Modeling Excavation Chamber of EPB Tunnel Boring Machine by Discrete Element Method

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Abstract

Earth Pressure Balance (EPB) tunnel boring machines are widely utilized for the excavation of subway tunnels. These machines leverage the pressure generated by the excavated materials within the excavation chamber to stabilize the tunnel face. The pressure in the excavation chamber is modulated by varying the speed of the screw conveyor, making the precise control of this rotation speed critically important. Such adjustments facilitate the management of the tunnel face and influence the overall settlement of the tunnel structure. This study models the tunnel excavation of Tabriz Metro Line 2, employing an EPB shield that operates under earth pressure conditions. The excavated material is accumulated in a chamber located behind the cutter-head, which generates the requisite pressure at the work face. This pressure is regulated through the screw conveyor mechanism. The simulation was conducted using a three-dimensional particle flow code based on the discrete element method. The findings indicate that when the pressure at the face is decreased to 50% of the maximum pressure exerted by the horizontal jacks of the shield drive, significant and hazardous ground surface settlements occur. Conversely, at elevated pressures, a consistent settlement of 1.9 cm was recorded. Additionally, a reduction in the cutter-head rotation speed from 2 rpm resulted in a decline of the work face, while an increase in speed corresponded with the same 1.9 cm settlement. The discrete element method effectively models the drilling process. The validity of the modeling outcomes was corroborated by data acquired from instrumentation.

Keywords: EPB, PFC3D, DEM, TBM, Screw conveyor, Ground surface settlement

1- **Introduction**

Nowadays, due to the limited surface areas in urban areas and the need to expand subway networks and underground communication routes in crowded and large cities, the use of mechanized tunneling methods is inevitable. The full-face Tunnel Boring Machine (TBM) is one of the most well-known and widely used machines for mechanized tunnel excavation, with about 80% of the world's large tunnels being constructed using this Machine [1, 2].

The excavation of underground spaces disturbs the initial stress distribution and leads to its redistribution within the ground, resulting in displacements around the excavated space and potential surface settlement. In the discussion of preventing ground surface settlement and maintaining the stability of the excavation face, the pressure exerted on the excavation face and the injection of grout into the face are two essential parameters [3-5].

Various methods are used in tunnel boring machines to control the advancing excavation face. The Earth Pressure Balance (EPB) shield technology is based on the use of excavated materials as a support agent and for controlling the face pressure. In this method, to prevent the collapse of the excavation face and the ingress of water into the tunnel (when the excavation cross-section is below the groundwater level), the excavated soil and rock fragments are accumulated and compacted in the excavation chamber immediately behind the cutter-head. Numerical modeling has been used by researchers to identify the influence of various parameters in the excavation process (with the EPB shield TBMs) on ground surface settlement, such as the pressure exerted on the excavation face, the advance rate, the time of installing the support system, and the depth of the tunnel excavation process from the ground surface [5-11]. Simulations in the FLAC software have shown that when the EPB machine passes through weak soil layers, the ground settlement can be controlled by adjusting the face pressure and the grout injection pressure between the segments and the tunnel wall [12].

One of the foundational and extensively utilized numerical techniques for modeling EPB excavation chambers is Computational Fluid Dynamics (CFD). This method is particularly adept at examining the dynamics of two-phase mixtures, including combinations of soil and air or soil and foam, within the excavation environment [13]. However, CFD models may struggle to accurately represent the discrete characteristics of granular materials, such as soil particles, which can result in errors when forecasting muck behavior. The Finite Difference Method (FDM) is commonly employed to assess ground settlements caused by Tunnel Boring Machine (TBM) excavation. This technique is especially effective in simulating the behavior of the soil continuum surrounding the tunnel [14-17]. CFD models may not fully capture the discrete nature of granular materials, such as soil particles, which can lead to inaccuracies in predicting muck behavior.

The Discrete Element Method (DEM) serves as a robust tool for modeling the behavior of granular materials, such as soil particles, within the excavation chamber. This approach is particularly beneficial for investigating the movement and pressure distribution of muck during the excavation process [18].

The review of previous research indicates that numerical simulation is an acceptable method for analyzing the influence of structural parameters on system performance and controlling ground surface settlement. With the advancements in numerical simulation software, more suitable and improved results can be obtained compared to the past. In short, among the previous modeling results, the following can be mentioned. Increasing the penetration rate of the tunnel boring machine (TBM) cutter-head into the ground, while keeping the rate of extraction of the compressed materials from the excavation chamber (via the screw conveyor) constant, or decreasing the rate of extraction of compressed materials while keeping the cutter-head penetration rate constant, will result in an increase in the pressure exerted on the excavation face and vice versa [19].

This study focuses on identifying the optimal pressure to be exerted on the tunnel excavation face during the operation of a Tunnel Boring Machine (TBM) utilizing the Earth Pressure Balance (EPB) method, as well as managing the excavation face. To achieve this, numerical simulations of the ground and excavation chamber were conducted using particle flow software grounded in the discrete element method (DEM). In DEM, each rigid (non-deformable) element operates independently, with interactions between particles occurring at their contact points in accordance with the force-displacement relationship.

A discontinue-granular model was here developed to simulate the process of excavating ground by a cutter head and producing the balance earth pressure in the chamber for first time in line 2 Tabriz subway. Also, balancing the pressure of the chamber with the ground pressure was simulated by modeling an operation of a screw conveyor. It controls the cutter head pressure via taking extra materials out from the chamber. The mentioned model was established by a particle flow code in 3 dimensions (PFC3D). This code is based on distinct element method (DEM); a solid material is simulated by assembling many rigid-spherical particles. Each particle operates independently, and the action-interaction in the collision of two particle is calculated by the force-displacement relationship. The movement of particles followed from Newton's second law [20, 21].

This research begins with a concise overview of the discrete element method and the associated particle flow software. Subsequently, it presents a case study involving Metro Line 2 in Tabriz, detailing the geo-mechanical characteristics of the ground. The study models the TBM excavation process, the control of the excavation face, and the resulting ground surface settlement when employing the EPB method, concluding with a discussion of the findings.

