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Assessment of Ground Surface Settlement and Volume Loss in Mechanized Tunnelling Using Field Data and Numerical Modelling: A Case Study of Tabriz Metro Line 2

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Abstract

Mechanized tunnelling in soft soils often results in ground settlement both around the tunnel and at the surface, which can potentially damage urban infrastructure and surrounding buildings. Several geological and operational factors influence the extent of ground settlement. This paper investigates the actual ground settlement caused by over 10 kilometers of tunnelling along Tabriz Metro Line 2, with a particular focus on the materials and positions of the tunnelling machine. The results show that 55-60% of the total settlements occur behind the shield of the tunnelling machine, which is consistent with Thewes' (2009) diagram. The surrounding soil was categorized, and using data from settlement pins, the actual Volume Loss (VL) was analyzed across three geological sections consisting of sandy, clayey, and mixed materials. The findings reveal that volume loss in sandy materials is greater than in clayey and mixed soils, at approximately 1.02%. Additionally, the volume loss in mixed soils was calculated to be 0.82%, while in clay soils, it was 0.53%. To assess the impact of different materials on surface settlement, numerical modeling was carried out using Plaxis 3D software. The numerical results, considering volume losses of 1.05% for sandy materials, 0.8% for mixed materials, and 0.5% for clay materials, closely matched the actual settlement data.

1. Introduction

The increase in the global population in recent decades has significantly accelerated urbanization. Consequently, cities, especially metropolises, are facing unavoidable and heavier traffic compared to the not-so-distant past on roads, highways, and expressways. To manage and control this rising volume of urban traffic, the construction of urban metro systems can play a crucial role.

In recent years, the intrinsic value of land in densely populated urban areas has risen substantially, prompting the rapid development of underground spaces and infrastructures such as shopping centres and metro networks. Tunnelling in urban traffic environments particularly in large metropolitan cities is widely regarded as a high-uncertainty endeavour. As such, effective risk management in tunnelling, especially in mechanized excavation within densely populated areas, is of paramount importance. Among the various challenges associated with urban excavation, surface settlement poses a particularly significant risk due to its potential to trigger accidents, increase hazards, and escalate project costs and timelines. Accordingly, a comprehensive understanding of the methods used to estimate and mitigate settlement is essential to reducing the inherent risks involved. It is crucial to first predict, analyse, and categorize surface settlement risks in order to implement appropriate strategies such as monitoring and control, risk transfer, elimination, acceptance, or reduction for a specific mechanized tunnelling project. In recent years, mechanized excavation methods, particularly shield tunnelling, have been widely adopted in metro tunnel construction. This method offers several advantages, including high tunnelling speed and

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minimal disruption to surface traffic, making it a preferred choice for urban underground projects. [1-2].

The impact of tunnelling with a full-face Tunnel Boring Machine (TBM) on the settlement of surrounding soils is undoubtedly a critical consideration. When deformation of the soil adjacent to the excavation exceeds acceptable limits, significant technical and financial risks become unavoidable. Studies have shown that to mitigate surface settlement caused by lateral earth pressure—particularly during excavation in soft soils within densely populated urban environments—the use of Earth Pressure Balance (EPB) TBMs is recommended. The operating principle of EPB machines involves maintaining equilibrium between the earth pressure behind the cutterhead and the stress at the tunnel face, thereby neutralizing or at least minimizing the deformation of surrounding soil during excavation. Nevertheless, even when an appropriate TBM is selected and optimal conditions are maintained, mechanized tunnelling projects remain vulnerable to surface settlement risks. Therefore, accurate estimation of surface settlement is essential in these projects [3]. Over recent decades, numerous methods and techniques have been developed and applied to evaluate and predict surface settlement. Broadly, the research in this field can be categorized into four main groups. The first group includes analytical approaches, which employ mathematical formulations based on soil and rock mechanics principles to estimate settlement for different tunnel types. [4-10].

The second group of studies in this field centres on laboratory-based investigations. Research in this category typically involves simulating tunnel components and their surrounding environments under conditions that replicate real-world tunnelling scenarios, albeit at a reduced scale in controlled laboratory settings [11-13]. The third category comprises numerical modelling studies, which generally utilize computational techniques such as the Finite Element Method (FEM) and the Finite Difference Method (FDM) to estimate the extent of settlement induced by excavation in tunnelling projects [14-23]. Lastly, the fourth group of research focuses on employing soft computing techniques to achieve accurate predictions of ground surface settlement. These approaches rely on empirical data and often involve the application of artificial neural networks and other machine learning methods to model the complex behaviour of ground deformation due to tunnelling [3, 24].

Mohammadi et al. [25] investigated the impact of unknown shafts and cavities on urban tunnelling using an EPBM (Earth Pressure Balance Machine) in Tehran Metro Line 7. Through 3D numerical modelling in Flac 3D, they demonstrated that the presence of these obstacles, particularly in front of the tunnel face, causes significant disturbances in the ground and increases surface settlement. The ground behaviour varies across different sections of the tunnel boring machine, including the tunnel face, cutterhead, shield, and segments.

Fattahi and Jiryaee [26] investigated surface settlement caused by mechanized tunnelling using reliability analysis methods (FORM, SORM, and Monte Carlo). By employing a GMDH neural network, the limit state function was modeled, and the most sensitive parameters, including injection pressure behind the segment and groundwater level, were identified. The numerical results showed that the maximum probability of excessive settlement significantly increased when an obstacle was present in front of the excavation face.

The deformation behavior of a circular underground opening in hard soil was investigated using a three-dimensional physical model by Fu et al. [27]. The experimental results showed that variations in tunnel depth, soil properties, and excavation pressure significantly affected the settlement and deformations. Specifically, at greater depths, surface settlement was reported to be up to 25% higher than at shallower depths. Additionally, with increased excavation pressure, deformations were reduced by up to 15%. The empirical models were able to accurately predict the ground behavior and surface settlements, contributing to the improvement of underground tunnel design in hard soils.

Kazempour Osalou et al. [28] used the Proportional Hazards Model (PHM) to analyze surface settlement caused by tunnelling in Line 2 of the Tabriz Metro. The results indicated that the injection pressure behind the segment, the ratio of tunnel depth to groundwater level, and the drained shear strength had a direct and significant effect (at the 5% level) on the probability of settlement. Specifically, increasing the injection pressure reduced the probability of exceeding safe settlement values, while an increase in drained shear strength increased this probability.

Barri et al. [29] conducted laboratory experiments and numerical modelling to investigate the effect of grout mixture and injection pressure on surface settlement during TBM excavation. In this study, grout mixtures of cement and bentonite with varying percentages of soil (up to 40%) were used. The results showed that adding soil up to 40% increased compressive strength by 300%, elastic modulus by 156%, and cohesion by 100%. Additionally, increasing the grout injection pressure up to 120 kPa led to a 17% reduction in surface settlement. These findings emphasize the significant role of grout composition and injection pressure in controlling ground deformation and improving the safety of mechanized tunnelling.

In this study, for the first time, real ground settlement data collected over more than 10 kilometers of mechanized tunnelling under varying geotechnical conditions have been integrated with detailed numerical modelling using Plaxis 3D.

2. Analysis of Ground Settlement Due to Tunnel Excavation

The construction of any type of tunnel in various soil conditions necessitates excavation and the removal of a portion of the earth materials. This process alters the stress distribution system within the tunnel area, leading to wall and tunnel face convergence, which results in both horizontal and vertical displacements around the tunnel. Depending on the thickness of the overburden, some of these displacements reach the ground surface, ultimately causing deformations known as "ground settlement due to tunnel excavation." This phenomenon can potentially damage existing surface structures. Therefore, predicting and estimating the extent of ground settlement resulting from tunnelling , especially in urban environments that directly impact people's lives, is of particular importance [30].

