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Numerical Modelling of Backfill Grouting Approaches in EPB Tunneling

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Abstract

One of the main issues involved during tunnel construction with tunnel boring machines is the tail gap grouting. This gap is between the external diameter of tunnel lining and the excavation boundary that is filled with high-pressure grouting materials. In this work, three different approaches of gap grouting modeling in the FLAC3D software are investigated with a special attention to the influence of the grout material hardening process. In the first approach, the grout is modeled as a liquid during injection, and considering the TBM advancement and its hardening time, the grout characteristics are changed to the properties of the solid grouting. In the second approach, the grouting material from the beginning of injection is considered with the properties of solid grouting in the model, and the liquid phase is ignored. In the third approach, without considering the back-filled grouting area in the model geometry, only the injection pressure is applied to the end of the shield and behind the installed segments. The validity of the approaches is evaluated with respect to the maximum ground surface settlement. All the three approaches estimate different surface settlement but the result of the first approach is closer to the monitoring data. Also as a sensitivity analysis, in this work, we investigate the effect of the elastic modulus of liquid and solid grouting materials on the amount of surface settlement that can help to gain a more accurate insight into the effect of grout mixture.

1. Introduction

Increasing urbanization, and the development of cities and limited ground available to build on lead to traffic problems. Thus the use of underground spaces and tunneling projects have dramatically grown in the recent years as far as tunneling projects in most major cities of Iran are ongoing or understudying. Underground construction may cause serious damages to the surface and the existing underground structures, so the effect of the tunnel construction should be minimized by prediction of the ground behavior and surface settlement.

Mechanized tunneling has many advantages over the other conventional tunneling methods that include the possibility of excavating in different types of soils and geotechnical complex conditions such as the high groundwater level, soft ground or low overburden, and the ability to control surface settlements. Thus it has been one of the most widely used methods of excavation and tunnel construction in the recent decades, especially in urban areas.

Mechanized tunneling is known as a complicated construction process that involves the interaction between tunnels and surrounding environment, design of the support pressure in the tunnel face, tail void, etc. Therefore, a reliable prediction of the tunneling effects combined with timely control of the process for a safe construction and failure prevention is required.

There are various analytical methods available to predict the effects of tunneling, especially the amount of surface settlement [1-5]. The increasing development of computer technology and the

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possibility of significant predictions in the mechanism of structures have led to the use of advanced computer models since the 1980s.

In last years, various numerical models of the tunneling process have been carried out by the researchers, each of which has added some aspects of the mechanized tunneling process to the numerical model [6-14]. The aim of these models is to pay attention to a number of processes that occur during excavation such as applying face pressure and shield cutting, effect of annular void behind the shield and the grout injection in this void, and installation of segmental concrete lining, TBM weight, and other equipment. Greenwood (2003) has carried out a parametric study to evaluate the influences of different construction parameters on the surface settlements above tunnels in soft ground using the finite element method in the "PLAXIS [3D]" software for the earth pressure balance (EPB) shield tunneling method [15]. Kasper and Meschke (2004) have proposed a 3D finite element model for shield tunneling, which often considers the relevant components and construction stages [16]. In another study, they investigated the face and grouting pressure impacts and the TBM design principles such as the shield movement and loading on the tunnel lining [7].

Nagel and Meschke (2011) have simulated the backfill pressure distribution using a finite difference method, and the results of their work were more consistent with the monitoring data than the other conventional methods [17].

Lambrughi et al. (2012) have investigated the sensitivity analysis of face and grouting pressure and the soil behavioral models in the surface settlement of the Madrid's metro project [11]. Li et al. (2015) have studied the 3D ground deformation during slurry shield pressurized–face tunneling using the finite element (FE) method, and the results obtained showed a good agreement with the monitoring data. Also this work emphasizes on important TBM parameters, specifically face pressure, annulus pressure, and grouting behavior, and their influence on the ground settlement.

Although there has been a great deal of practical experience in the industrial projects [18, 19], and many numerical methods have been used to simulate the injection process in the tunneling, the validity and accuracy of any of these models have not yet been investigated. Therefore, the purpose of this study is to examine three different approaches for modeling backfill grouting using the finite difference method in EPB TBM tunneling, and to investigate their effects on the surface settlement. For validation, the numerical model constructed was compared with the monitoring data from the chainage 0 + 750 m of Tabriz metro line 2. Also the surface settlement has been calculated using the experimental formulas of Loganathan and Polos (1998). Finally, a numerical parametric analysis of the influence of the liquid and solid grout material properties in surface settlement rate has been presented.

2. Tail void backfilling

One of the important advantages of mechanized tunneling with shield TBMs is the installation of a permanent support system using prefabricated reinforced concrete segments, so in this method, an empty space is created between the external diameter of the tunnel lining and the excavation boundary. After the segments are installed inside the shield, the empty space behind the rings is filled with one or two component grouts. The advantages of backfilled grouting are [18] as follow:

- To minimize surface settlement, if this space is not filled accurately and completely, the movement of the earth towards void will cause the surface settlement. Due to the diameter of the excavation and the outer diameter of the segments, the volume of this void varies between 6% and 8% of the excavation volume;
- Avoids entering point loads to the segmental support system that by filling the entire blank space behind the segments, a homogeneous and uniform contact surface is created that will prevent an uneven loading;
- Holds the segments in place and prevents floating upward;
- Supports the load transferred to the lining by TBM back-up;
- Completes the tunnel sealing.

Thus, in general, gap grouting reduces the surface settlement and causes to increase the tunnel stability.

