevated topography consists of sedimentary rocks and is outcropped in Mastan Mountain. These types of rocks were encountered in the end of tunnel path. The geological age in this region goes back to Jurassic-Cretaceous-Tertiary period (Eftekhari *et al.* 2016).

4. Solution concept to overcome the squeezing ground conditions

Continuous tunneling using either a TBM-S or a TBMDS is in principle, gentle on the rock mass because of the full-face circular excavation with rapid closure of the ring. If a new tunnel is being driven, a relatively stiff segment ring is installed. The free stand-up time of the rock mass until the installation of the segment ring and the filling of the annular gap only permits deformation of the rock mass to a limited extent. In this case, the usable deformation space for the rock mass is the sum of the overcoat by the TBM and the taper of the shield (Aalianvari and Eftekhari, 2016). Once the usable annular space has been used up by plastic deformations, then the segment lining has to resist the remaining ground pressure (Fig. 4).

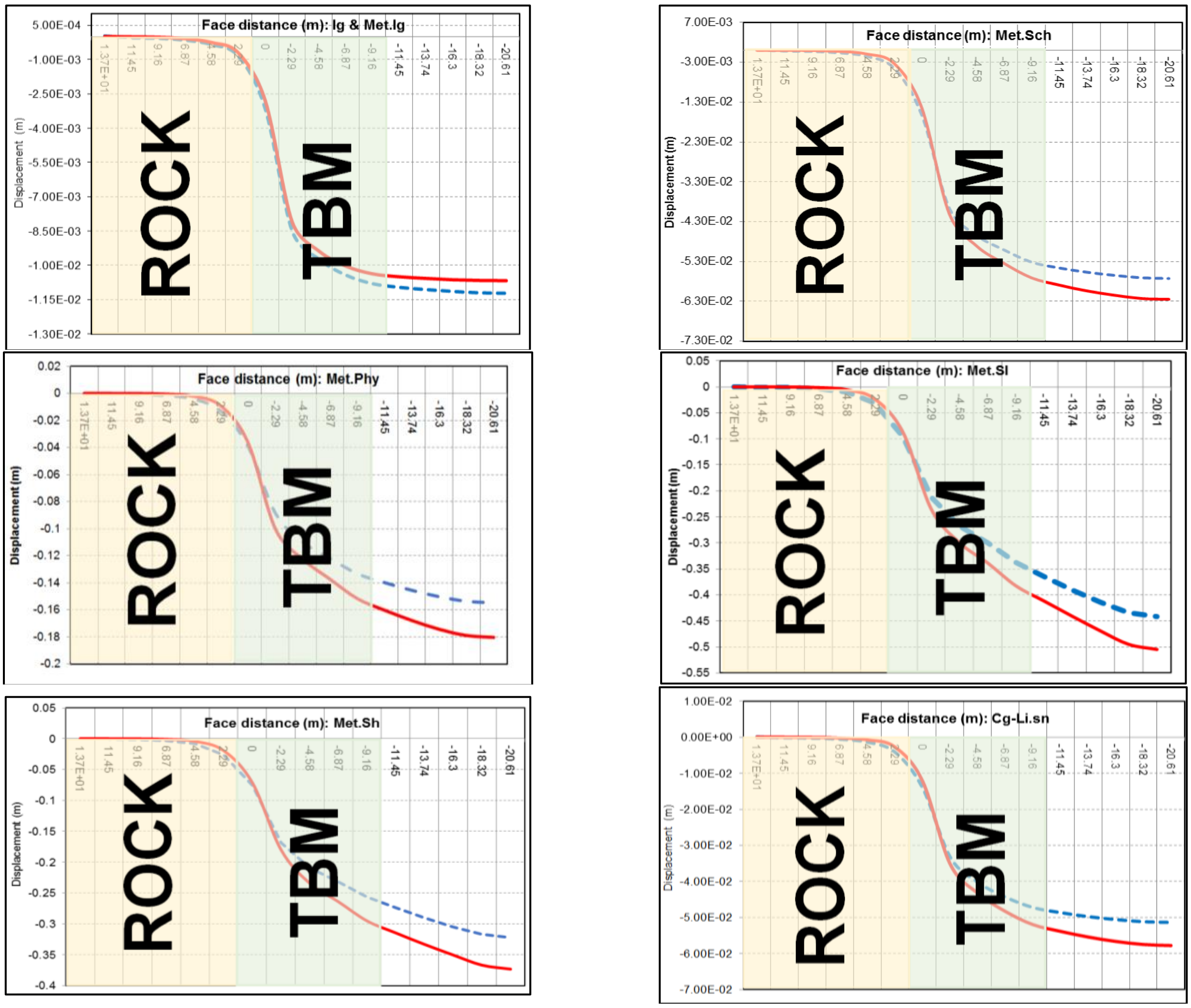

Fig. 5 Longitudinal Deformation Profiles (LDP) of tunnel wall and roof for different rock units in tunnel. Red line: X disp. – Blue line: Z disp

Fig. 6 A number of pictures taken from the occurred TBM jamming and the conducted TBM releasing operations (Eftekhari *et al.* 2016)

Since geometrical parameters of the underground excavations and the Geo-mechanical characteristics of the surrounding rock mass can be imported in numerical methods with more simple presumptions, the results would be more accurate compared to analytical approaches. Therefore, numerical modeling is employed