In Figure 1, a representation of the phenomenon of ground settlement due to tunnel excavation is illustrated. Many researchers have studied the issue of settlement during mechanized excavation, leading to the development of various methodologies in this area. Terzaghi and Peck established foundational principles for tunnel design and provided a comprehensive report summarizing tunnelling operations in soft soils up to that time. Peck demonstrated that the ground settlement curve resulting from tunnel excavation (as shown in Figure 1) closely resembles a normal distribution curve. He proposed a relationship for the surface settlement profile, which can be expressed mathematically as follows:

$$\boldsymbol{S_v(x) = S_{v,max} . e^{(\frac{-x^2}{2i^2})}} \quad (1)$$

In this relationship, (i) represents the horizontal distance from the centre of the tunnel to the inflection point of the curve, and it can be derived from the following equation [8], [31]:

$$i = K.(Z_0 - Z) \quad (2)$$

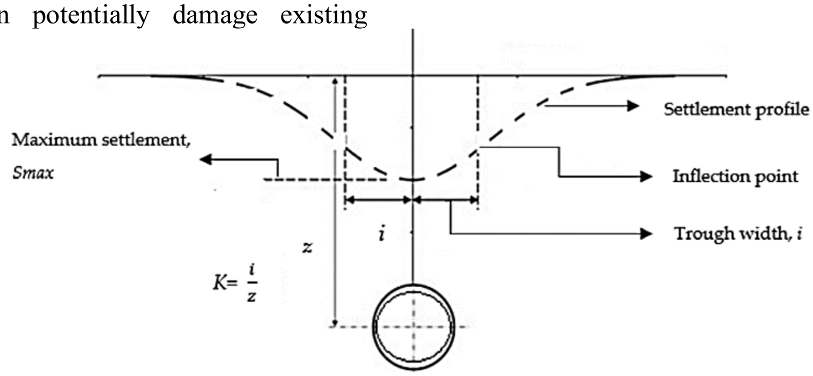


Figure 1. The profile of ground settlement due to tunnel excavation [8].

One of the important parameters in Peck's proposed relationship is the maximum settlement parameter. According to the primary settlement equation, the maximum settlement amount in this method depends on the volume loss resulting from excavation, and the shape of the settlement curve is determined by the parameter K, known as the geotechnical condition coefficient. Therefore, the key parameters for evaluating the shape and magnitude of ground settlement include the following:

1. Parameter K: This parameter defines the shape of the settlement curve.
2. Elevation Z: This parameter is dependent on the overburden of the tunnel.
3. Volume Loss VL: This parameter indicates the amount of volume loss due to excavation.

Volume loss in mechanized tunnelling is a critical factor resulting from tunnel excavation and the removal of materials from the ground, leading to the release of stresses in the surrounding soil. As a consequence, adjacent sections of the excavation tend to move inward toward the tunnel, causing the actual volume of excavated materials to exceed the nominal volume of the tunnel cross-section. This excess volume of excavated material is referred to as volume loss (VL).

Assuming that the materials are very soft and fill the area around the shield after excavation, the volume loss (VL) can be expressed as the ratio of the reduction in the cross-sectional area of the excavation to the initial cross-sectional area of the tunnel. This can be calculated using the following equation:

$$V_L = \frac{A_{excavation} - A_{sheild}}{A_{excavation}} \quad (3)$$

Where

V_L – Volume loss (%),

$A_{excavation}$– Actual excavated cross-sectional area (m^2),

A_{sheild}– Shield cross-sectional area (m^2).

In this context, an excavation refers to the cross-sectional area of the excavation, while a shield denotes the area of the tunnel after the soil has collapsed behind the shield, or in other words, the cross-sectional area of the shield at its end. The difference in these areas is illustrated in Figure 2. In theoretical relationships, the two mentioned areas correspond to Figure 2(a), whereas in reality, the gap created by the tunnelling machine is oval-shaped (as shown in Figure 2(b)). The additional excavation created is an inherent aspect of the mechanized tunnelling method and varies across different machines [32].

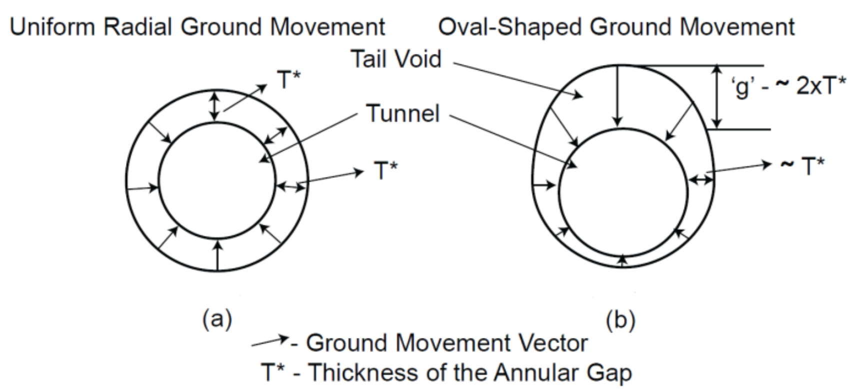


Figure 2. Circular and Elliptical Deformation Patterns Around Tunnels [32].

As shown in Figure 3, the three primary factors contributing to over-excavation volume and consequently ground settlement include: (1) the difference between the excavation diameter and the shield, (2) the gap between the shield and the segmental lining, and (3) incomplete grout injection. The shields of most tunnelling machines are conical in shape to facilitate machine propulsion, and the greatest difference in diameter occurs at the rear end of the shield compared to the cutter head.

In mechanized tunnelling, the geometric configuration of the tunnelling machine contributes significantly to volume loss, while the collapse of the excavation faces due to insufficient pressure applied to the ground can also be a critical factor influencing settlement. According to experiences from urban tunnelling projects, the factors affecting increased volume loss during mechanized excavation include:

1. Collapse of the Excavation Face: This factor can account for 10–20% of the total volume loss. Insufficient support or pressure can lead to failure at the excavation face, resulting in additional material displacement.
2. Difference Between Excavation Diameter and Shield Diameter: This difference can contribute 40–50% to the overall volume loss. The conical shape of the shield creates a gap that leads to excess excavation.
3. Improper Grouting Behind Segments: This can result in 30–50% of volume loss. Inadequate grouting may fail to fill voids created during excavation, leading to further ground movement and settlement [33].

Assuming that there is no significant collapse of the excavation face and that the grouting behind the segments is performed adequately, disregarding deformations caused by these two factors, the amount of volume loss will be related to soil resistance conditions, tunnel geometry, and whether the excavation conditions are normal or critical [33].

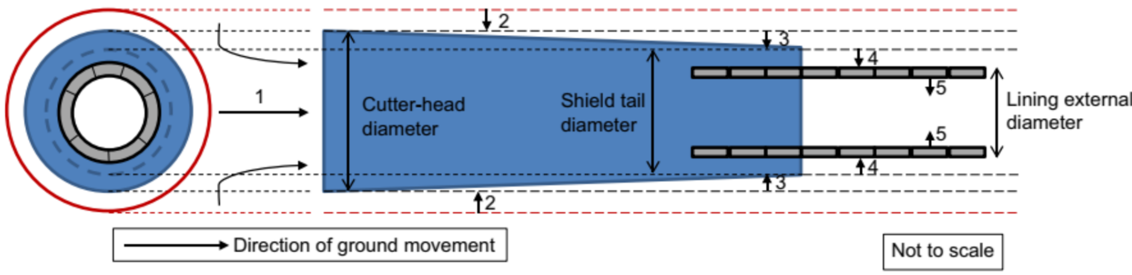


Figure 3. Illustration on components of volume loss [34].

Numerous studies have been conducted to determine the numerical values of ground settlement (volume loss). Various researchers have proposed values for this parameter based on geological and geotechnical conditions of the tunnel alignment, the materials involved, tunnelling methods, and other influencing factors. For instance, the research conducted by Guglielmetti et al. [35] provides valuable insights into this topic. According to their study, for conditions where the excavation and overburden materials are soil, the following volume loss values (VL) are suggested based on geotechnical conditions:

- For cohesive soils: VL=0.8%
- For granular soils: VL=1.0%

It is observed that the volume loss VL has an inverse relationship with soil cohesion; as the cohesion of the soil increases, the volume loss during excavation decreases. Table 1 presents the values suggested by some different researchers for this parameter [35].

Table 1. Proposed Volume Loss Values (VL) by Researchers Based on Soil Type [1], [4], [32], [35].