Blom et al. (1999) have modeled many details of the TBM tunneling process by 3D FEM in the ANSYS software. They considered the effects of the interaction between tunnel and ground, segment structures, filling material between rings of segments, thrust force, and grout phase changes from liquid to solid. They also investigated the effects of the injection process on segment loading and stated that transformation of the liquid-phase into the solid phase does not occur rapidly, and there is a conversion area between these two states that depends on the TBM advancing speed. Finally, with a special strength of the grout, considering the time of grout hardening, the effect of external loads on the lining deformations could be controlled [19].

Lambrughi et al. (2012) have modeled the grouting of void behind the shield as continuous linear elastic elements. The grouting pressure has been simulated by means of an isotropic and uniformly pressure around the tunnel. A low stiffness for the injected area near the shield and increasing stiffness for the injected elements away from the shield have been applied to calculate the mechanical properties of the grout hardening.

Using the hardening law for grout (Eq. (1)), which is a function of changing the modulus of elasticity with time, the amount of hardening of the grout in 12 hours was calculated and applied in their model.

$$E^T = \begin{cases} E_{ini} & T = 0 \\ E_g \left[1 - e^{-0.2\left(\frac{T}{T0}\right)}\right] & T \geq T_0 \end{cases} \quad (1)$$

Where E_T is the Young's modulus of grout at time T, Eg is the Young's modulus of the grout after complete hardening, and E_{ini} is the initial value for the Young's modulus that should be estimated. Some information such as the advance rate of TBM is required to obtain the grout hardening changes with distance from the shield [11].

In order to simulate the phase change of the grout from the liquid to the solid phase, Mollon et al. (2013), according to Figure 1, have assumed liquid grout for the length of L_{inj} behind the shield and solid grout for the back of the L_{inj}. and modeled the grout material behavior by volume elements in perfect elastic [13].

DO (2014) has used the same volumetric elements to model the grout materials, except that he did not take into account the liquid phase [20].

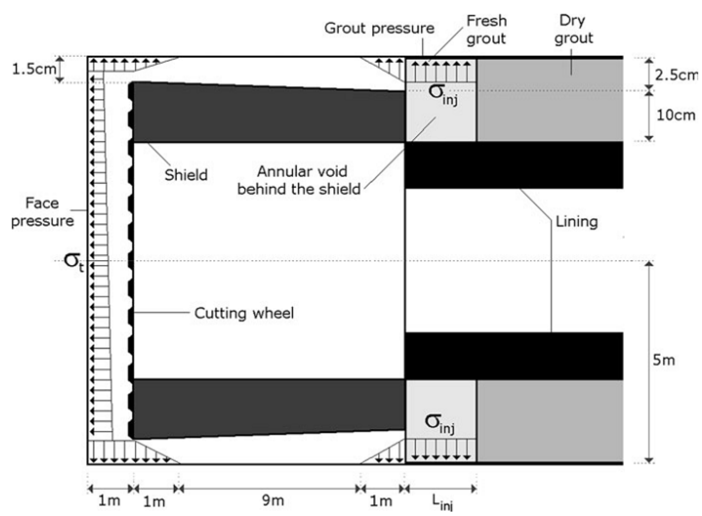

Figure 1. Layout of TBM [13].

As mentioned above, some researchers have used the method of considering the grout material hardening process during the TBM tunneling, and many modelers have ignored its time-dependent phenomenon, so from the first stage of injection, they used the hardened grout properties, and even just some researchers modeled the injection pressure as a circular pressure around the excavated tunnel without considering the grout characteristics [21]. Therefore, in this research work, three approaches were used to model the gap grouting process in order to evaluate their accuracy in estimating the maximum surface settlement rate. In the first approach, the grout was first simulated in the liquid form, and considering the advance of TBM and the hardening time of grout, the grout characteristics were changed to the solid grout. In this way, the grout time-dependent properties, which included the elastic modulus and the Poisson coefficient in the solid and liquid states, were introduced into the model. In the second approach, the grout material from the beginning of injection came with the characteristics of solid grout in the model and the liquid phase was not considered. Finally, in the third approach, regardless of the required area for grouting in the modeling geometry and the grout material properties, only the injection pressure was applied to the end of the shield and behind the installed segments. The simulation results were investigated and compared with the case study of Tabriz metro line 2.

3. Case study

Tabriz is one of the major metropolises of Iran. Due to its population, traffic situation, and density of

surface structures, it is necessary to build an underground transportation system in this city.
The 2nd line of Tabriz metro was designed with a total length of about 22 km of 9.45 m tunnel diameter and 20 stations (Figure 2). Due to the Tabriz old texture and the existence of historic buildings along metro line 2, it was necessary to study minimizing the impact of the construction of the subway on the surface structures. The geotechnical investigation of line 2 was done by drilling 53 boreholes and 17 wells along the route [22]. This part of Tabriz in the investigated depth (about 30 m) consists mainly of fine-grained overburden. Groundwater depth varies from 5 to 18 m in this limited area.

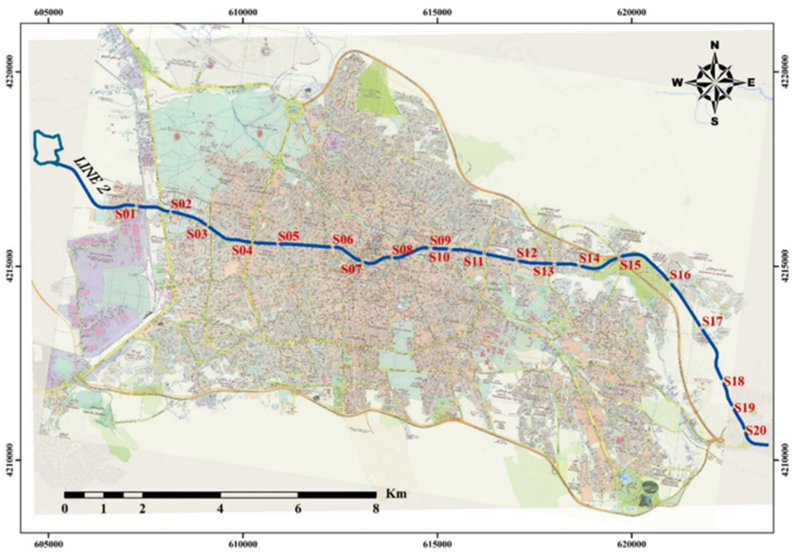

Figure 2 Plan of Tabriz metro line 2.