2 - **Discrete Element Method**

In this research, the excavation process of the ground using a full-face tunnel boring machine within a pressure balance shield is simulated using the three-dimensional Particle Flow Code (PFC3D) software, which is based on the Discrete Element Method (DEM). In this software, a solid object is assembled by a large number of spherical discrete elements (particles or balls) that are independent and can move freely. In PFC3D, rigid walls are defined at the boundaries of the model to apply the boundary conditions. The boundary forces are applied to the model at the contact points between the discrete elements and the walls. The interaction between the particles, as well as between a particle and a wall, is defined at the contact points. The force applied on a particle or a wall at the contact point is calculated based on the force-displacement law. Therefore, the stiffness must be defined for the contacts, and each contact is considered as a set of springs with a specific stiffness. The models in PFC3D are solved using the explicit method, meaning that the equations are solved at specific time intervals. In each time step, the contacts between the particles are identified, and using the force-displacement law, the contact forces are measured. Then, the discrete elements move (based on Newton's second law) and the new positions of the particles are identified at the end of the time step. Figure 1 shows the contact between two spherical particles in the PFC3D software. At the contact points between the rigid elements, a number of dashpots are placed in parallel with the contact simulation springs to gradually dissipate the kinetic energy generated by the movement of the particles and prevent disturbance in the model [22-24].

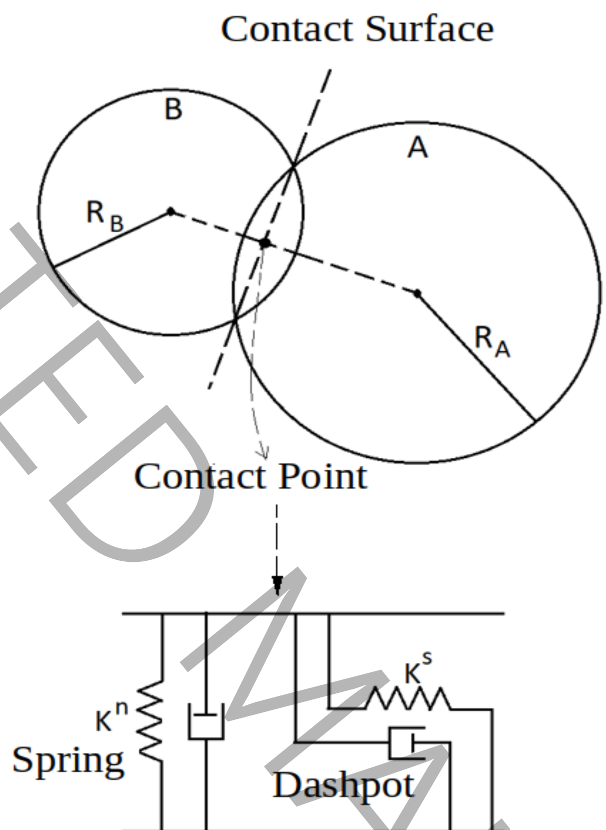


Fig. 1. Contact point between spherical particles in PFC3D [22].

The contact forces were shown in following [24]:

$$
\begin{aligned}
&F^n = F_0^n + K^n \Delta\partial_n \qquad if \quad \Delta\partial_n < 0 \\
&F^n = F_0^n \qquad\qquad\qquad if \quad \Delta\partial_n \geq 0 \\
&F^s = F_0^s - K^s \Delta\partial_s
\end{aligned}
\tag{1}
$$

Where: F^n, F^s, $\Delta\partial_n$ and $\Delta\partial_s$ are the normal, shear,relative normal and shear displacement (due to the movement particles relative to each other), F_0^n and F_0^n are the remaining normal and shear contact force from last step calculation, respectively and K^n and K^s are the normal and shear stiffness, respectively.

The input parameters to the particle flow software, which determine the particle motion and the interaction between the particles in contact, are defined as the micro-mechanical properties. If E is the Young's modulus at the contact point between two rigid particles or between a particle and a wall, the contact stiffnesses are measured as follows [24]:

$$K^n = {[\pi r^2 E]}/{L}$$
$$K^s = \alpha K^s \quad (2)$$

Where r and L are the minimum radius and sum of particles radii that are in contact with each other, respectively, α is a constant value.

In the particle flow software, a bond can be defined at the contact point between two discrete elements. This bond has a shear and a normal resistance, which are introduced by the user to the software. The normal and shear stiffnesses of this bond are simulated by placing a series of springs (in parallel with the springs modeling the contact stiffness) at the contact point, as shown in Figure 2. This bond is called a "parallel bond".

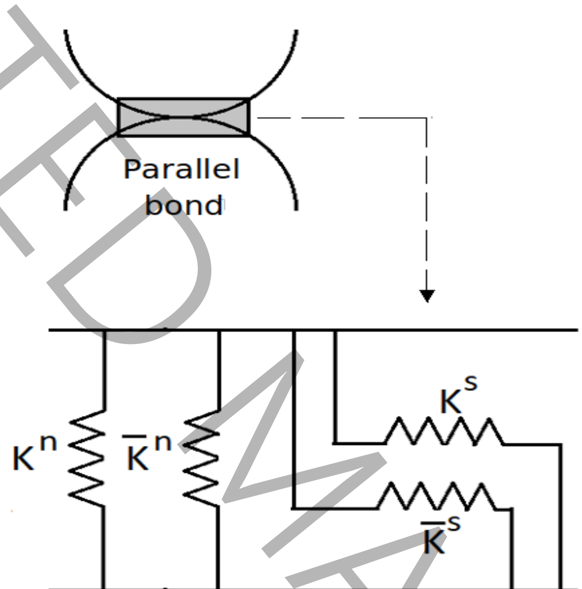


Fig. 2. Modeling parallel bond between two particles by springs [24].