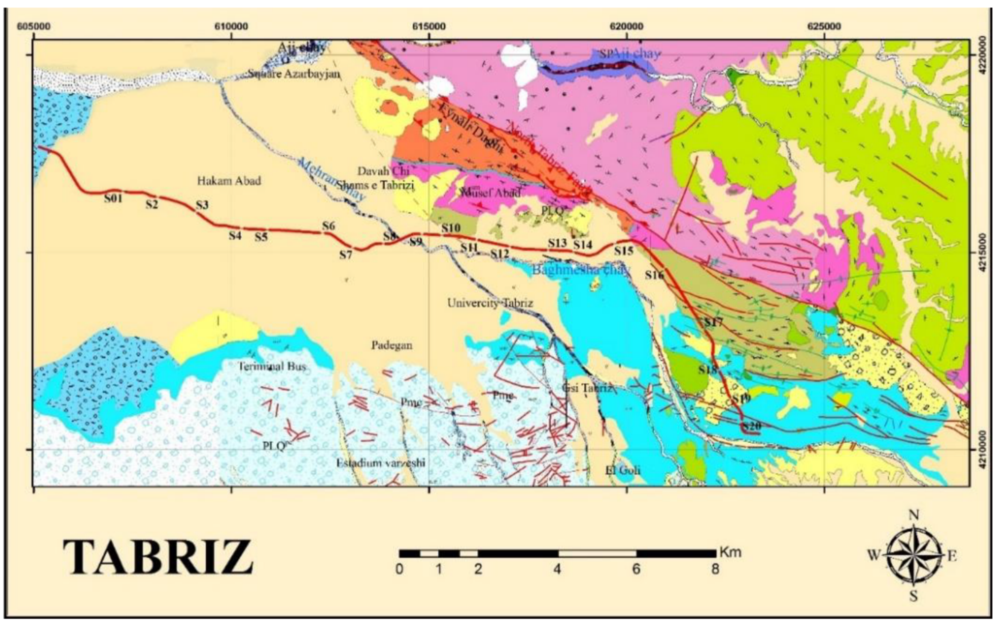
Cited References	Soil Type	Volume Loss (VL%)
O'Reilly and New (1982)	Dense Sand	0.1 – 0.2
	Soft Clay	0.1 – 1
	Clay with Abundant Sand	0.5 – 1
Guglielmetti et al. (2008)	Sandy Materials	1
	Clayey Materials	0.8
Loganathan (2011)	Clayey Materials	1.5
Zhang et al. (2014)	Coarse Materials	0.78 – 0.96

3. Settlement in Line 2 of Tabriz Metro

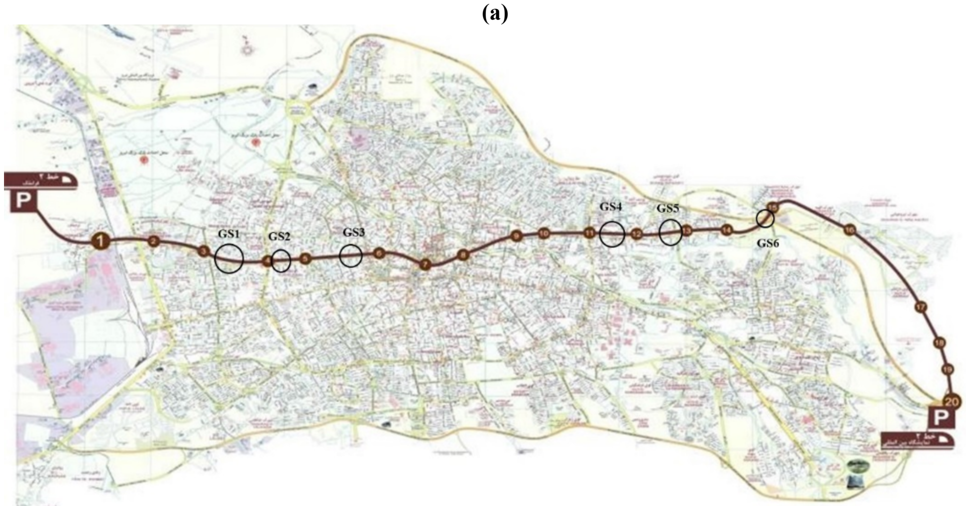
In this study, data from the excavation of over 10 kilometers of Line 2 of the Tabriz Metro has been utilized. Line 2 of the Tabriz Urban Railway spans approximately 22 kilometers and consists of three sections: the western section (from the depot to Daneshsara Square), the eastern section (from Daneshsara Square to Baghmisheh), and the eastern extension (from Baghmisheh to the vicinity of the Tabriz International Exhibition). Each section contains 8, 8, and 4 stations, respectively, totaling 20 stations. As illustrated in Figure 4, this line begins in the depot and parking area near the railway in the western part of Tabriz and passes through Qaramalek and Qara-Aghaj Street (Quds) before reaching the central areas of the city near the bazaar. The line continues after crossing Daneshsara Square and beneath the Mehran River to Abbasi Street and Shahid Fahmideh Square. From Shahid Fahmideh Square, it extends towards Baghmisheh Township and, after changing direction towards the southeast, ultimately concludes near the Tabriz International Exhibition. The areas of geotechnical profiles GS1 to GS6 are illustrated in Figure 4.

The tunnel of Line 2 of the Tabriz Metro, with a diameter of 9.49 meters, has been excavated using two tunnelling machines starting from the western and eastern shafts. The excavation of the western section occurs through multiple layers, predominantly consisting of alternating sandy and clayey materials, with varying geotechnical parameters at different depths. In contrast, the geotechnical profile of the eastern section primarily features marl and sandstone layers. However, after passing Station 11, the material composition changes to predominantly alternating sandy and clayey materials. The groundwater levels along the western route vary between 11 to 28 meters, while in the eastern route, they range from 3 to 35 meters throughout the project. A statistical study has been conducted on the settlements recorded due to mechanized tunnelling to analyze the results of ground settlement along Line 2 in both the western and eastern sections.

In this context, data on surface settlement at various stages of excavation (including the area in front of the excavation face, the shield area, and behind the segments) were recorded and processed. The results of this processing are presented in Table 2. For this purpose, 958 settlement measurement data points were analyzed, and the recorded surface settlement at each stage of excavation was examined and compared. The results show a good correlation with the findings from the thewes (2009) chart (see Figure 5). According to the results presented in Table 2, the maximum and average settlements in front of the excavation face range between 10% to 15%, while the maximum and average settlements in the shield area range from 25% to 35%. In contrast, the settlements behind the segments range from 50% to 60%. Thus, it is evident that the highest level of settlement occurs behind the segments, primarily influenced by the grouting injection behind them. Consequently, further investigations have been conducted based on data from this section, with settlement behind the shield selected as the benchmark for settlement analysis. From this point onward, the reported settlements will refer to ground settlement behind the shield [33].



(a)



(b)

Figure 4. a) Geological map of the tunnel of Tabriz Metro Line 2 area, b) Description of Line 2 of Tabriz Metro Route

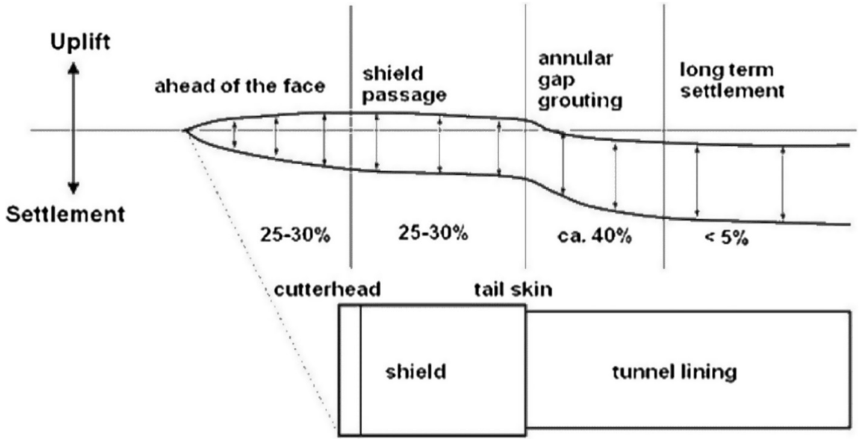


Figure 5. Schematic development of settlements and percentage of total settlement [33].