In this research work, the excavated tunnel in the chainage of 4 + 870 to 4 + 930 between the S2 and S3 stations was studied. The geology section of this chainage is presented in Figure 3. The alluvial layers are often fine-grained, and sandy layers are observed between them. Underground water conditions were studied during and after boreholes drilling, and it showed that the groundwater level was about 13.1 m below the surface. Due to the low depth of the tunnel and the geotechnical conditions of the area, the surface settlement due to the tunnel excavation should be at the least rate. Therefore, a correct prediction and an accurate design are required taking into account the operating parameters such as the face and grouting pressures.

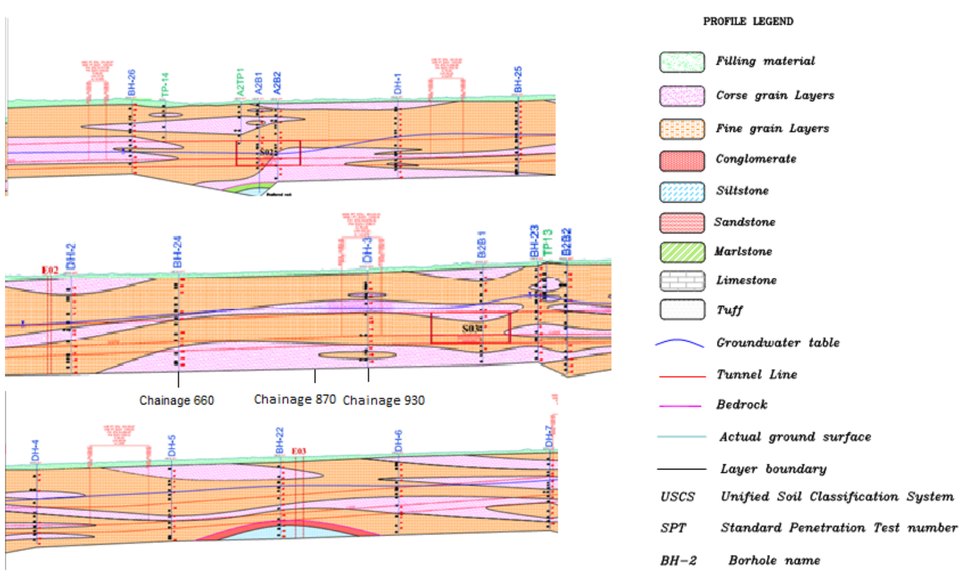

Figure 3. Geological section of Tabriz metro line 2.

4. Monitoring surface settlement

Using the available facilities and as a standard method in this field, pins are applied to measure the surface ground settlements. Figure 4 shows the positions of the installed pins in the studied area. The pins are mounted just above the axis of the tunnel to identify the most important parameters on the maximum surface settlement in the recording operation. The column diagram of the actual surface settlement in the measuring point is shown in Figure 5.

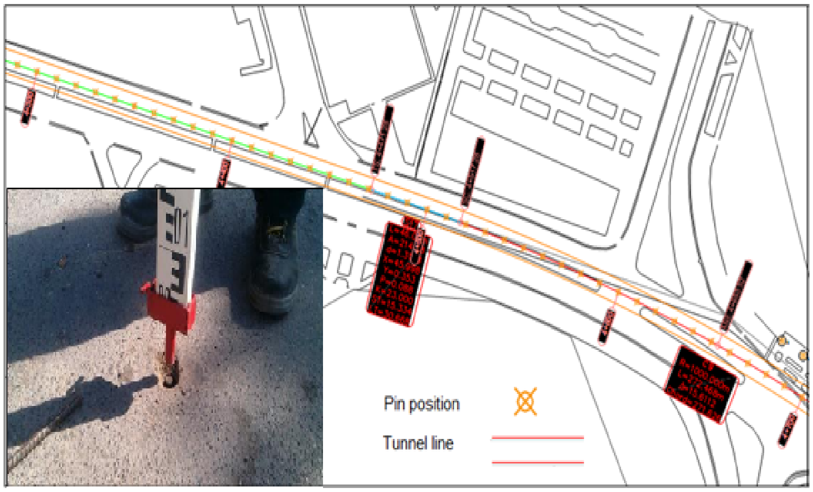

Figure 4. Positions of the installed pins [28].

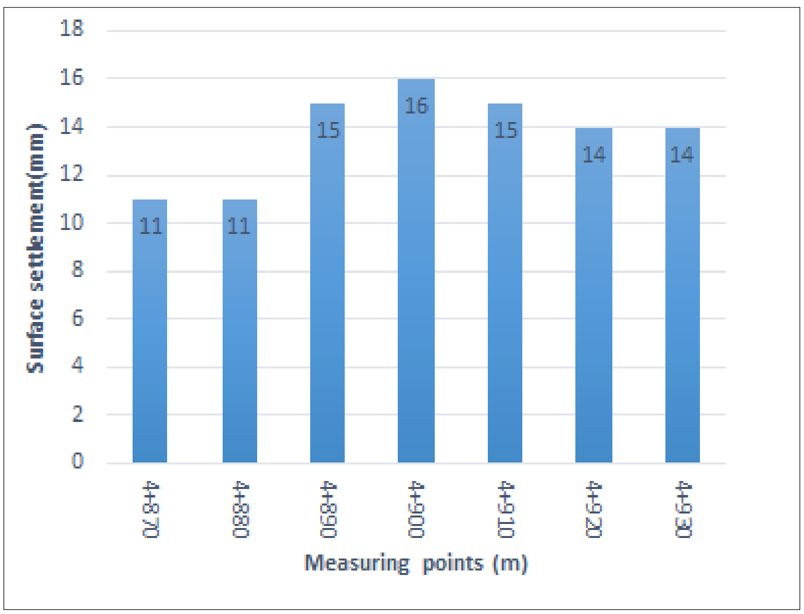

Figure 5. Maximum surface settlement through the tunnel route.