in this study to come into more accurate conclusions from recognizing squeezing phenomenon. The tunnel Longitudinal Deformation Profile (LDP) provides the radial displacement variation along the tunnel axis. The main objective of determining this profile is to obtain the convergence distribution of the points adjacent to tunnel face and also estimate the radial displacement in the tunnel face. The LDP graphs of the tunnel for roof and wall have been drawn in 6 critical sections (Cg-Li.sn, Met.Sh, Met.Sl, Met.Phy, Met.Sch, Ig and Met.Ig units) through numerical analysis

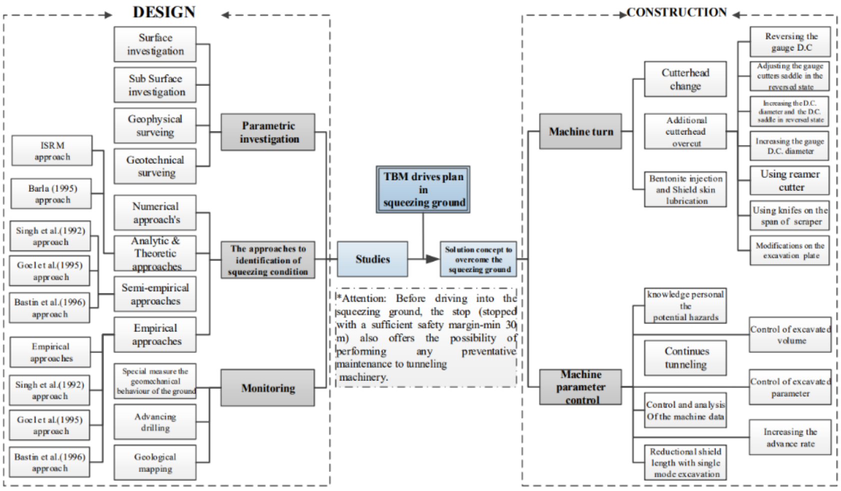

Fig. 7 The diagram for the preventing TBM jamming

(Fig. 5).

According to the LDP graphs, a proportion of total displacements of points in the tunnel wall occur ahead of the tunnel face (the part of the tunnel which has not been yet excavated). As can be seen in the LDPs of different formations, the maximum convergences refer to Slate and Shale rocks. The unfavorable ground conditions in a 5 km distance of the Golab tunnel (Lot 1) with moderate to high convergence rates have been problematic for continuous excavation. In order to prevent TBM stoppage, various measures such as increasing the advance rate, overcutting techniques, filling the gap between the ground and shield with low-friction substances, modifications in the cutter head muck buckets and excavation operation in single mode were suggested accordingly. In spite of conducting a number of these techniques, the existing weak shale and slate rocks with intense squeezing potential together with limitations imposed on the overcutting operation by cutter head led to 6 times of shield jamming (Fig. 6).