Although several operational factors such as maintaining consistent face pressure, continuous excavation without frequent interruptions, appropriate injection pressure, and theoretical injection volume play a role in ground settlement, it is equally important to account for the influence of geological parameters and the stratigraphy along the excavation path on surface settlement and volume loss in mechanized tunnelling. The maximum and average settlements behind the segments in both the western and eastern sections are presented in Table 3. The data indicate that in the western section, maximum and average settlements behind the segments remain relatively consistent across all three types of stratification. In contrast, the eastern section, particularly under mixed ground conditions, exhibits significant variations in these values. This variation is primarily attributed to the differing stratigraphic conditions and material types encountered along the eastern alignment. Specifically, the presence of interbedded marl and sandstone layers with higher resistance characteristics than sand and clay has led to substantial discrepancies between maximum and average settlements in mixed conditions. Consequently, an analysis of soil types and the volume loss resulting from tunnel excavation was carried out using empirical data.

Table 2. Results of Settlement Measurements from Line 2 of Tabriz Metro.

Measurement Area	Maximum Settlement (mm)	Minimum Settlement (mm)	Average Settlement (mm)
Behind Shield	21 (55%)	1	12 (60%)
Shield Area	12 (32%)	1	5 (25%)
In Front of Excavation Face	5 (13%)	1	3 (15%)
Total Data Points		952	

To compare the settlement amounts behind the segment and across different geological layers, the geological layers have been classified into three groups. The materials containing 70% granular constituents, including SM (Silty Sand), SC (Clayey Sand), and SP (Sandy Gravel), are categorized as sandy soils. The materials predominantly composed of fine particles, such as ML (Silty Clay) and CL (Clay), are classified as clay soils. The combination of these two types is considered as mixed soil

Table 3. Classification of Settlement Behind Segments in Different Materials.

	Average Settlement (mm)			Maximum Settlement (mm)		
	Sand	Clay	Mixed	Sand	Clay	Mixed
Eastern Route	20	15	13	20	15	34
Western Route	12	12	12	25	24	23

4. Calculation of Actual Volume Loss Along Line 2 of Tabriz Metro

To date, no specific method has been established for calculating volume loss for different soil types. However, if access to actual maximum settlement results at the ground surface is available, existing relationships for maximum settlement provided by O'Reilly and New can be utilized to calculate the actual volume loss that has occurred. Relationship 4 is provided by Mair et al. (1993) to calculate maximum surface settlement:

$$S_{max} = 0.313 * V_l * \frac{D^2}{K * Z_0} \quad (4)$$

Where

S_{max} – Maximum ground surface settlement (m),

D – Tunnel diameter (m),

Z_0 – Depth from ground level to tunnel crown (m),

K – Geotechnical coefficient defining the shape of the settlement trough [4].

By utilizing actual maximum settlement values, it is possible to calculate the actual volume loss that occurs as a result of tunnelling . In this section of the study, given the availability of actual settlement values from over 1,000 settlement pins, the real value of this parameter will be estimated based on discussions presented in previous sections. For these calculations, the parameter K has been considered in accordance with the geological conditions, with values ranging from 0.4 to 0.5. Figure 6 illustrates the calculated volume loss values in the form of bar charts. For each section, calculations have been performed based on the number of available settlement pins. As observed, different volume loss values (VL) have been calculated based on the recorded settlements. To ensure accurate predictions, the maximum volume loss has been selected for each section. Table 4 shows the numerical values of volume loss for selected sections. The geotechnical profile of the selected sections is displayed in Figure 7.

Table 4. Volume Loss Values Obtained from Relationship 3 for Selected Sections.

Section Number	Modelling Section	Material Type	Actual Settlements (mm)	Volume Loss (VL)
GS2	6500 – 6350	Clay	20	0.53
GS4	13300 – 13150	Mixed	25	0.82
GS6	16155 – 15980	Sand	31	1.02

5. Numerical Modelling

In this section, to compare the actual settlement values observed in Line 2 of the Tabriz Metro with the results from numerical studies, modelling was conducted using Plaxis 3D software across various sections. This software was selected as a geotechnical program due to its capability to model underground structures within soil environments, allowing for the simulation of variables such as face pressure, grouting pressure, and ultimately providing powerful outputs for simulation. The issue analyzed in this simulation is the determination of maximum ground settlement during tunnelling operations using a TBM-EPB (Tunnel Boring Machine - Earth Pressure Balance) behind the shield and comparing settlements resulting from volume loss in different soil types. In this section, six sections along the project line were selected for modelling based on the materials present in the tunnel section and the materials used for grouting behind the segments. Accordingly, two sections were modeled in sandy soil, two in clayey soil, and two in mixed soil. The geotechnical profile and layering of these sections are illustrated in Figure 7. In the conducted modelling, the information for each section was initially based on the existing layering, groundwater levels, and geotechnical parameters [36]. Additionally, the parameters of the TBM, including face pressure and grouting pressure, were selected according to actual operational parameters. The volume loss values for all soil types were considered to be 1.05 based on Table 1.

For modelling the tunnel section according to Moller [37], a geometry dimension of 60m x 60m x 80m was selected. To reduce computational time and due to the symmetry in the model, half of the model was chosen for simulation, with the ground surface considered as the upper boundary of the model. The positions of the lateral boundaries, boundary conditions, and element types were selected to ensure that they do not affect the stress and strain fields. Figure 8 illustrates the overall geometry constructed within the software. Figure 9 comprehensively depicts the excavation stages and shield movement throughout the tunnelling process. The characteristics of the tunnelling machine and the precast concrete lining have been integrated into the model based on the specifications outlined in Table 5.

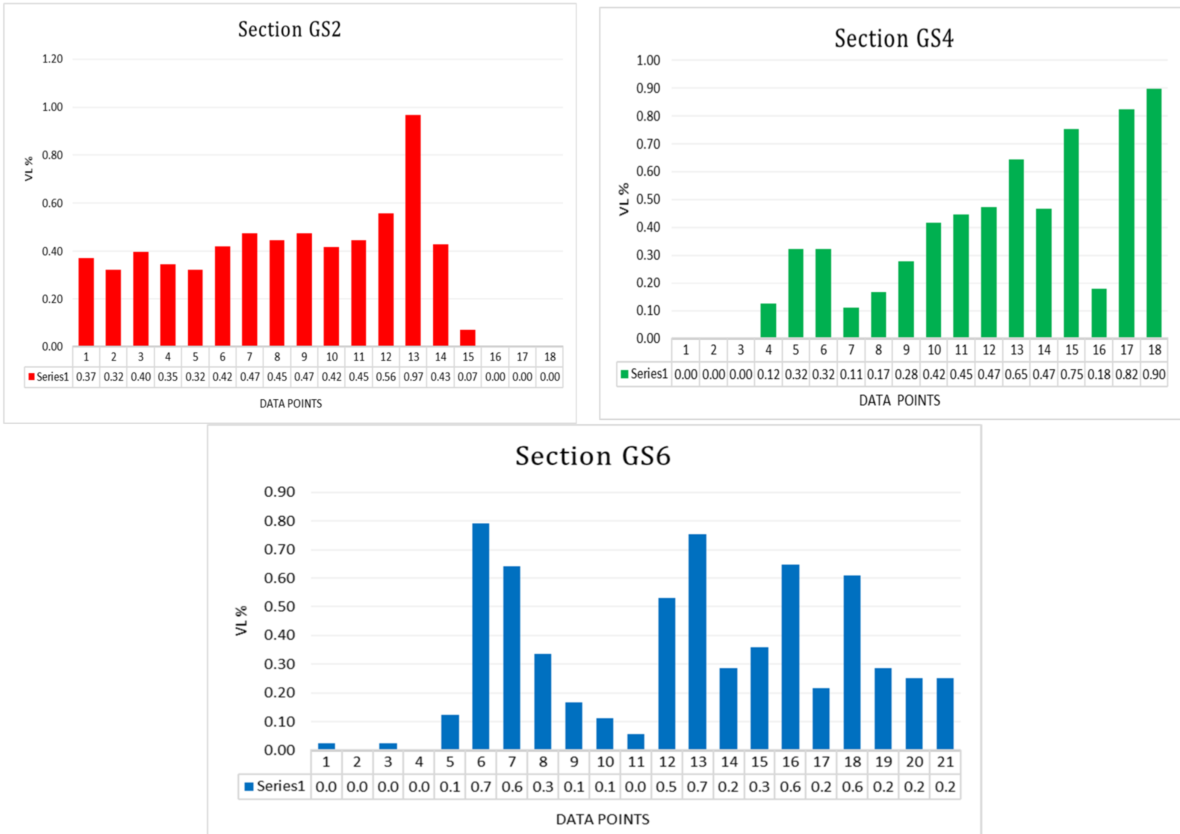
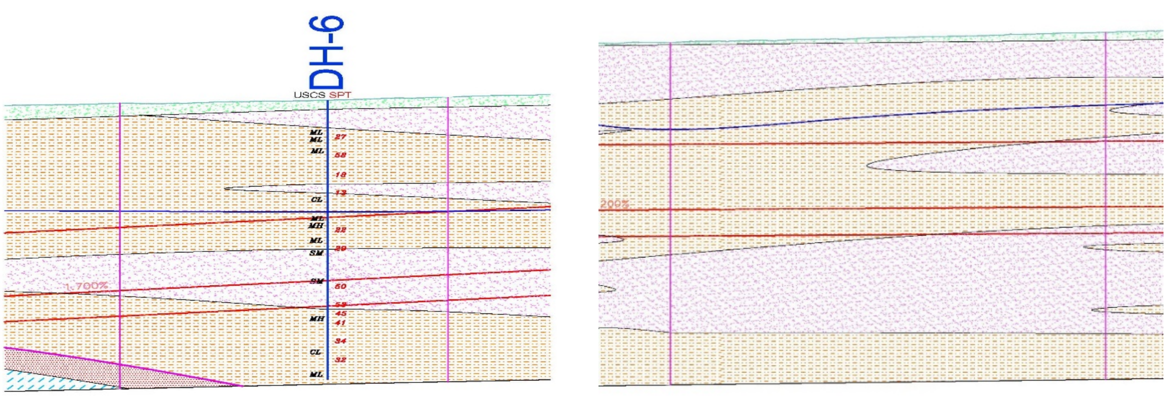