5. Numerical modeling

The FLAC3D code based on the finite difference method was used for modeling EPB TBM excavation. Some simplifications and assumptions including homogeneous and isotropic for the soil and the environment behaviors were considered. The linear elastic-completely plastic Mohr-Coulomb constitutive model was used for soil, while the segmental lining and the backfill grouting materials were modeled with an elastic behavior. The excavation diameter of the tunnel was 9.5 m with a 0.35 m thickness of lining and a 0.15 m gap grouting behind the segment. The overburden height was about 11 m in this section of tunnel route (chainage 4 + 870 to 4 + 930). The geotechnical properties of the soil layers that were used in the model are presented in Table 1.

Table 1. Layers of soil and geotechnical parameters

Layer	Soil type	Thickness (*m*)	ɣ (*Kg/m*^{3})		E (*MPa*)	ν	C (*KPa*)	φ
			Dry	Saturated				
1	Filling material	1	1610	1940	30	0.35	0	32
2	CL-ML1	3	1580	1920	12.5	0.41	9	23
3	ML	7.3	1520	1890	15	0.38	7	27
4	SM1	1.8	1590	1870	35	0.35	7	32
5	CL-ML2	7.9	1730	2110	30	0.37	15	27
6	SM2	29	1760	2030	75	0.33	9	34

The ratio of the horizontal to the vertical stress for each layer was calculated using the formula K = 1 – Sin φ, and used in the model. The dimensions of the model were chosen as X = 124.8 m, more than 2H and 4D (H is the height of the overburden and D is the tunnel diameter), Y = 60 m, about 7D and Z = 55 m, more than H and 4D (Figure 6a). These values were chosen according to the dimensions proposed by Lambrughi et al. [11]. The surface loads related to the buildings and traffic load were chosen to be 30 kPa and 20 kPa, respectively. The groundwater was considered as a pore pressure in the model. The monitoring point was in the center line of the tunnel and Y = 30 m.

The upper model boundary was set to be free, the lowest boundary for the vertical movement was fixed, and the other boundaries in the X and Y directions were fixed to prevent any movement.

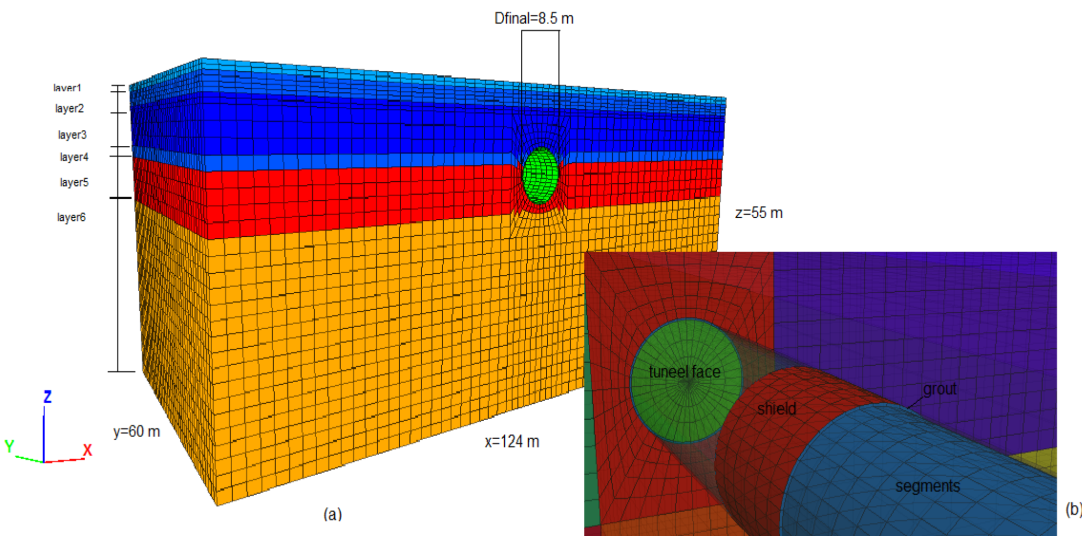

Figure 6. (a) 3D of adopted mesh of model (b) Shied, lining, grout, and tunnel face in 3D FD model.

The excavation sequences modeled were as follow:

- Tunnel excavating equivalent to segment length (1.5 m);
- Applying tunnel face pressure in the excavation face;
- Generation of tunnel boring machine elements (shield);
- Solving the model;
- Removing the face pressure on the tunnel face and repeating the above steps;
- Applying the grouting pressure, and generation of segments and grout materials after 9 m (equal to shield length);
- Solving the model;
- Repeating the above steps until excavation reaches the end.

The face and grouting pressures were 90 kPa and 140 kPa, respectively, according to the tunnel project data. The shell elements were used to model the shield and segments. No-slipping interface of grouting material to the segments and also to the surrounding soil of the tunnel was considered. Due to the continuous injection of the grout behind the segments, sealing of the segments, and the presence of appropriate face pressure, the water ingress into the tunnel was not considered during the tunnel construction phase. In other words, the water level during the construction operation was not changed, and the geotechnical characteristics of the soil around the tunnel were assumed to be constant. The grouting pressure was modelled as a radial and uniform pressure.