Furthermore normal and shear force ($\overline{F}^n$ and $\overline{F}^s$) and normal and shear moment ($\overline{M}^n$ and $\overline{M}^s$) induced in the bond (due to the relative movement of the two particles) are measured as follows [24]:

$$\overline{F}^n = \overline{F}^n_0 + \overline{K}^n A \Delta \partial_n$$
$$\overline{F}^s = \overline{F}^s_0 - \overline{K}^s A \Delta \partial_s \quad (3)$$
$$\overline{M}^n = \overline{K}^s - J \Delta \theta_n$$
$$\overline{M}^s = \overline{K}^s - I \Delta \theta_s$$

Where $\Delta\theta_n$ and $\Delta\theta_s$ are the normal and shear rotation of particle relative to each other, respectively, $\overline{K}^n$ and $\overline{K}^s$ are the normal and shear stiffness of the bond, respectively.

$$\overline{K}^n = A\overline{E}/\overline{L}$$
$$\overline{K}^s = \beta \overline{K}^n \quad (4)$$

$$\overline{A}=\pi\overline{R}^2$$
$$I=0.25\pi\overline{R}^4 \qquad (5)$$
$$J=0.5\pi\overline{R}^4$$

Where $\overline{L}$ and $\overline{R}$ are the length and radius of cross section of bond and respectively, $\overline{E}$ and β are Young's modulus of the bond and a constant value, respectively.

With the displacement of the two particles (connected to each other through the parallel bond), a normal and shear stress is induced in the bond. If these stresses exceed the normal and shear resistance of the bond, the bond will break, and a micro-crack will form. The induced normal stress ($\overline{\sigma}$) and shear stress ($\overline{\tau}$) in the bond are measured using the following formulas [24]:

$$\overline{\sigma}=\frac{\|\overline{F}^n\|}{\overline{A}}+\frac{\|\overline{M}^n\|\overline{R}}{I}$$
$$\overline{\tau}=\frac{\|\overline{F}^s\|}{\overline{A}}+\frac{\|\overline{M}^s\|\overline{R}}{J} \qquad (6)$$

The earlier design of the Tabriz Metro utilized the FLAC software, which is based on the Finite Difference Method (FDM). In contrast, an evaluation of the Discrete Element Method (DEM) through the PFC (Particle Flow Code) software indicates several advantages over FDM. Notable benefits of DEM (PFC) in comparison to FDM (FLAC) include its capability to effectively model granular materials, realistic representation of contact mechanics, management of significant deformations and movements, and the ability to accommodate complex geometrical shapes. Furthermore, DEM facilitates dynamic simulations, transitions from micro to macro behavior, and provides adaptable boundary conditions. PFC is designed to simulate granular materials and particulate systems by treating each particle individually. This allows for detailed modeling of interactions, forces, and friction, which is important for understanding granular flows and packing. PFC captures complex contact mechanics, including normal and shear forces, vital for particle behavior under load. DEM lets particles move freely without mesh restrictions, avoiding distortion issues. It also handles irregular particles and complex shapes better than FDM and excels in simulating dynamic events like impacts and collisions.

3 - Metro Line 2 in Tabriz

The Tabriz Urban Train Line 2 project requires careful consideration of the soil characteristics along the route in order to select the most suitable mechanized excavator for the excavation work. The grain size distribution of the soil is a critical factor that influences the performance and efficiency of the equipment. In particular, the use of Tunnel Boring Machines (TBM) necessitates a thorough understanding of the soil composition to ensure precise operation and avoid potential complications. The soil composition along the route of Tabriz metro Line 2 varies between fine and coarse alluvial deposits, which are commonly found in Tabriz city. This diversity in soil types poses a challenge for the construction team, as different excavators may be required to effectively handle the varying grain sizes. Figure 3 illustrates the distribution of these alluvial deposits, providing valuable insight into the geological conditions that must be carefully navigated during the construction process. By taking into account the grain size distribution of the soil, engineers and contractors can make informed decisions regarding the selection and operation of mechanized excavators. This comprehensive understanding of the soil characteristics is essential for ensuring the successful completion of the tunneling work along Tabriz Urban Train Line 2.

Soil parameters, including information about soil composition, density, moisture content, and grain size distribution, were acquired from the specialized tunneling consultant who conducted extensive soil testing and analysis at the project site. The consultant utilized various geotechnical methods such as borehole sampling, in-situ testing, and laboratory analysis to gather detailed data on the soil conditions to ensure the engineering team had accurate and reliable information for designing the tunneling and excavation processes.

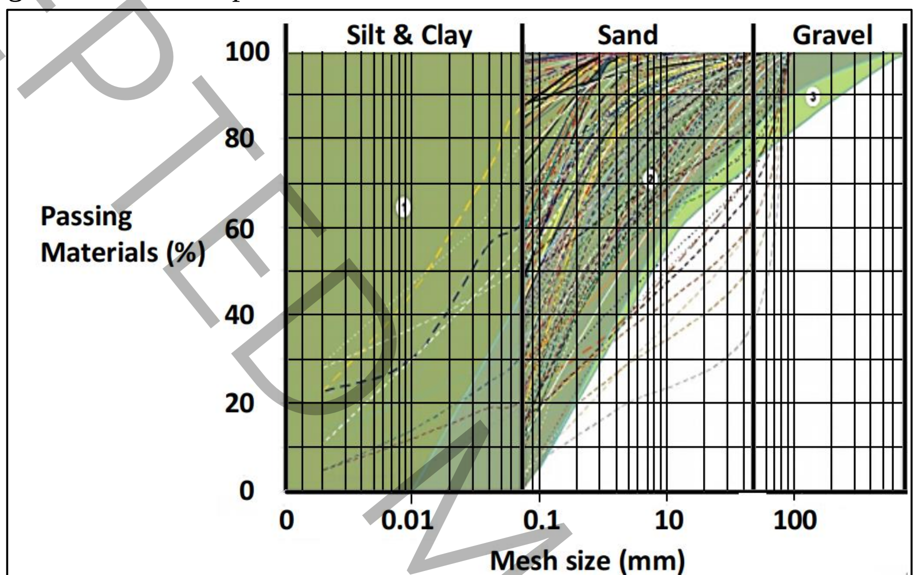


Fig. 3. Soil grain size distribution along the tunnel between Station S01 and Station S16

In the excavation of Metro Line 2 in Tabriz, a full-face tunnel boring machine with an Earth Pressure Balance (EPB) shield is used. In this machine, the excavated soil and rock fragments are transported to a chamber behind the cutter-head, called the excavation chamber. The compaction of the materials in the excavation chamber exerts pressure on the advancing excavation face, maintaining its stability and preventing water ingress. The pressure in this chamber is controlled by a screw conveyor that transfers the materials out of the chamber. The tunnel alignment of Metro Line 2 in Tabriz includes dry, coarse-grained alluvial layers with a small amount of clay fines. Figure 3 shows the soil types and their size distribution in the tunnel excavation route; a wide range of dry fine and coarse soils is located in the drilling path. The groundwater levels in the examined region are significantly low, and this issue has been largely overlooked. Table 1 shows the average physical and mechanical properties of the soil along the excavation path, obtained from laboratory tests on the collected samples

[25].