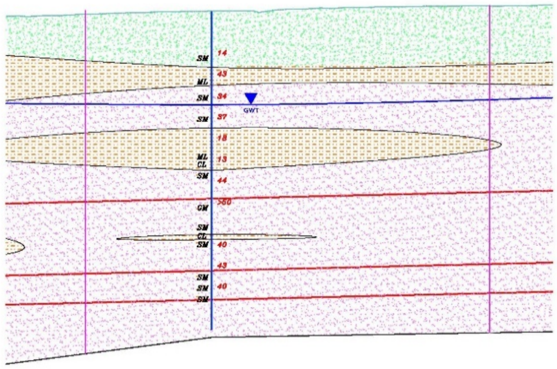
Figure 6. Calculated Volume Loss Values Based on Measured Actual Settlements.



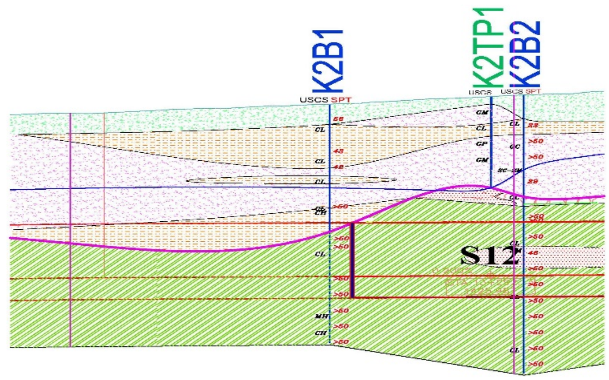
- Section Identification: GS1 (80 m)
- Kilometer Range: 5770 – 5850
- Soil Type: Mixed Soil

- Section Identification: GS2 (150 m)
- Kilometer Range: 6350 – 6500
- Soil Type: Clayey Soil

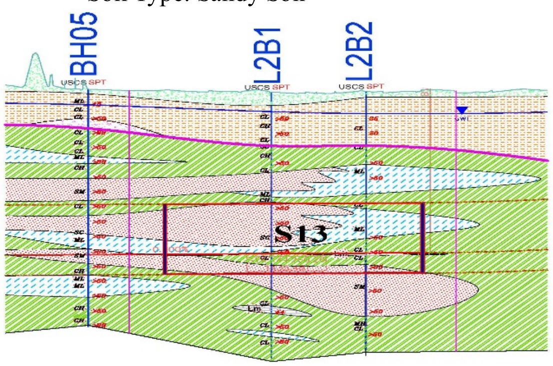
Figure 7. Geotechnical Profile and Subsurface Information of Selected Sections (The depth of the profile is down to -30 meters).



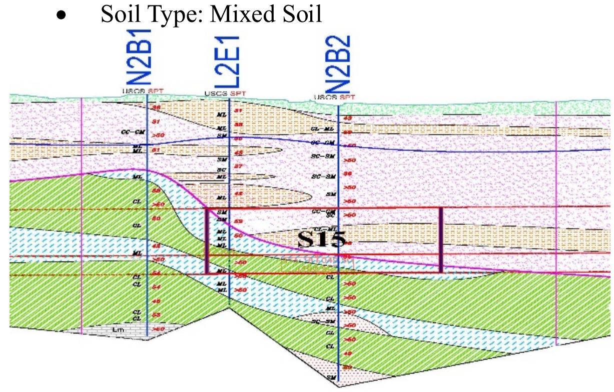
- Section Identification: GS3 (130 m)
- Kilometer Range: 7710 – 7840
- Soil Type: Sandy Soil



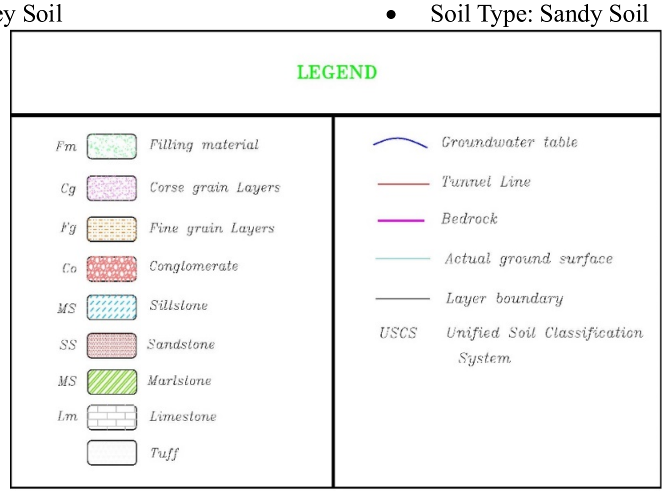
- Section Identification: GS4 (150 m)
- Kilometer Range: 13150 – 13300
- Soil Type: Mixed Soil



- Section Identification: GS5 (120 m)
- Kilometer Range: 14200 – 14320
- Soil Type: Clayey Soil



- Section Identification: GS6 (175 m)
- Kilometer Range: 15980 –16155
- Soil Type: Sandy Soil



Continuous of Figure 7. Geotechnical Profile and Subsurface Information of Selected Sections (The depth of the profile is down to -30 meters).