5.1. Validation of model

Before examining the impact of the three modeling approaches on the maximum surface settlement, the accuracy of the results obtained with the numerical model developed must be verified.

In the early stages of construction of the Tabriz metro line 2 tunnel (chinage 0 + 750 m), the grouting setup system failed, and so the grouting operation was not done in the empty space behind the segments that caused a surface settlement of about 11.2 cm. Therefore, by incorporating the relevant parameters in the numerical model without considering the injection pressure and the backfilling process in the numerical model, a maximum surface in this area was obtained to be 10.7 cm. The difference between the numerical model and the monitoring data was less than 10%, and the numerical model was validated.

Among the analytical methods, the method that takes into account the backfill grouting area and its performance in estimating the maximum surface settlement is the Loganathan and Polos (1998) method; they proposed Equation (2) for the prediction of surface settlement for a single tunnel [1]:

$$s = 4(1-\vartheta)\varepsilon R^2 \frac{H_0}{H_0^2 + x^2} exp\left[\frac{-1.38x^2}{(H_0^2 + R)^2}\right] \tag{2}$$

where x is the horizontal distance from the tunnel centerline, H_0 is the tunnel axis depth, Ɛ is a radial ground loss obtained by Equation (3):

$$\varepsilon = \frac{4gR + g^2}{4R^2} \tag{3}$$

And g is the gap parameter. Lee et al. (1992) expressed that the gap parameter could be as the maximum settlement at the tunnel crown, and it may be shown as [23]:

$$g = G_p + u_{3D}^* + \omega \tag{4}$$

where G_p is the difference between the maximum outside diameter of the tunneling machine and the outside diameter of the lining for the circular tunnel; if grouting is used to fill this gap, the value of G_p is expected to be in the order of 0.07-0.1 times of the initial value [5]; ω is the quality of workmanship, and is taken into account as a minimum of 0.6 G_p and $1/3u_i$, where u_i refers to the elasto-plastic plane strain displacement at the crown and is estimated by Equation (5):

$$\frac{u_i}{R} = 1 - \left(\frac{1}{1 + \frac{2(1+\vartheta)C_u}{E_u}\left[\exp\left(\frac{N-1}{2}\right)\right]^2}\right)^{1/2} \tag{5}$$

Where E and ϑ_u are the undrain modulus and the Poisson's ratio, respectively; R is the radius of the excavated opening; and N is the stability number.

Broms and Bennermark (1967) have proposed the stability number for support-less excavation of undrain clay that is estimated by Equation (6) [24]:

$$N = \frac{\sigma_s + \gamma z_0 - \sigma_T}{C_u} \tag{6}$$

where σ_s is the pressure of overburden, γ is the total unit weight of soil, z_0 is the depth of tunnel axis, σ_T is the face support pressure at the center of the tunnel face, and C_u is the undrain cohesion of the soil; also u_{3D}^* shows the equivalent 3D elasto-plastic displacement at the tunnel face. If the EPB shield machine is used for tunnel excavation, the term u_{3D}^* in Equation (4) is equal to zero [25]. The parameters calculated by the empirical formulas in this work are expressed in Table 2.

Table 2. The calculated values for empirical formulas

G_p (mm)	u_{3D}^* (mm)	ω (mm)	g (mm)	Smax Loganathan and Polos. (mm)
12.75	0	7.65	20.4	21.3

6. Numerical modelling of different approaches

As mentioned in Section 2, the gap grouting modeled by the different approaches so far and a detailed investigation of the modeling method influence have not been conducted yet. Thus in this work, three different modelling approaches of grouting processes were investigated. The results obtained were evaluated with respect to the maximum ground surface settlement and compared with the monitoring data.

6.1. Time-dependent hardening grout (app 1)

One of the methods available for modeling the process of gap grouting is to consider its properties from liquid to solid state and its process of hardening. To achieve this, the behavior of the

grout was assumed to be linear elastic and the time-dependent properties of it was modeled by taking into account the Young's modulus and Poisson ratio of liquid and solid grout. These properties are summarized in Table 3.
Due to the laboratory experimental results, the initial hardening time of grout was estimated to be about 8 hours [26]. A constant advance speed of 0.75 m/h was assumed for TBM, so the grouting pressure in the numerical modeling was expected for four rings. In other words, after the 4 steps of the segment installation and the grouting pressure applying, the grout hardening process was completed and the grouting pressure was removed. Changes in the properties of the grout material in these four steps were considered linearly. These sequences are shown in Figure 7.

Table 3. Properties of shield, segment, liquid grout, and hardened grout

	Shield	Segment	Liquid grout	Hardened grout
Density (Kg/m^3)	7850	2500	1800	1800
Young's modulus (GPa)	210	30	$5*10^{-3}$	$20*10^{-3}$
Poisson's ratio	0.17	0.2	0.47	0.3
Thickness (m)	0.1	0.35	0.15	0.15