Table. 1 Average physical and mechanical properties of the soil with foam [25].

Property	Value
Density (**kg/m^3**)	1800
Uniaxial compressive strength (**Mpa)**	58
Young's modulus (**Gpa)**	1.4
Poisson ratio	0.33

4 – Numerical simulation of excavation chamber

EPB numerical simulating is conducted utilizing the discrete element method across three distinct phases: the initial phase involves the representation of the excavation chamber, followed by the modeling of the screw belt, and concluding with the simulation of the soil and finally excavating process [26].

In this research, the specifics of Tunnel cover modeling are not taken into account. The lack of tunnel overburden modeling in numerical simulations can be attributed to various factors, such as the challenges associated with accurately depicting ground conditions and the tendency to concentrate on particular aspects of tunnel dynamics. Although the depth of overburden plays a crucial role in determining stress distribution and ground displacement, numerous studies tend to emphasize other variables or simplify their models to improve computational efficiency. Research frequently highlights the interactions between tunneling techniques and adjacent rock formations, which may not require detailed overburden modeling [27].

Accurate overburden modeling necessitates comprehensive knowledge of soil characteristics, which can exhibit considerable variability. Many simulations concentrate on specific tunneling phenomena, such as stress alterations induced by excavation, rather than addressing the complete overburden profile [28]. By omitting overburden from models, researchers can achieve quicker simulations, which is essential for projects with tight timelines [29].

The first step in simulating the performance of the EPB machine is to create the model geometry in the software. The precise dimensions and configuration of the cuter head were created using AutoCAD and subsequently incorporated into the model. The layout of the cuter head is illustrated in Figure 4. The models of the shield body, the excavation chamber, and the screw conveyor are shown in Figures 5, 6, and 7. These models are created using rigid walls in the PFC3D software. The shield length is 20 meters with a diameter of 9.5 meters. The 1.5-meter length at the end of the shield is considered the excavation chamber. The 20-meter length allows for calculating the volume of the excavated soil. The screw conveyor is placed at a 30-degree angle relative to the excavation chamber. To model the actual screw conveyor dimensions, its length is 7 meters, with an inner and outer diameter of 0.22 and 1 meter, respectively, and a width (spiral blade) of 0.8 meters. The screw conveyor is designed to start moving and transfer some of the materials from the chamber to the outside when the chamber pressure exceeds the defined value for the machine, thereby controlling the pressure exerted on the excavation face. In order to enhance the efficiency of the excavation process, an intricate model of the agitator arms was meticulously designed. These arms were strategically placed to prevent the materials inside the excavation chamber from becoming excessively sticky and solidifying, which could potentially hinder the overall progress.

Additionally, extensive simulations were conducted to analyze the cutter-head and the cutting tools located on it. These simulations utilized rigid plates to accurately mimic the intricate movements and functions of the cutting tools, ensuring optimal performance during the excavation process. By implementing this designs, the excavation process was streamlined and the potential for complications due to material adhesiveness and solidification was significantly minimized.