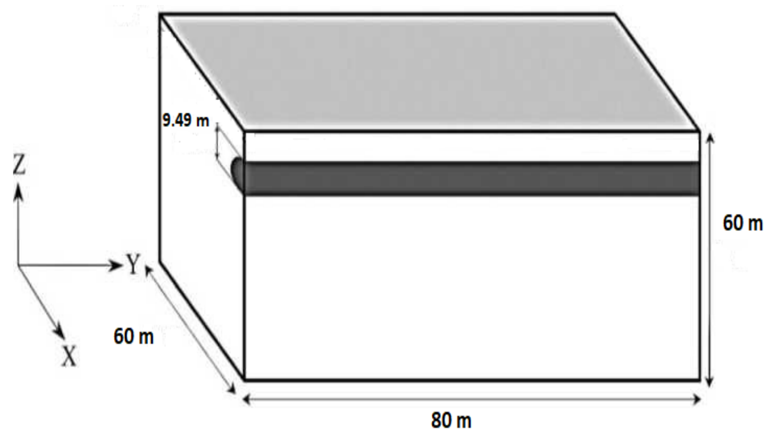
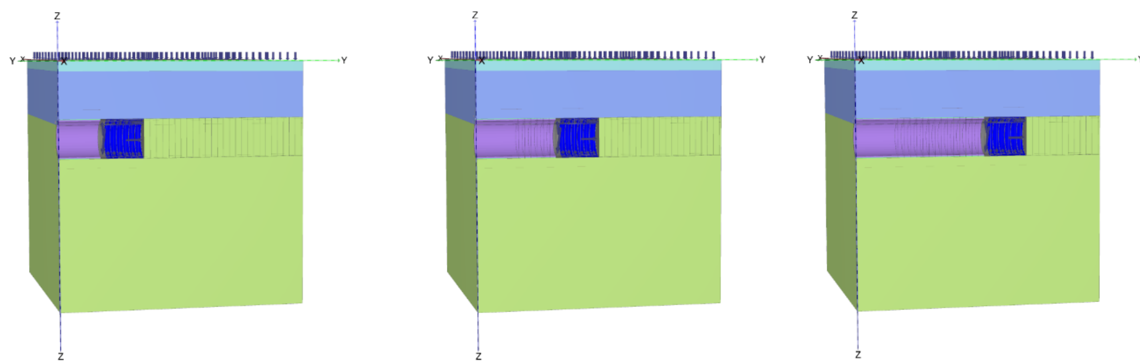


Figure 8. Geometry and Dimensions of the Model Constructed in PLAXIS



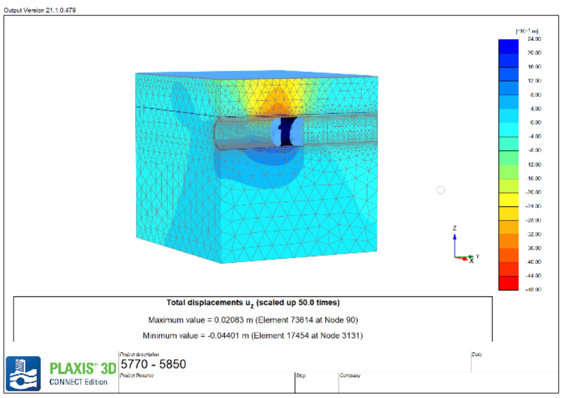
(a) (b) (c)

Figure 9. Excavation Stages and Shield Movement of the Tunnelling Machine in PLAXIS, a) Advance of the shield of the boring machine in model, b, c) Tunnel advance in model and installation of segments).

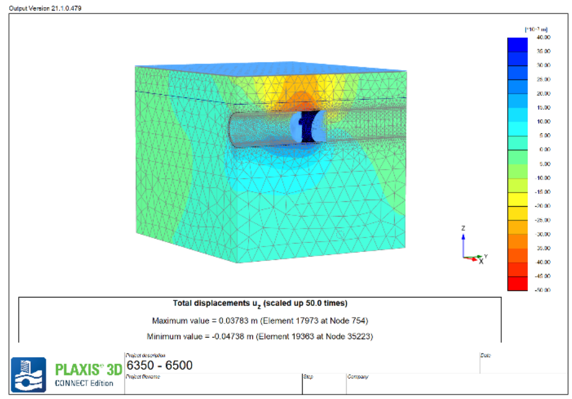
Table 5. Parameters Applied in Numerical Modelling for the Tunnelling Machine, Segment, and Grouting Behind the Segment.

Parameters	Grouting Behind Segment	Segment	Tunnelling Machine (EPB)
Properties	Elastic	Elastic	Elastic
Modulus of Elasticity (Pa)	-	-	2.1*1011
Bulk Modulus (Pa)	$2.667*10^7$	$1.945*10^{10}$	-
Shear Modulus (Pa)	$1.6*10^7$	$1.458*10^{10}$	
Thickness	0.15 m	0.35 m	0.1 m
Density (kg/m³)	1500	2600	7850

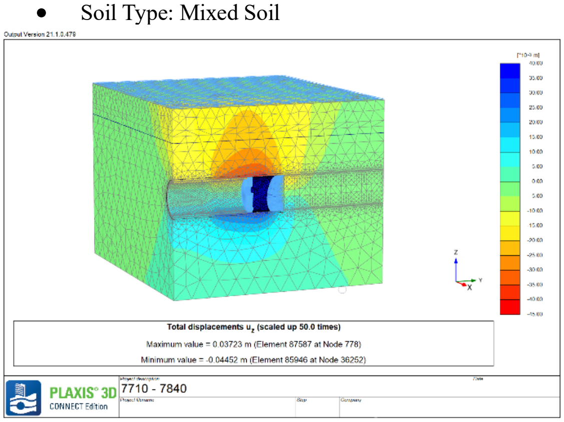
After preparing the model geometry, the initial geotechnical data was entered, including the layering of the model and the meshing process. In this meshing, the fundamental elements of the soil are represented in three-dimensional, four-faced, and ten-node configurations. The size of the elements was selected to balance computational accuracy and solution time effectively. Consequently, a finer mesh was selected near the excavation site, while larger element sizes were chosen in areas farther away. Upon completing the meshing process, the model reached an initial equilibrium state through the application of initial stresses. After the surface load was applied to the model, the tunnelling operation commenced with an excavation advance of 9 meters (equivalent to the length of the shield of the tunnelling machine), repeated over 6 cycles. As excavation progressed, the shield of the machine was removed in the first excavation step at the beginning of the model, while simultaneously activating the grout elements with specified characteristics to install the first precast concrete lining. The grouting pressure was applied to the tunnel environment and the external surface of the tunnel lining. Subsequently, for each excavation phase at the tunnel face, a corresponding installation of the lining was performed at the end of the shield, with this operation being repeated in succession. Figure 10 presents a visualization of the modelling outputs for the tunnel sections.



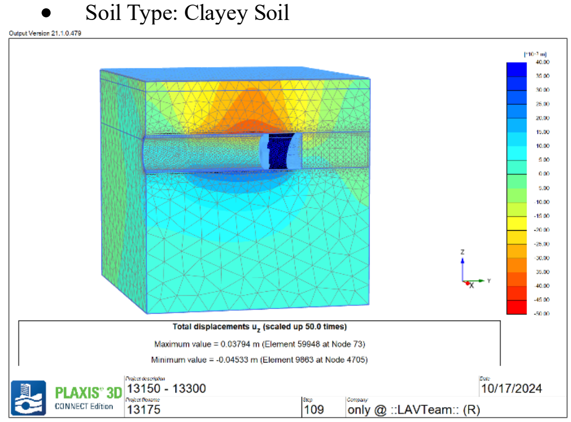
- Section Identification: GS1
- Kilometer Range: 5770 – 5850
- Soil Type: Mixed Soil



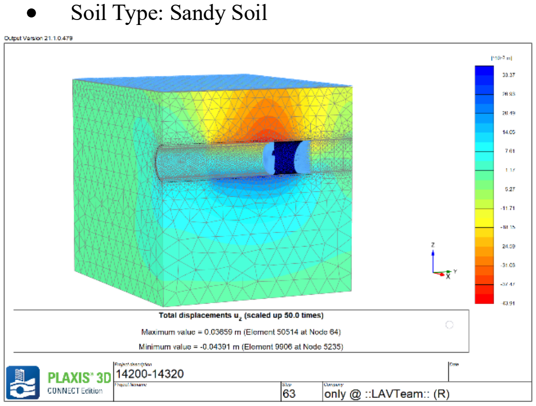
- Section Identification: GS2
- Kilometer Range: 6350 – 6500
- Soil Type: Clayey Soil



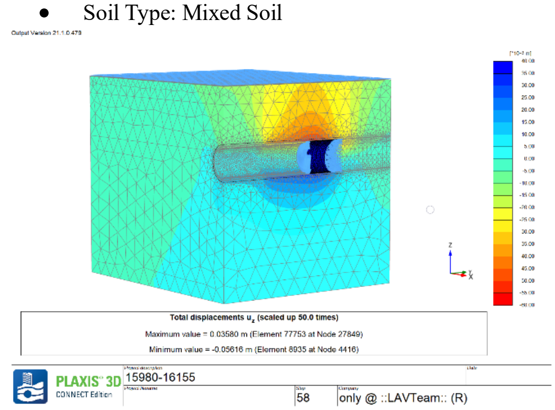
- Section Identification: GS3
- Kilometer Range: 7710 – 7840
- Soil Type: Sandy Soil



- Section Identification: GS4
- Kilometer Range: 13150 – 13300
- Soil Type: Mixed Soil



- Section Identification: GS5
- Kilometer Range: 14200 – 14320
- Soil Type: Clayey Soil



- Section Identification: GS6
- Kilometer Range: 15980 –16155
- Soil Type: Sandy Soil

Figure 10. Settlement Contours from Numerical Modelling in Selected Sections

6. Numerical Results Analysis

After completing the modelling and obtaining outputs from the software, the settlement graphs for each section were plotted in Figure 11. It is observed that the maximum settlement occurs at the crown of the tunnel and at the ground surface, varying between 19 to 30 millimeters depending on the type of materials used. A comparison was also made between the settlements obtained from the numerical method and actual measured settlements, with the results presented in Table 6.