5. Description of operational measures for preventing TBM jamming

In order to overcome the squeezing condition issues in mechanized excavation, most of the TBMs have been provided with capabilities for increasing the diameter of excavation (also known as overcutting) as well as a number of holes on the shield for injecting lubricators around the TBM outer surface. However, these capabilities were not previously designed for the Wirth TBM applied in Golab tunnel. Thus, some modifications and operational measures were carried out to pass through these hazardous conditions and decrease the downtime's pertaining to TBM stoppage. In Fig. 7, the diagram is shown for the preventing TBM jamming. In the following, a brief explanation is given.

5.1 The excavation crews knowledge upon the potential hazards

The excavation crews should be sufficiently aware of the ahead geological condition in order to adjust the TBM performance parameters such as the rotation speed and torque values of the cutter head. Proper modifications on these parameters could prevent unusual loads and vibrations to the surrounding ground in harsh geological conditions. Additionally, the downtimes pertaining to the TBM maintenance operation must be minimized by providing alternative backup equipment.

5.2 Increasing the advance rate

The TBM jamming risk lowers by increasing the advance rate of the machine. However, keeping a constant higher advance rate in a specific zone cannot be always fulfilled. Water rushes into the tunnel face, damages to the cutter head and disc cutters, etc. could stop the TBM excavation. Subsequently, slow and persistent deformations of the ground may jam the TBM shield and hinder the TBM performance when restarting the excavation.

The influence of TBM advance rate on the convergence rate of the surrounding rock and the TBM regripping pressure (applied by the segmental lining cylinders) is indicated by a diagram in figure 11. As can be seen, by increasing the advance rate of 42 m/day, the displacement at the end of TBM shield reaches to 5 cm. However, in order to overcome the pressure imposed on the TBM, an approximate regripping pressure of 250 bars must be applied by the segmental cylinders. In other words, the applied regripping pressure is also a very important parameter. The highlighted area in the graph (Fig. 5) is the worst condition in these rock formations.

5.3 Increasing the excavation diameter for different advance rates

Shielded TBMs are to a great extent vulnerable to rapid convergence rates in squeezing rocks. The following information is presented regarding the TBM performance in squeezing rocks.

• Once the convergence value is less than 3%, double-shield and single-shield TBMs are helpful. However, double-shield TBMs are most recommended due to better overall performance.