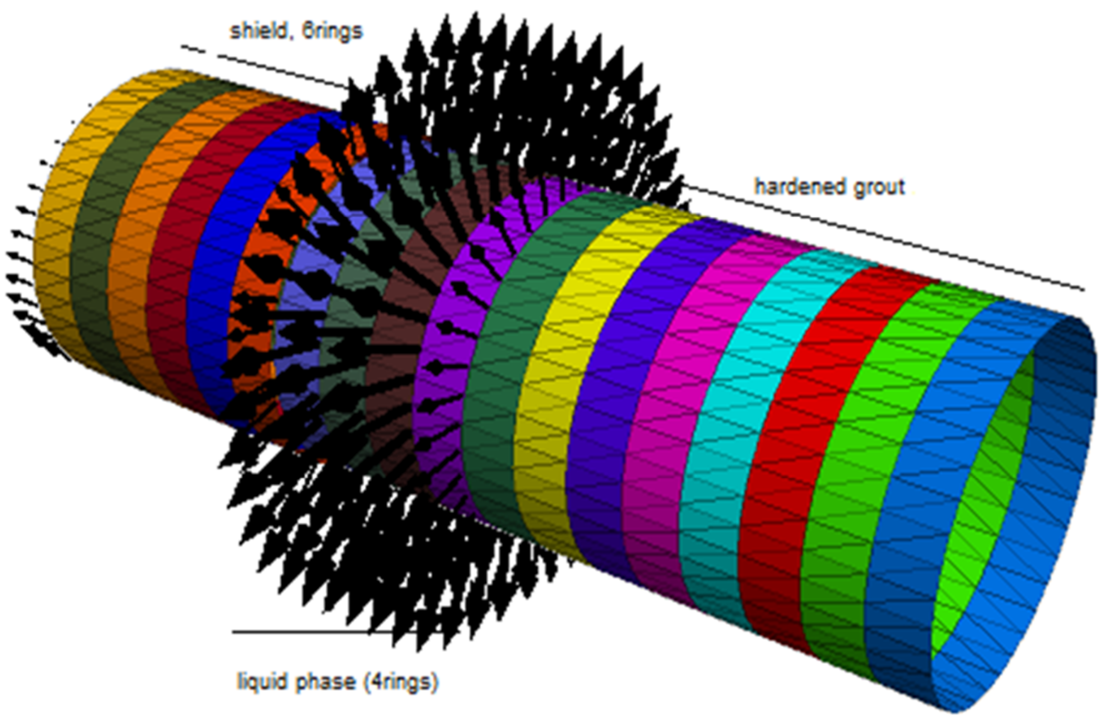

Figure 7. Modeling sequence used in app 1.

6.2. Hardened grout (app 2)

In this approach, after 6 steps of excavations (equal to 9 m, the length of shield), the shield elements were removed, and the backfill grouting and segment installation were modeled. The hardened grout characteristics were considered from the beginning in the injected region. Figure 8 shows the sequence of app 2. According to this figure, after the length of the shield (six rings), for the one ring, the grouting pressure with characteristics of the hardened grout was modeled, and then by the advancement of the tunnel, the grouting pressure was removed from this ring and transferred to the next ring.

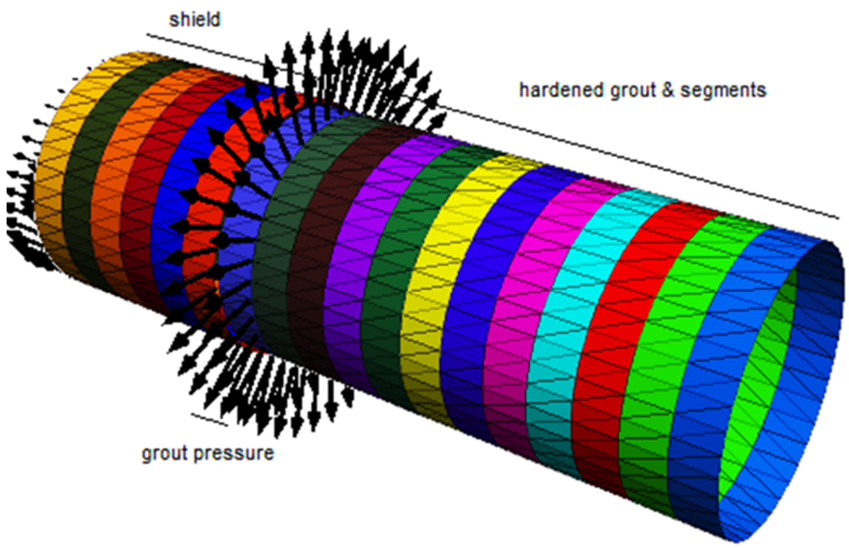

Figure 8. Modeling sequence used in app 2.

6.3. Only grouting pressure (app 3)

In this approach, the modeling was very simplified regardless of the specifications of the grouting materials and the area for injecting operations, and just the grouting pressure was applied as a radial and uniform pressure. After removing the shield elements, the grouting pressure on the tunnel surface was applied, and then with segment installation, it was removed.

6.4. Surface settlements of three different approaches

Figure 9 shows the vertical surface displacement from the monitoring data and numerical modeling in the monitoring point (Y = 30 m). The measured data was the surface settlement straight above the tunnel centerline during excavation. In this figure, the X axis represents the distance between the monitoring data and the tunnel face; this distance is positive before TBM arriving the monitoring point and negative after passing it. Figure 10 indicates the vertical displacement contour (z) after about 40 m excavation of the tunnel. The maximum settlement values from the three approaches of modeling were compared with the monitoring data and empirical method in Table 4.