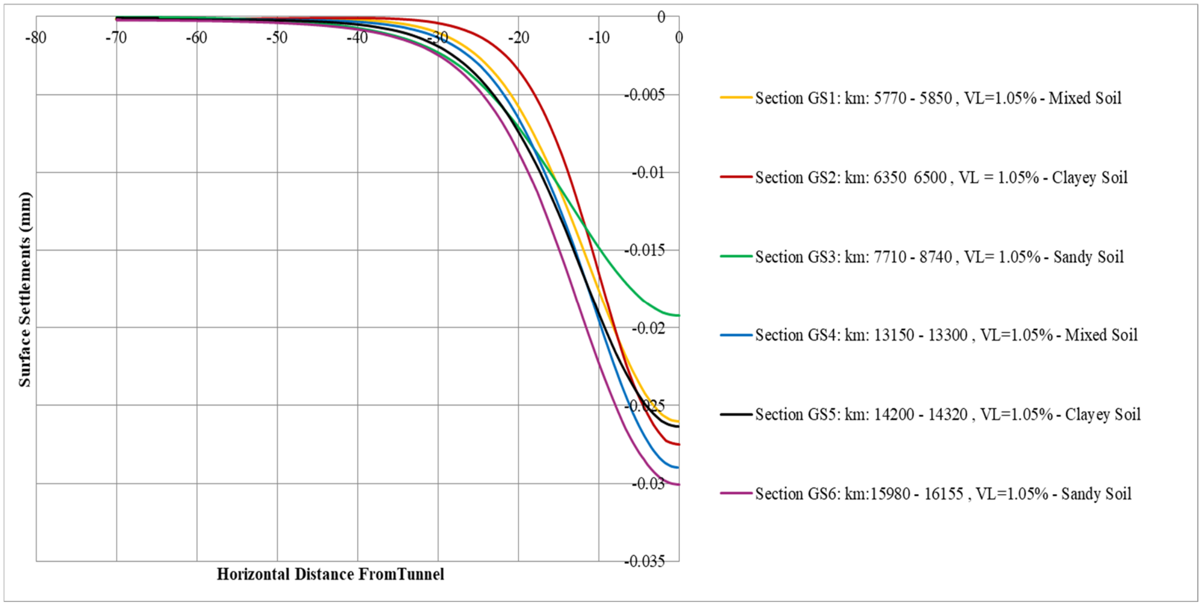


Figure 11. Settlement Graphs from Numerical Method in Selected Sections

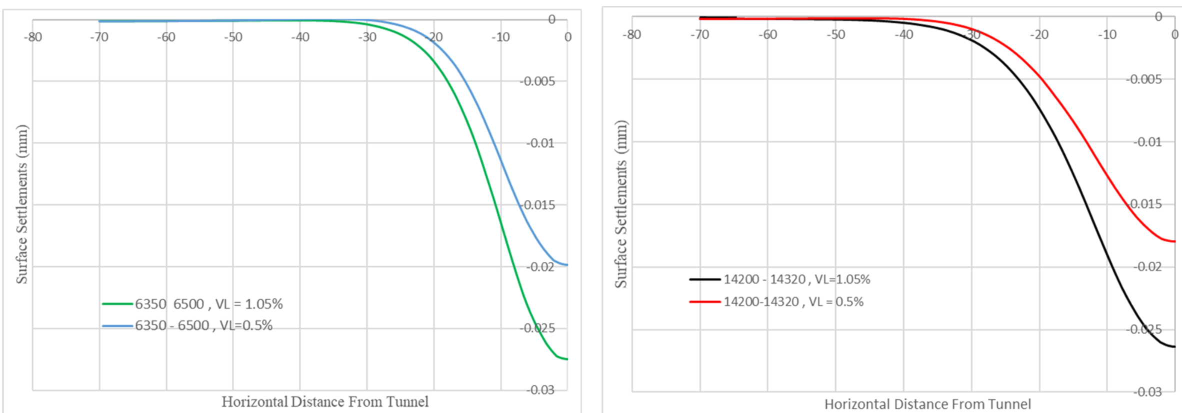
Table 6. Settlement Results from Numerical Modelling in Selected Sections.

Section Number	Actual Settlement (mm)	Numerical Settlement (mm)
GS1	21	26
GS2	20	27
GS3	20	19
GS4	25	29
GS5	19	26
GS6	31	30

The comparison of actual and numerical settlement results indicates that the settlement values in sandy soils closely align with the measured actual settlements. Specifically, Figure 12 presents both the measured and numerically simulated settlements for all six sections. A good agreement is observed in sections GS3 and GS6 (sandy soil), whereas discrepancies are found in clayey and mixed soil sections. Additionally, a comparison of modelling results with tunnel settlements in clay and mixed materials reveals that the settlements resulting from tunnelling in these materials are less than those predicted by the model, indicating that the actual settlement values are lower. This observation is evident in sections GS1, GS2, GS4, and GS5. Given that the tunnelling parameters in the modelling were consistent, the observed discrepancies and lack of alignment can be attributed to geological factors and parameters such as volume loss, which are influenced by soil type and local geotechnical conditions. The results indicate that variations in volume loss across different soil types have led to differences between the modeled and actual settlement outcomes. To achieve accurate real-world settlements and improve future predictions of settlement values, it is essential to revisit and refine the parameters related to geological conditions and volume loss.

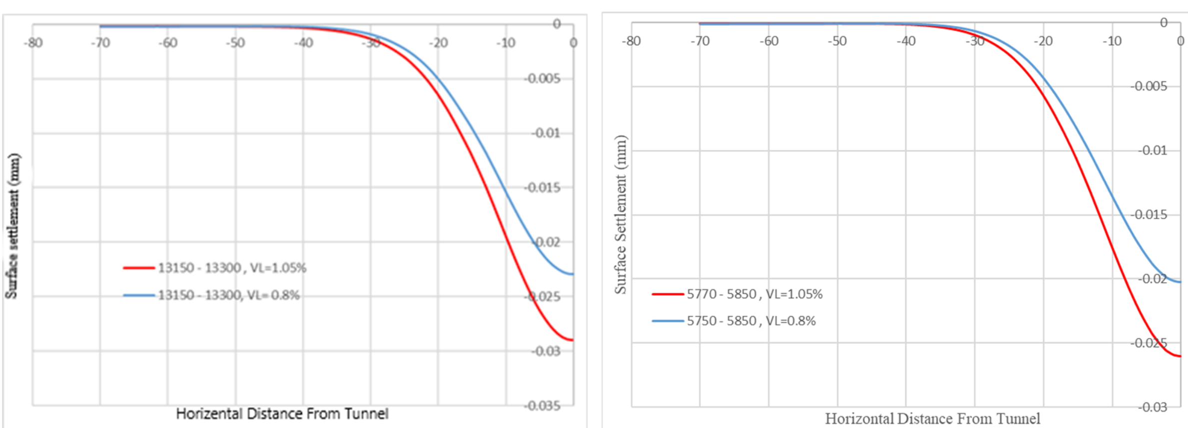
The volume loss parameter in the conducted modelling for predicting ground settlement was set at 1.05% based on previous studies and Table 1. However, there has not yet been a definitive method established for accurately determining this parameter. At this stage, hypothetical values for the volume loss parameter were considered to achieve more precise predictions of settlement in clay soils (GS2, GS5) and mixed materials (GS1, GS4). To achieve accurate real-world ground settlement predictions for clay soils, a volume loss parameter of 0.5% was selected, while for mixed soils, this parameter was set at 0.8%. The modelling was then conducted again using these revised values. The resulting settlement graphs corresponding to this updated modelling are presented in Figure 13. The results indicate that the settlements obtained from the numerical method, using the new volume loss parameters, have led to lower settlement values in clay soils. Specifically, in section GS5, the settlement decreased from 26 mm to 18 mm. Similarly, in section GS2, the settlement reduced from 27 mm to 19 mm. In fact, based on the results obtained, it can be concluded that a lower volume loss (VL) has occurred in clay soils. Given the alignment between the modelling results and actual measurements, it can be stated that in the modeled clay soils, the volume loss is approximately %VL ≈0.5%.