• In case the convergence value varies in the range of

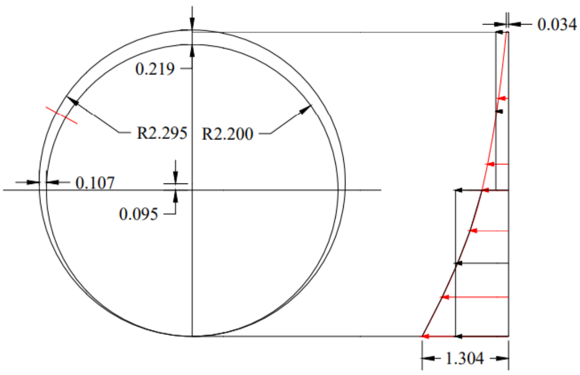

Fig. 8 The gauge cutters saddle in the reversed state

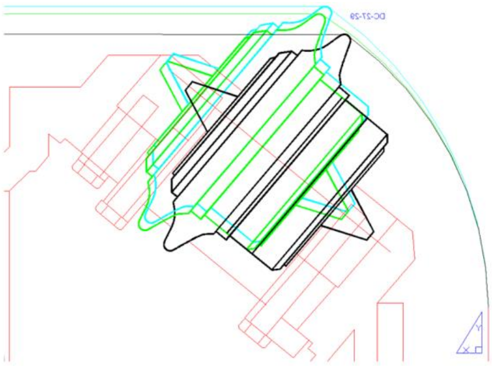

Fig. 9 The pressure acting on the shield in an overcutting of 3.5 cm in diameter

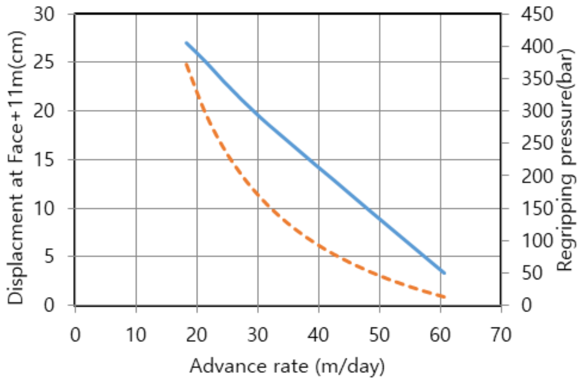

Fig. 10 The penetration rate needed to overcome ground pressure for an overcutting of 3.5 cm Red line: Disp. face+11m (cm)- Blue line: Regripping pressure (bar)

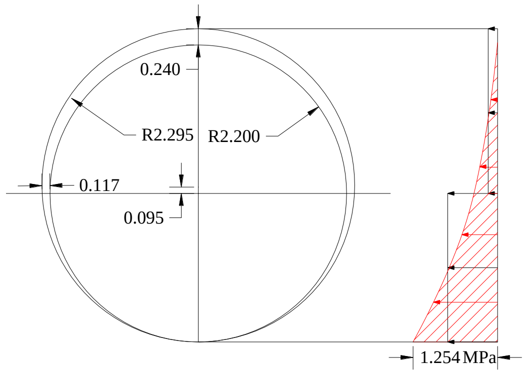

Fig. 11 Increasing the disc cutter diameter and adjusting the disc cutter saddle in reversed state

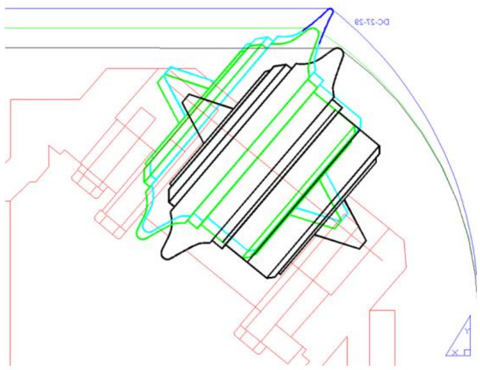

Fig. 12 The pressure acting on the shield in an overcutting of 5 cm in diameter

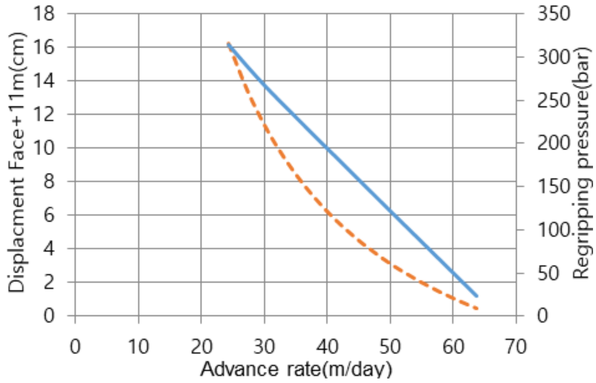

Fig. 13 The penetration rate needed to overcome ground pressure for an overcutting of 5 cm Red line: Disp. face+11m (cm)- Blue line: Regripping pressure (bar)

3% to 5%, single-shield TBMs are preferred due to their shorter shields. The segmental lining installation could be problematic because of sealing with grout and weaker capabilities in controlling the displacements.

• If the convergence value exceeds 5%, applying segmental lining as the final support system would be limited and even impossible. Using open TBMs brings about issues for the gripper. Since shielded TBMs are prone to jamming, employing these TBMs are not recommended.

Overcutting method has been offered in most of the TBMs for solving these issues. Indeed, the gap between shield and tunnel excavation perimeter can be increased from 6 to 8 cm to 12-25 cm. In the following subsections, some techniques are offered by which passing through high-squeezing regions of the Golab tunnel with the shielded TBM would be possible.

5.3.1 Reversing the gauge disc cutters

Golab tunnel TBM cutter head was initially designed with 36 disc cutters (with 17" inches diameter) (See Fig. 2). The excavation diameter is 4525 mm. By reversing the gauge disc cutters, the excavation radius would rise by 32 mm which gives an overall excavation diameter of 4589 mm. Fig. 11 shows the gauge disc cutters in normal and reversed states. The overcutting extent is 145 mm behind the wall segments and 215 mm behind the roof segments.