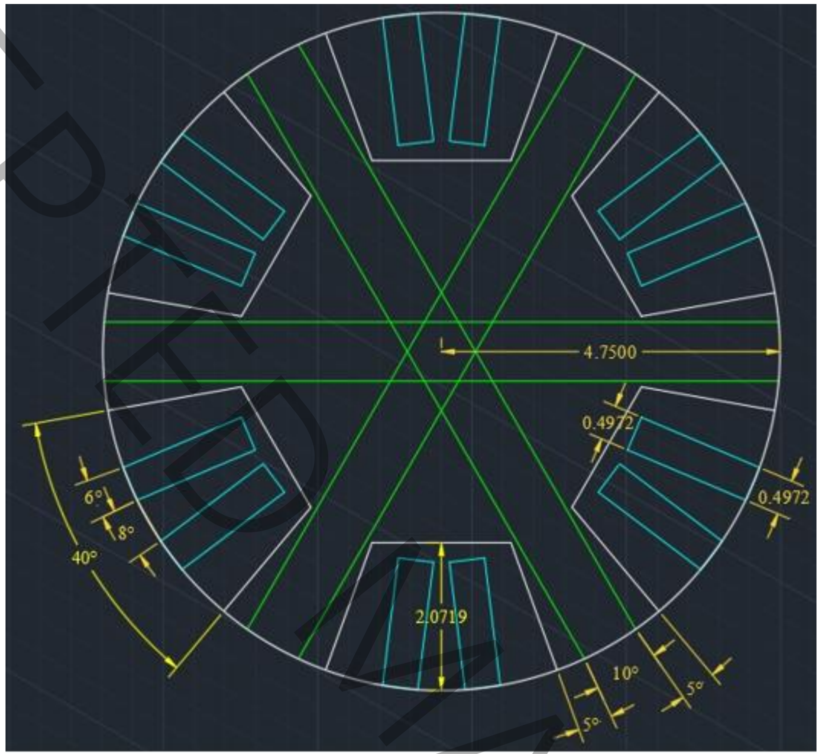


Fig. 4. Excavator head dimensions in AutoCAD

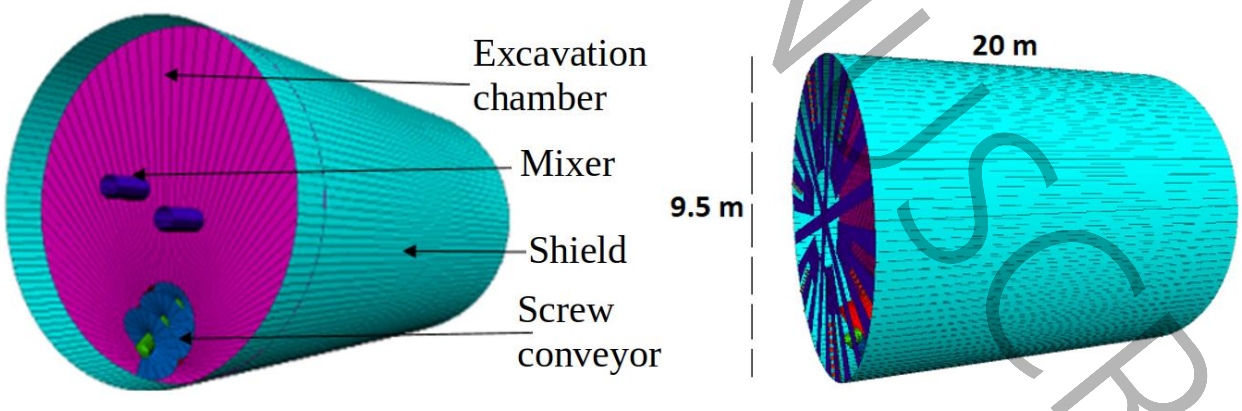


Fig. 5. DEM model of EPB shield

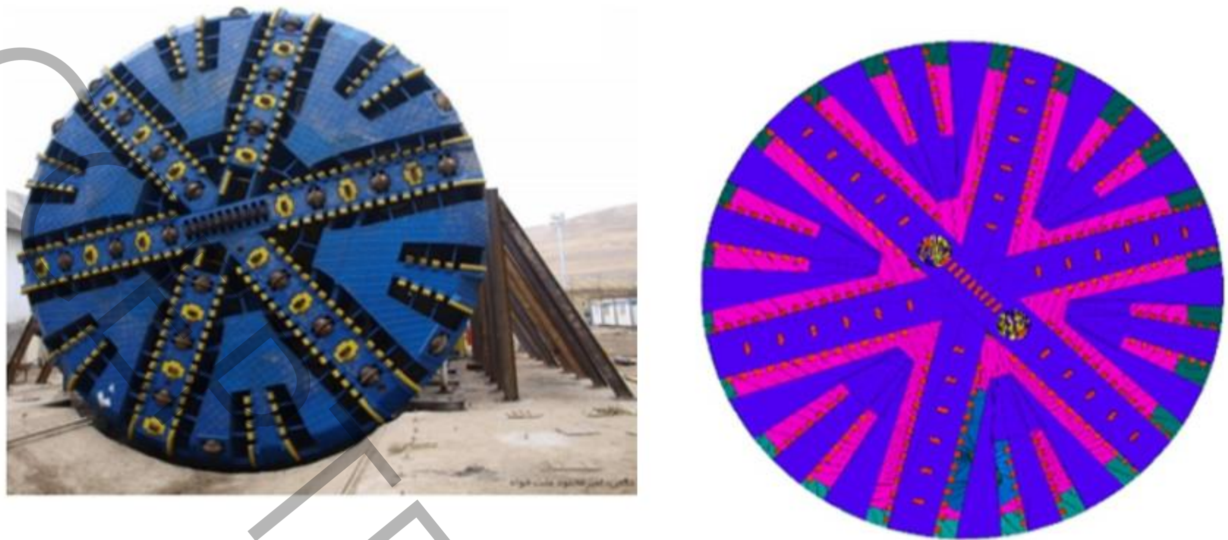


Fig. 6. DEM model of cutter-head

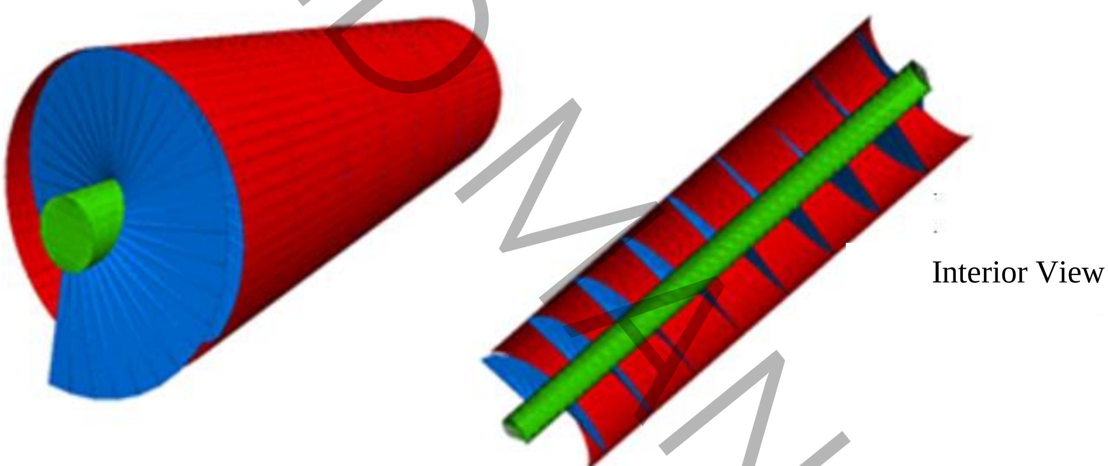


Fig. 7. DEM model of screw conveyor

5 - Numerical simulation of ground and soil

The soil along the excavation path is modeled as a discontinuous medium composed of an assembly of spherical rigid particles (discrete elements). In other words, the mechanical behavior of the soil is simulated through the interaction of the particles in contact with each other. Therefore, the macro behavior of the soil depends on the micro-properties defined for the particles, their contacts, and the bonds between them. The micro-properties that are defined as input parameters for PFC3D cannot be directly measured from field and laboratory tests. Therefore, as shown in Figure 8, a cylindrical sample of 100 mm height and 50 mm diameter was created, consisting of 15,000 particles with a radius of 1 to 1.68 mm. By performing a standard uniaxial compression test on this sample, the strength parameters of the model (compressive strength and Young's modulus) were identified. To calibrate the model, the input micro-properties (density of discrete elements, contact and parallel bond Young's modulus, bond strength, and the ratio of shear to normal stiffness) were adjusted until the compressive strength and Young's modulus approximately matched the experimental results (Table 1). These micro-properties, which led to results similar to the experimental values, were then considered the soil micro-properties, as shown in Table 2.