Figure 12. Bar Charts Comparing Numerical and Actual Measured Settlements.



a) Section GS2 **b) Section GS5**

Figure 13. Comparison of Settlement Values in Clay Soils with Volume Loss of 1.05% and 0.5%



a) Section GS4 **b) Section GS1**

Figure 14. Comparison of Settlement Values in Mixed Soils with Volume Loss of 1.05% and 0.8%

The numerical modelling for mixed soils was repeated with a revised volume loss parameter. The results comparing the volume loss values in mixed soils are presented in Figure 14. Additionally, the bar charts in Figure 15 illustrate that sections GS1 and GS4 show good alignment with actual measured settlements at a volume loss of 0.8%. This indicates that the volume loss (VL) occurring in mixed soils is approximately equal to the value considered in the modelling (0.8%). Table 7 illustrates the relationship between various volume loss values and actual settlement measurements across different soil types.

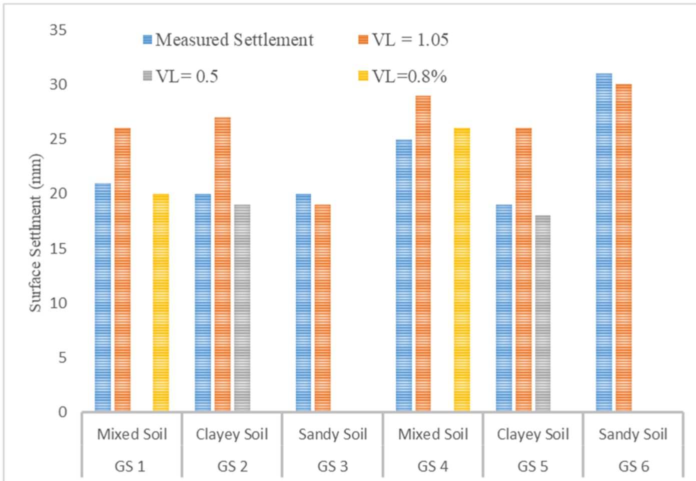


Figure 15. Comparative Settlement Graphs from Numerical Method at Various Volume Loss (VL) Values

Table 7. Comparison of Ground Settlement Values in Different Soil Types at Various Volume Loss (VL) Percentages.

Section Number	Soil Type	Settlement at VL = 1.05% (mm)	Settlement at VL = 0.8% (mm)	Settlement at VL = 0.5% (mm)	Actual Settlement (mm)
GS1	Mixed	26	20	-	21
GS2	Clay	27	-	19	20
GS3	Sand	19	-	-	20
GS4	Mixed	29	23	-	25
GS5	Clay	26	-	18	19
GS6	Sand	30	-	-	31

7. Conclusions

Ground settlement caused by tunnelling in urban environments is a matter of significant concern and sensitivity. In this study, a statistical analysis of surface settlement was performed at various positions relative to the tunnelling machine. The surrounding soils were classified into three categories: sandy, clayey, and mixed soils. Volume loss values were calculated based on actual settlement measurements along the eastern and western sections of the tunnel throughout its full length. Furthermore, six representative sections along the Tabriz Metro Line 2 alignment were selected for numerical modelling using Plaxis 3D software. The results of the numerical simulations were then compared with the recorded field settlements to evaluate the effect of volume loss across different soil types.

The evaluations indicate that the maximum ground settlement occurs behind the shield of the tunnelling machine. This phenomenon is primarily attributed to factors such as the change in excavation diameter at the rear of the shield and volume loss. To examine the influence of soil stratification on volume loss, actual volume loss values were calculated using settlement pin data across three sections with differing geological conditions. The highest recorded volume loss was 1.02% in section GS6 (sandy soil), followed by 0.82% in section GS4 (mixed soil), and 0.67% in section GS2 (clayey soil).

According to numerical analyses, ground settlement along the tunnel axis is greater in sandy soils compared to clayey and mixed soils. This trend is primarily attributed to differences in volume loss. To evaluate this effect, numerical modelling was performed using Plaxis 3D software. The results show that in sandy soils, a volume loss of 1.05% produces settlement values that closely match actual field measurements. In clayey soils, a volume loss of 0.50% yields similarly accurate results, while in mixed soils, a volume loss of 0.80% leads to modeled settlements that also correspond well with observed values.

Based on the findings of this study, several directions for future research are suggested: a) Extending the numerical modelling approach to twin tunnel configurations and investigating their impact on surface structures and surrounding infrastructure. b) Exploring the use of innovative grouting materials to further reduce surface settlement, thereby improving the overall stability and safety of tunnelling operations. These areas of future research have the potential to enhance the predictive accuracy and practical applications of tunnelling practices in urban environments, particularly in projects involving complex geotechnical conditions

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ارزیابی نشست سطح زمین و افت حجم در حفاری مکانیزه تونل با استفاده از داده‌های میدانی و مدلسازی عددی: مطالعه موردی خط ۲ مترو تبریز

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کلمات کلیدی

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چکیده

حفاری مکانیزه در زمین¬های نرم باعث بروز نشست در خاک¬های اطراف تونل و سطح زمین می¬شود که این موضوع به تأسیسات شهری و ساختمان¬های اطراف آن آسیب وارد می¬کند. عوامل زمین شناسی و عملیاتی مختلفی بر روی میزان نشست زمین تأثیرگذار می¬باشد. در این مقاله به بررسی میزان نشست واقعی سطح زمین تحت تأثیر حفاری بیش از ۱۰ کیلومتر از خط دو متروی تبریز در مصالح گوناگون و در موقعیت¬های مختلف دستگاه حفار پرداخته شده است. نتایج بدست آمده نشان می¬دهدکه ۶۰-۵۵ درصد از کل نشست¬ها در پشت سپر دستگاه حفار اتفاق می¬افتد که تطابق خوبی با نمودار تووز ۲۰۰۶ دارد. سپس خاک اطراف تونل دسته¬بندی شده و با استفاده از داده¬های پین¬های نشست سنجی میزان افت حجم (VL) واقعی زمین در سه مقطع زمین شناسی در مصالح ماسه¬ای، رسی و مخلوط بررسی شده است. در ادامه محاسبه افت حجم رخ داده در ۳ مقطع از طول تونل در مصالح متفاوت انجام شد که نتایج نشان می¬دهد افت حجم رخ داده در مصالح ماسه¬ای بیشتر از مصالح رسی و مخلوط و در حدود ۱/۰۲درصد می¬باشد. همچنین افت حجم رخ داده در خاک¬های مخلوط ۰/۸۲درصد و در خاک رسی ۰/۵۳ درصد محاسبه شده است. در ادامه جهت بررسی افت حجم مصالح متفاوت بر روی میزان نشست سطح زمین به روش عددی و مقایسه آن با مقادیر واقعی، ۶ مقطع زمین شناسی انتخاب و مدل سازی در نرم افزار Plaxis 3D انجام شد. نتایج نشان می¬دهد میزان نشست حاصل از روش عددی در مصالح ماسه¬ای با در نظر گرفتن افت حجم ۱/۰۵درصد، در مصالح مخلوط افت حجم ۰/۸درصد و در مصالح رسی افت حجم ۰/۵درصد تطابق خوبی با نشست واقعی رخ داده دارد.

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