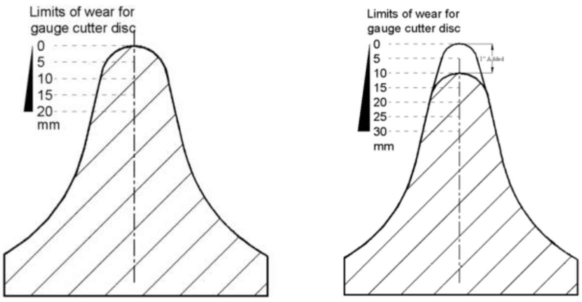

Fig. 14 Increasing the gauge disc cutters diameter

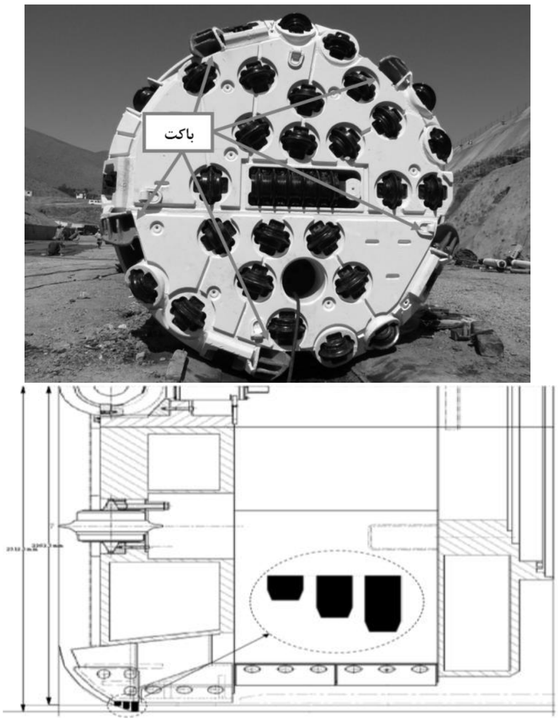

Fig. 15 Using knifes on the span of scraper

5.3.2 Adjusting the gauge cutters saddle in the reversed state

When the TBM was jammed in the squeezing regions of Golab tunnel, the best solution for restarting the excavation and passing through these regions was adjusting the gauge cutter saddles and pushing it through the outer area. Employing this technique resulted in an approximate overcutting of 3.5 cm in diameter (Fig. 8). The space gap between the shield and ground in this state would be 10.7 cm in the walls and 21.9 cm in the roof. An approximate 10.7 cm displacement in 3 m distance from the tunnel face in this state brings the shield and ground contact. According to the diagram in Figure9, the pressure acting on the shield decreases to less than 200 bars in an advance rate of 40 m/day. It should be noted that the variables of all diagrams in this paper have been estimated for the Slate rock mass formation as the worst geological condition. The allowable advance rate for an overcutting of 3/5 cm is presented in Fig. 10.

5.3.3 Increasing the disc cutter diameter and adjusting the disc cutter saddle in reverse state

One of the other techniques in this regard is to increase the gauge disc cutter diameter. For this purpose, some modifications in the disc cutter saddle are also required. Increasing the disc cutter diameter by 1 inch together as well as adjustments to the disc cutter saddle (10 mm) could potentially give rise to an overcutting space of 2 inches(See Fig. 11). By applying this approach, the excavation diameter changes to 4640 mm which is equivalent to a space gap of 240 mm between the shield and ground in roof and 117 mm in walls. The diagram in Fig. 12 indicates the ground pressure acting on the shield when it gets in contact with the shield taking place in a 4 m distance from tunnel face. According to Fig. 13, an advance rate of 35-40 m/day and a regripping pressure of 200 bars need to be applied by the machine to overcome squeezing.