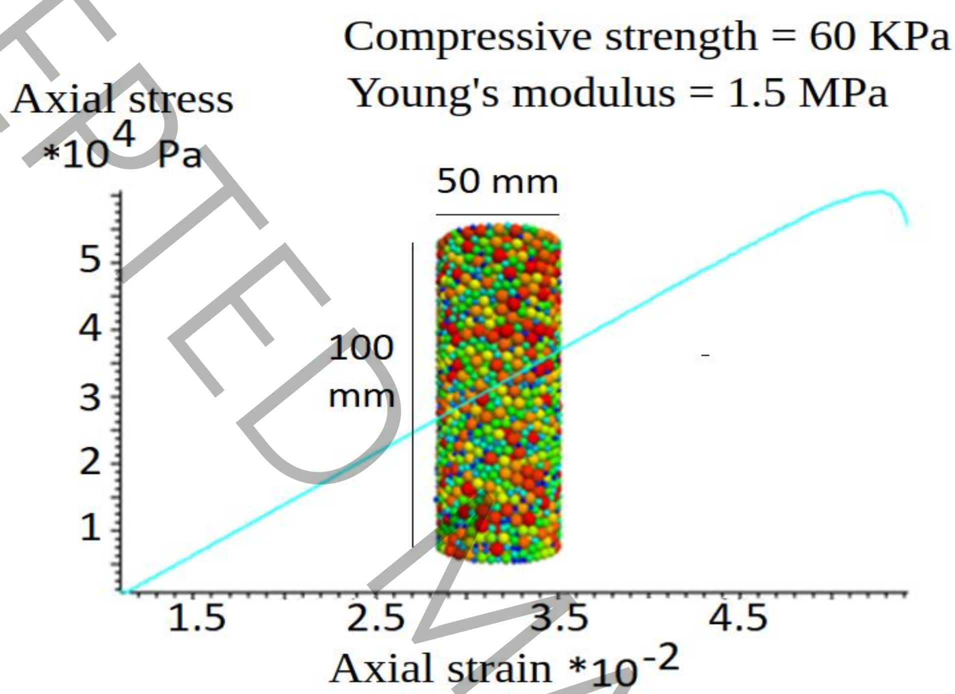


Fig. 8. DEM modeling uniaxial compressive test applied to soil

Table 2. Micro-properties of soil obtained from DEM model of compressive test

micro-properties	Value
Particle density	1800
Young's modulus of contact between two particles	1.65 Mpa
$\mathbf{K^s/K^n}$	1
Young's modulus of parallel bond	1.65 MPa
Tensile strength of bond	70 KPa
Shear strength of bond	70 KPa
$\mathbf{\overline{K}^s/\overline{K}^n}$	1

6 - Numerical simulation of excavation process

Figure 9 shows the simulated model of the excavation process and the performance of the screw conveyor. Considering the excavation depth of Metro Line 2 in Tabriz (25 meters) and the soil density, a normal-compressive stress of 450 KPa was applied to the TBM and the modeled soil at the excavation face. The horizontal stress is regarded as one-third of the vertical stress. Then, the shield moved forward (at a speed of 0.00026 m/s) while the cutter-head rotated, excavating the ground. The soil particles detached from the excavation face entered the excavation chamber and were compressed. When the pressure in this chamber exceeded 40 KPa, the conveyor belt transferred some of the soil particles from the chamber to the outside to maintain the pressure at 40 KPa.

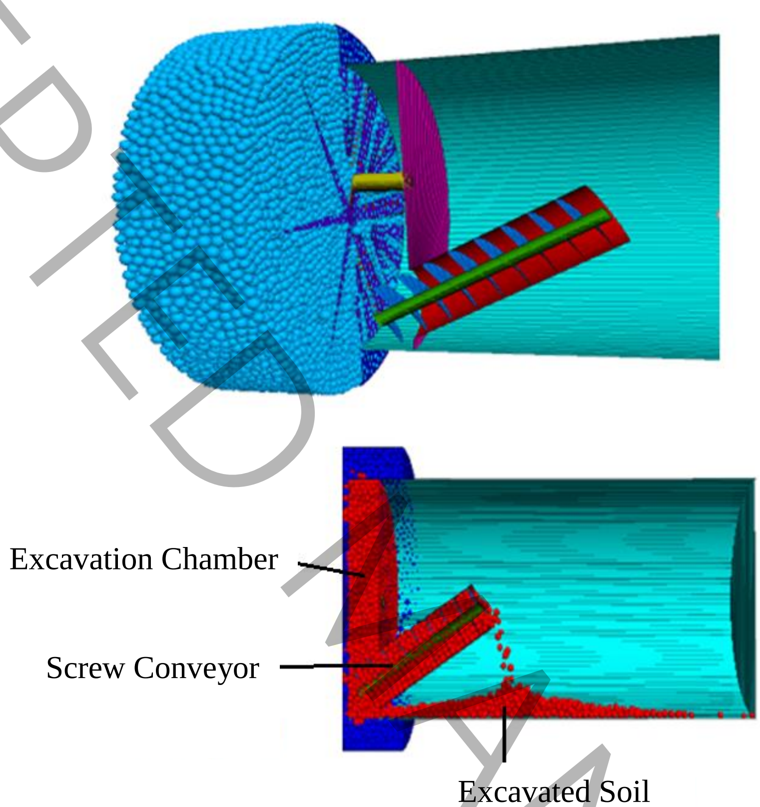
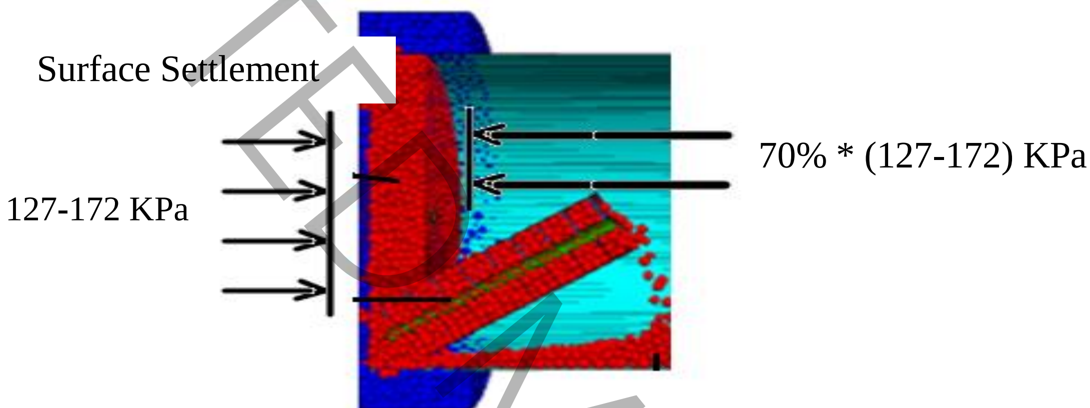