Table 4. Comparison between predicated values of three approaches and measured data of Smax

	Monitoring data	app 1	app 2	app 3	Loganathan and Polos
S_{max} (mm)	16	15.4	14.5	12.1	21.3

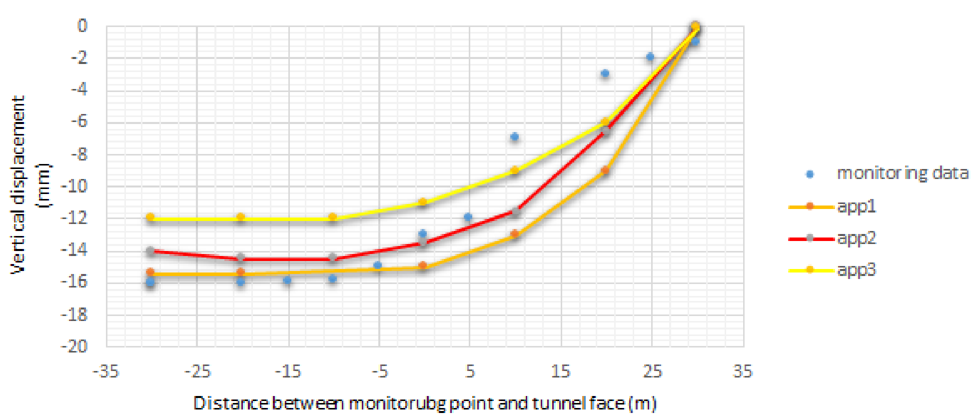

Figure 9. Comparison between 3D model results and monitoring data.

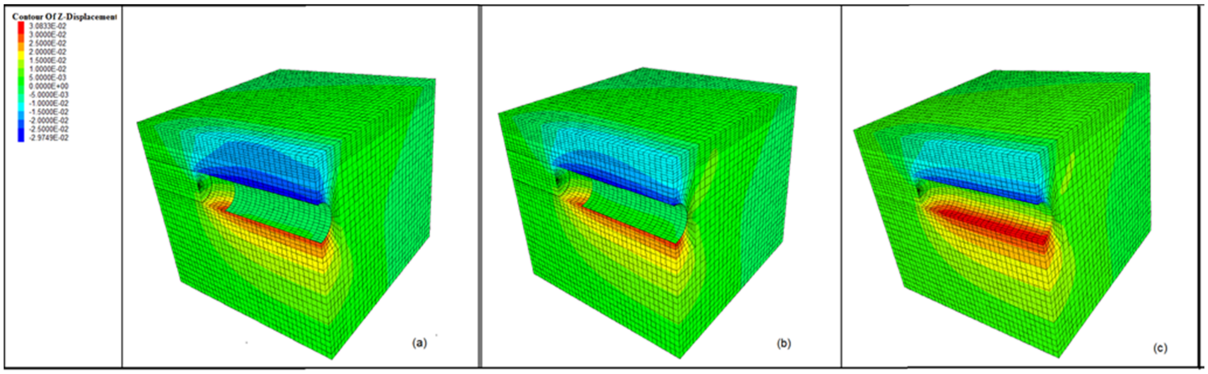

Figure 10. Contour of vertical displacement (a) app 1; (b) app 2; and (c) app 3 (units is m).

As shown, there is a reasonable match between the numerical modeling and the monitoring deformation.

In order to evaluate exactly the vertical displacement of the ground surface in the transverse-section, four points in Y = 30 m were selected in the ground surface areas of the model, and the vertical displacements of these points were recorded. Figure 11 shows the surface settlement in the transverse-section. The results obtained indicate that the three approaches of modeling show the same trend, and the maximum settlement obtained from app 1 has a difference of about 0.6 mm with the monitoring data, while this difference in the 2nd and 3rd approaches are 1.5 and 3.9 mm, respectively. Thus the maximum settlement reached at app 1 is closer to the maximum settlement from the monitoring data.

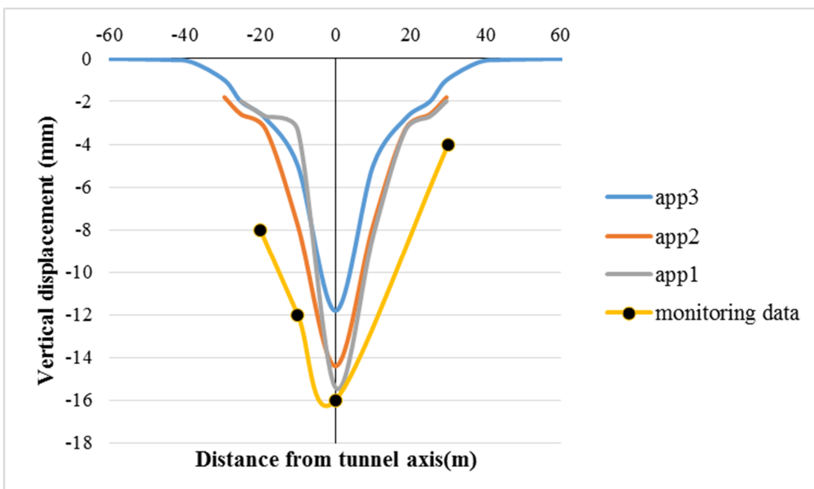

Figure 11. Surface settlement in tunnel transverse-section.

7. Parametric analysis of grout properties

In this section, a parametric analysis was performed using the numerical modelling (app 1) in order to characterize the influence of the grout properties on the surface settlement. Sharghi et al. (2017) have presented that by increasing the amount of the cement in the grout mixture, the elasticity modulus of grout in both the liquid and solid phases is increased [27]. Given this fact, different amounts of elastic modulus for the liquid and solid grout materials was applied in the numerical model for parametric study according to Table 5. Seven states of the liquid and solid grout elastic modulus were assumed for analysis, where the elastic modules of the liquid grout were 1/4 of the elastic modulus of the solid grout [27].

According to Figure 12, by increasing the elastic modulus of grout, the surface settlement was reduced. In other words, the amount of the cement in the backfill grout mix can have an impact on the surface settlement in EPB tunneling. Also with an 83% increase in the grout elasticity modulus, the surface settlement decreased by 25%. It should be noted that increasing the amount of cement is associated with the operating limitations. Therefore, the optimal amount of cement should be found experimentally at the project site.

Table 5. Grout properties in different states.