5.3.4 Increasing the gauge disc cutter diameter

As it was mentioned, reversing the gauge disc cutters changes the excavation diameter to 4589 mm. However, this amount of overcutting is not sufficient due to the unfavorable ground state and the intense convergence rates. Therefore, increasing the gauge disc cutter diameter could be considered as another alternative for restarting the excavation process and passing through the harsh geological condition. If this technique can be applied, the excavation diameter could increase up to 4640 mm and provide a gap space of 240 mm in roof and 117 mm in the walls between the shield and the surrounding rock.

5.3.5 Using knifes on the span of the scraper

5 muck buckets have been designed for the Golab tunnel TBM cutter head. When the TBM encounters squeezing foliated rocks with intense schistose texture, using this knife on the span of muck buckets could facilitate the overcutting process.

5.3.6 Using reamer cutter

Due to the existence of foliated weak rocks in the tunnel path, reamer cutter can also be used according to Fig. 20. In case this type of disc cutter is used, the excavation diameter changes to 4580 mm. As a result, the gap space would be 88 mm in walls and 180 mm in the roof. However, since the disc cutters were reversed in the squeezing zones, applying the reamer cutter would be of no use. It should also be noted that the reamer cutter can be applicable for very short lengths in weak rocks and be applied as a means of widening the space around the gauge disc cutters for the removing process.

5.3.7 Modifications on the excavation plate

Scrapers on the cutter head have a high edge length that exceeds the shield diameter. Thus, the cutter head rotation damages the surrounding weak rocks. In order to improve the applied force from the excavation plate to the loading hatches, the excavation plate perimeter was modified. For this purpose, the size of the material loading scrapers was decreased by installation of fixed plates. (See Fig. 17). These steel plates have an approximate thickness of 40 mm and are curved in accordance with the shield geometry. Installation of these plates around the scrapers lowers the possibility of damaging collision between the gauge disc cutters and the surrounding rock.

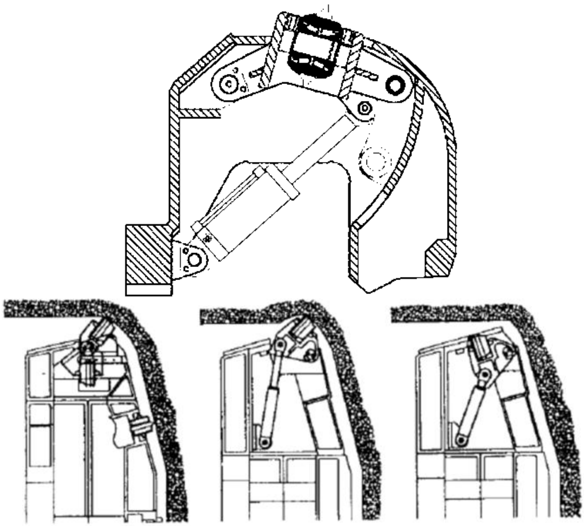

Fig. 16 Solution for radial overcut by increasing the excavation diameter

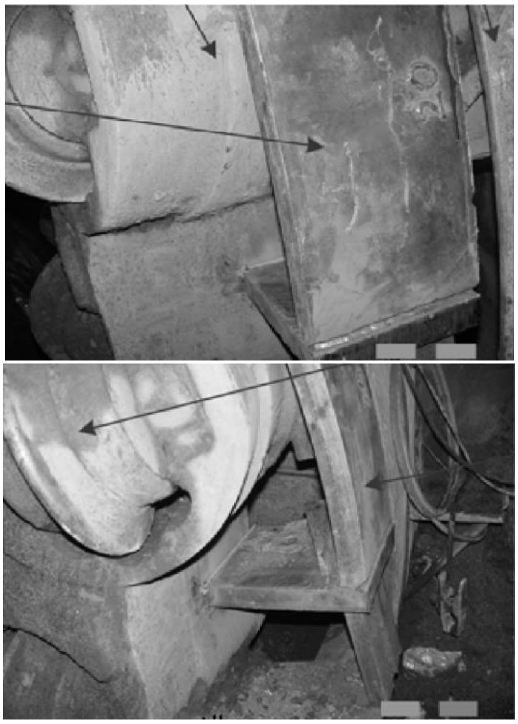

Fig. 17 Modifications on the excavation plate

5.4 Bentonite injection and Shield skin lubrication

The friction between the shield and ground is the main issue leading to shield jamming in squeezing grounds. In other words, the failing squeezing ground fills the gap between the shield and ground, which consequently imposes a pressure on the shield and requires a high regripping pressure for restarting the excavation. Therefore, the injection of a deformable lubricant and resistant material in this space could significantly reduce the friction and facilitate the excavation in critical zones. As for the soils in EPB machines, bentonite is used as the lubricant material with high viscosity between the shield and soil so as to prevent ground settlement and collapse.