Fig. 9. DEM model of excavation process and performance of screw conveyor

Due to the available resources, the excavated soil volume was used as a validation criterion for the model. After 1.5 meters of advancement, the volume of soil entering the excavation chamber was estimated to be 104 m³ (number of discrete elements inside the chamber multiplied by the average volume of the particles), which is close to the field-measured volume of 106 m³, thus validating the model. The pressure applied from the open part of the cutter-head to the excavation face (for penetration into the ground and excavation) is a percentage of the maximum pressure applied by the horizontal jacks. The constant pressure applied in Metro Line 2 in Tabriz is 80 KPa. In numerous tunnel excavation projects, it is observed that the maximum pressure exerted on the excavation face typically reaches approximately 70% of the maximum jack pressure. During the excavation process, various percentages of this pressure were concurrently applied to the excavation face, while monitoring surface settlement and face stability, as detailed in Table 3. The findings indicate that when pressures are maintained between 70% and 50% of the maximum jack pressure, the resulting surface settlement remains relatively consistent. However, a notable increase in surface settlement occurs with any further reduction in pressure. Consequently, it is feasible to apply a pressure of 50% of the maximum jack pressure to the excavation face, thereby achieving savings in costs. During the excavation process, the various pressures produced in by accumulated materials in the chamber have been concurrently applied to the cutter head, while the surface settlement and face stability were monitored, as shown in Figure 10. The values of chamber pressure was controlled by the screw conveyor. It has been programmed when the chamber pressure exceeded from the defined percentage of earth pressure, the conveyor started to take the extra materials out. The obtained results confirmed that the optimum-maintaining pressure was 70% of the earth pressure. The surface settlement data from the discrete element model is illustrated in Figure 11.

Fig. 10. Applied earth and chamber pressure



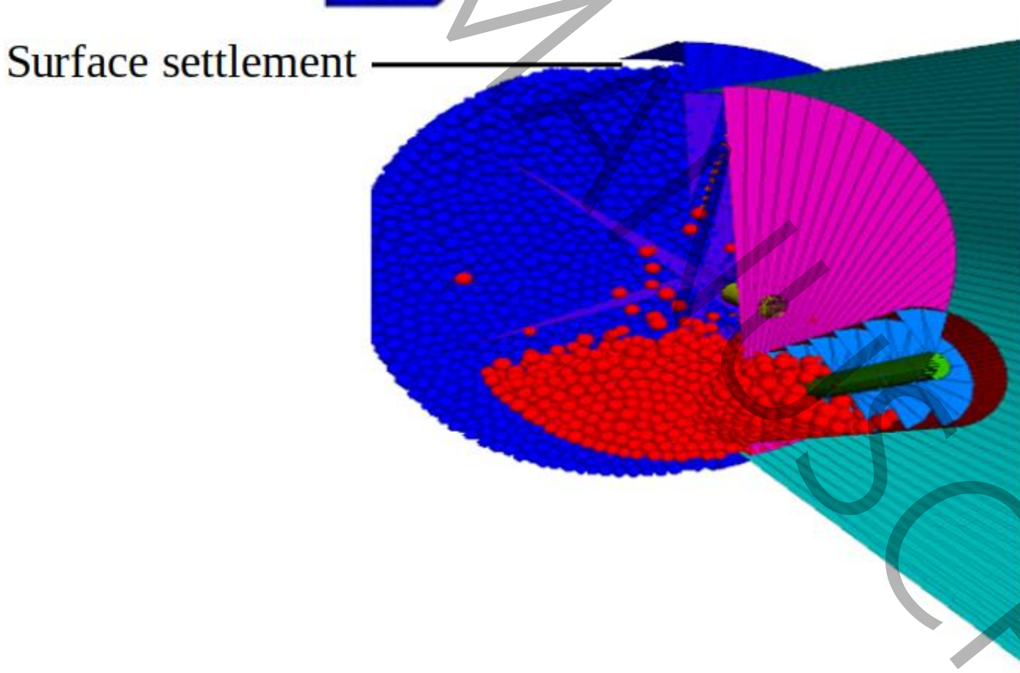


Fig. 11. Surface settlement in DEM model

Table 3. Settlements in different pressure applied to excavation face by DEM model

Settlement (cm)	Excavation chamber pressure (KPa)
1.8	150
1.8	140
1.8	130
1.9	110
2.3	90

The ground settlement observed above the working face at the metro Line 2 in Tabriz excavation site is illustrated in Figure 12 (Instrumentation results). The figure 12 reveals that the maximum recorded settlement is 0.020 meters (After 14 weeks), a value that provides valuable insight into the behavior of the ground during the excavation process. Interestingly, the settlement predicted by modeling under similar driving force conditions is only slightly lower at 0.019 meters, indicating a high level of accuracy in the predictive capabilities of the model. The comparison of the settlement values derived from the software with those measured in the field provides further confirmation of the validity of the modeling approach. This alignment between the predicted and actual settlement values demonstrates the effectiveness of the modeling technique in simulating the ground response to excavation activities.