State	Elastic modulus of solid grout (MPa)	Poison ratio of solid grout	Elastic modulus of liquid grout (MPa)	Poison ratio of solid grout	Complete grout hardening time (h)
1	10	0.3	2.5	0.47	8
2	15	0.3	3.75	0.47	8
3	20	0.3	5	0.47	8
4	25	0.3	6.25	0.47	8
5	35	0.3	8.75	0.47	8
6	45	0.3	11.25	0.47	8
7	60	0.3	15	0.47	8

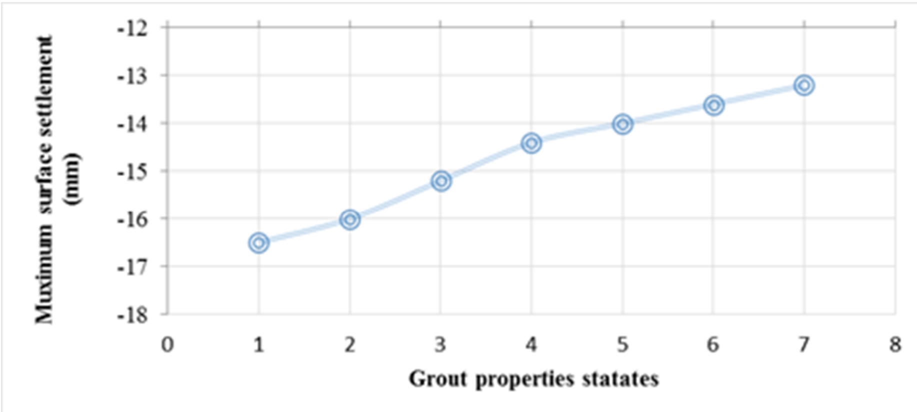

Figure 12. Maximum surface settlement in different grout states.

8. Conclusions

Numerical simulation is an important tool for providing reliable predictions of deformations for mechanized tunneling. Thus in order to more accurately simulate the mechanized tunneling process, the grouting process must also be considered. In this work, more details of the grouting process were investigated in the modeling of EPB mechanized tunneling to provide a decision-making horizon for the researchers to select the best modeling approach. The numerical model was validated using the monitoring data from Chinage 0 + 750 m of Tabriz metro line 2 tunnel. Based on the analyses performed, the following conclusions can be outlined:

1- The Loganathan and Polos analytical method was used to estimate the maximum surface settlement, and the results obtained showed that despite considering the backfill injection area in the calculation of this method, it had an error of about 35% with the monitoring data, due to simplifications and initial assumptions in the analytical methods.

2- In approach 1, the backfill grouting process was modeled by considering the injection hardening process and its material properties; the maximum surface settlement was obtained to be 15.4 mm.

3- In approach 2, considering the injection pressure and the properties of the hardened materials from the beginning of segment installation, the value of the surface settlement was estimated to be 14.5 mm.

4- In approach 3, by applying only the grouting pressure without modeling the empty space behind the segment, 12.1 mm was shown for the maximum surface settlement.

5- Given that the maximum surface settlement was 16 mm based on the monitoring data, it could be stated that app 1 showed a better agreement with the monitoring data. Therefore, this approach is recommended for 3D modeling.

6- In the parametrical study, the influence of grout mixture on the surface settlement was also investigated, and it was shown that by increasing the elastic modulus of the liquid and solid grout, the surface settlement was decreased.

7- Selecting the injection material with an elasticity modulus close to the elasticity modulus of soil around the tunnel, it is possible to control the amount of settlement due to the lack of a suitable filler. However, an empirical research work is required to confirm the results of the parametric analysis.

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مدلسازی عددی روش های تزریق در تونلسازی مکانیزه EPB

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چکیده:

یکی از مهمترین مواردی که در هنگام ساخت تونل با ماشین‌های حفاری مکانیزه مطرح است، تزریق پشت پوشش سگمنتی تونل است. این فاصله بین قطر خارجی پوشش تونل و قطر تونل حفاری شده، ایجاد می‌گردد که با تزریق مواد با فشار زیاد پر می‌شود. در این تحقیق، سه رویکرد متفاوت برای مدل‌سازی فرآیند تزریق پشت پوشش تونل در نرم افزار $FLAC^{3D}$ با توجه ویژه به تأثیر روند سخت‌شدن مواد تزریق مورد بررسی قرار گرفته است. در رویکرد اول، مواد تزریقی به عنوان مایع در هنگام تزریق درنظرگرفته شده است که با پیشروی TBM و زمان گیرش این مواد، ویژگی‌های مواد تزریقی به صورت مواد جامد تغییر می‌یابد. در رویکرد دوم، ماده تزریقی از لحظه تزریق با خصوصیات مواد جامد در مدل در نظر گرفته شده و فاز مایع نادیده گرفته شده است و در رویکرد سوم، بدون در نظر گرفتن ناحیه تزریق پشت پوشش در هندسه مدل، فقط فشار تزریق به انتهای سپر و پشت پوشش وارد می‌شود. اعتبار رویکردها با توجه به میزان حداکثر نشست سطحی زمین ارزیابی شده است. نتایج نشان دادند که هر سه رویکرد مقادیر مختلفی را تخمین می‌زنند، اما نتیجه روش اول به داده‌های ابزار نزدیک‌تر است. همچنین به عنوان تجزیه و تحلیل حساسیت، در این تحقیق اثر مدول الاستیسیته مواد مایع و جامد تزریق بر میزان نشت سطحی بررسی شده است که می تواند به یک بینش دقیق‌تر از تاثیر مخلوط تزریق در میزان نشست سطحی کمک کند.

کلمات کلیدی: فضای خالی پشت پوشش، تونلسازی مکانیزه باEPB، گیرش مواد تزریق، $FLAC^{3D}$، نشست سطحی.