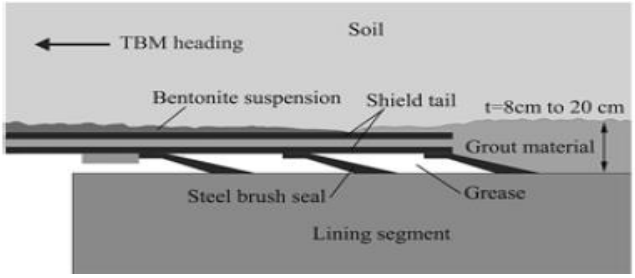

Fig. 18 The bentonite injection between the shield and ground

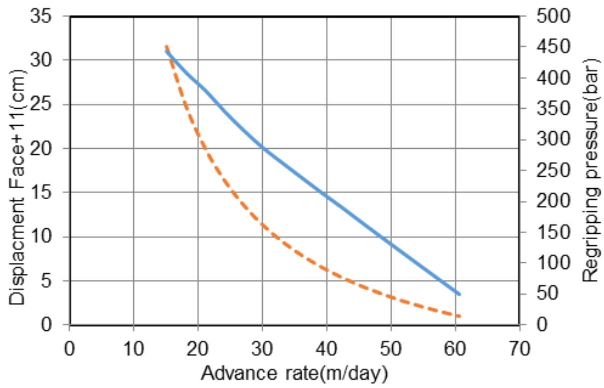

Fig. 19 The penetration rate needed to overcome ground pressure when using bentonite Red line: Disp. face+11m (cm)- Blue line: Regripping pressure (bar)

The bentonite injection could decrease the friction coefficient between the shield and machine from 0.4 to 0.3. The successful application of this technique in Golab tunnel could have provided the possibility of an advance rate of 35 m/day in a constant regripping pressure of 250 bars without any essential modifications to the disc cutter configuration (See Fig. 19).

5.5 Single-mode excavation

When TBM encounters severe squeezing grounds, the single-mode excavation method can be employed. To fulfill this approach, the thrust cylinders are compressed together, which consequently decreases the shield length and in the next step, segmental cylinders are applied for the excavation and advance operation.

6. Conclusions

Every tunneling project requires specific site investigations, Geotechnical drilling operations, geophysical studies, etc. to obtain a comprehensive geological model of the tunnel in depth. Severe squeezing problems during the construction of the Golab tunnel presented many challenges to the engineers and contractors on the project.In this regard, any initial prediction of severely weak and squeezing rocks requires a great proportion of time and cost to gain an acceptable understanding of the mechanism of this phenomenon. Afterwards, associated operational measures should be taken to overcome the potential hazardous conditions. In this research, a fairly acceptable prediction of the squeezing phenomenon was conducted based on primary investigations through numerical and analytical methods.

As the first measure to control this condition, the TBM operational staff and the backup providing crew should be initially educated to prevent this condition to some extent in order to avoid potential vibrations and abnormal loads on the cutter head. Some operational techniques were also suggested for passing through the severely squeezing grounds of Golab tunnel.

I. Increasing the excavation diameter for different advance rates

•Reversing the gauge disc cutters

• Adjusting the gauge cutters saddle in the reversed state

• Increasing the disc cutter diameter and adjusting the disc cutter saddle in reverse state

• Increasing the gauge disc cutter diameter

• Using knifes on the span of the scraper

• Using reamer cutter

• Modifications on the excavation plate

II. Bentonite injection and Shield skin lubrication

III. Single-mode excavation

Among these methods, the increase in advance rate, overcutting the excavation perimeter and excavation in the single-mode were carried out.

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