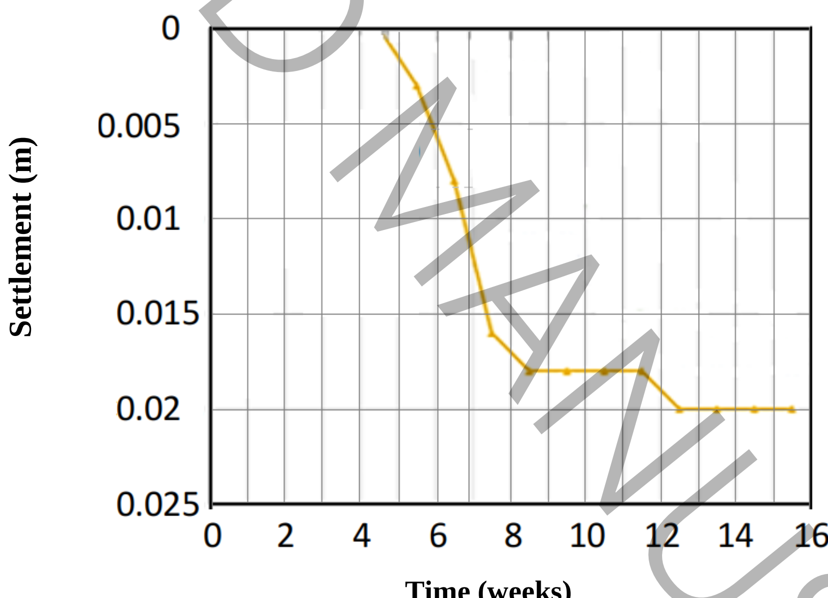


Fig. 12. Surface settlement Metro line 2 in Tabriz (Instrumentation results) [25].

The results also showed that the rotation speed of the cutter-head is one of the important factors affecting the surface settlement during tunnel excavation. Using the modeling, an optimal rotation speed of 2 rpm for the cutter-head was obtained, resulting in a maximum settlement of 0.019 m. This settlement is due to the consolidation of the soil in the excavation face during the disturbance caused by the excavation. Reducing the rotation speed below 2 rpm increases the surface settlement and the risk of face instability and collapse. Most available sources consider two factors for preventing surface settlement in EPB tunnel excavation: the grout injection pressure between the segments and the tunnel wall, and the pressure applied to the tunnel excavation face. However, this research has shown that the cutter-head rotation speed also has a significant impact on the surface settlement.

A discontinuous granular model has been developed to simulate the excavation process conducted by a cutter head, as well as to generate the corresponding balance earth pressure within the chamber in this research. This marks the first application of such a model in the context of Line 2 of the Tabriz metro. The application of Discrete Element Method (DEM) simulation within the excavation chamber of Earth Pressure Balance (EPB) Tunnel Boring Machines (TBMs) introduces innovative elements that improve the comprehension and optimization of tunneling activities. DEM facilitates an intricate modeling of particle interactions and ground behavior, which is essential for replicating the complex dynamics present in the EPB excavation chamber. This methodology yields valuable insights into the mechanical processes and operational conditions that affect TBM efficiency. DEM is particularly adept at simulating granular materials and accommodating large deformations, rendering it well-suited for modeling the ground conditions faced by TBMs. The simulations can closely mimic in situ ground conditions, thereby enhancing the management of TBM operational parameters, such as the speed of the screw conveyor. Furthermore, DEM simulations can forecast the effects of varying operational conditions on excavation performance. The method offers a comprehensive analysis of the excavation process, detailing the interaction forces among particles and the movement of soil within the excavation chamber. This understanding is vital for analyzing the mixing and flow dynamics of soil utilized in EPB tunneling. Additionally, the method enables the assessment of reaction forces and resistant torques at the cutterhead, shedding light on the mechanical stresses encountered during tunneling. Although DEM presents considerable benefits for simulating EPB TBM operations, it is computationally demanding and necessitates meticulous calibration of particle interactions to accurately represent real-world scenarios. Integrating it with other numerical methods, such as Finite Difference Method (FDM) or Finite Element Method (FEM), can alleviate these challenges by improving both the efficiency and accuracy of the simulations.

7 - Conclusion

In this study, the significance of managing urban ground settlement during the excavation of metro tunnels was emphasized. The excavation process for Tabriz Metro Line 2 was simulated using PFC3D software, which employs the Discrete Element Method (DEM). To validate the model, a comparison was made between the volume of soil excavated as determined by the DEM approach and the actual measured volume. The findings indicated that the DEM technique effectively replicates the excavation dynamics of an underground space utilizing an Earth Pressure Balance (EPB) machine, demonstrating a satisfactory level of accuracy in the performance of the excavation chamber. Within this model, various parameters were assessed, including the volume of soil entering the excavation chamber, the volume of soil discharged via the screw conveyor, the pressure exerted on the excavation face, and the ground settlement at different pressure levels applied by the cutter-head and its rotational speed. It was observed that in numerous tunnel excavation projects, the maximum pressure exerted on the excavation face typically reaches approximately 70% of the maximum pressure that horizontal jacks can deliver. In this investigation, various percentages of the maximum pressure (80 KPa) were applied to the excavation face throughout the excavation process, allowing for an evaluation of ground settlement and face stability. The results revealed that when the pressure on the excavation face ranged from 50% to 70% of the maximum jack pressure, the resulting settlement remained relatively constant at 1.9 cm. This consistency can be attributed to the consolidation of both the overlying soil and the soil at the excavation face, which is disturbed during the excavation process. Consequently, to optimize time and cost, it is suggested that 50% of the horizontal jack pressure may be utilized instead of the previously considered 70%. However, it is important to note that if the pressure on the excavation face falls below 50% of the jack pressure, a significant increase in ground settlement is observed. The findings indicated that a decrease in the cutter-head rotation speed from the optimal level of 2 rpm leads to a notable and substantial settlement of the ground surface. Conversely, when the rotation speed exceeds this optimal threshold, the ground settlement stabilizes at around 1.9 cm, attributed to the consolidation of the soil at the excavation face during the disturbance.

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