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Analysis of Soil andTunnel Interaction in Mechanized Full-Face DrillingStages and Its Impact onGroundSettlement (Case Study: Line 7 of Tehran Metro)

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ABSTRACT:
Tunnel drilling results in releasing of soil's in-situ stress, leading to land deformation. Some level of displacement always occurs at the tunnel drilling site. This displacement sequentially affects the ground surface, causing groundsettlement. To prevent the resulting groundsettlement, measures must be taken to minimize alterations in stresses and strains within the ground. EPB drilling machines are utilized for this purpose. In this study, the movement of the full-face EPB drilling machine has been modeled in the east-to-west segment of Tehran Metro Line 7, located at kilometer 650+11, where tunnelling operation is currently undergoing. The impact and interaction between the full-face EPB drilling machine and soil leads to a reduction in volume around the tunnel, which exhibits itself as groundsettlement on the ground surface. The movement of the EPB drilling machine through a complete cycle (step-wise drilling, injection, and step-wise segmental lining) is simulated using PLAXIS 3D Tunnel software, and displacement and settlement values on the ground surface are determined using the same software. To model and determine the effects of tunneling with shield plates, specific points for shield movement in the designated section have been identified, and the impact of shield movement on the ground surface and above the tunnel has been measured as soil displacement. In total, 410 measurements resulting from the interaction between soil and the tunnel have been recorded, which are exhibited as displacement on the surface. Furthermore, to achieve greater accuracy and validate the displacement levels, groundsettlement has also been determined using FLAC3D software. Using FLAC3D software, the stress state in the environment and longitudinal groundsettlement have been determined. The amount of groundsettlement has been measured using empirical-analytical relationships, and the results obtained from modeling and empirical relationships have been compared. The highest amount of settlement resulting from modeling with PLAXIS 3D Tunnel occurred at the end of the segmenting phase, with a value of 38.38 millimeters. The highest amount of settlement in FLAC3D software is 37.84 millimeters. The results from empirical and analytical relationships closely match the modeling results, with the error percentage in various methods calculated and determined in the end.

Keywords: EPB, GroundSettlement, PLAXIS 3D Tunnel, FLAC3D, Soil and Drilling Machine Interaction.

1. INTRODUCTION

Nowadays, there are three methods for determining the extent of groundsettlement including empirical, analytical and numerical methods. Among these methods, empirical and analytical approaches do not take into account the progressive stages of tunneling and fail to specify 3D displacement. This research employs the PLAXIS 3D Tunnel software to investigate and quantify the settlement and displacement resulting from EPB shield tunneling along the east-to-west segment of Tehran Metro Line 7, located at kilometer 650+11 on Helal Ahmar Street, before the Navab-Qazvin intersection. Furthermore, FLAC3D software is utilized to validate results and achieve accuracy in determining the extent of settlement. In this investigation, the interaction between soil and tunnel drilling machine was measured, considering its most significant impact on the ground surface and above the tunnel. The model used in this study has dimensions of 50×50×80 meters, designed as close to real-world conditions as possible.

Eight phases were considered for modeling: three for drilling, one for injection, and the rest for segmenting. In each phase, the effect of shield movement on the soil was represented by vertical displacements, resulting in 410 displacement cases within ten plates in the model. Maximum settlement was calculated using empirical and analytical formulas. The empirical Pek (1969) method and analytical equations of Loganathan and Bobet were utilized to determine the maximum settlement.

2. Defining the Problem

Regarding groundsettlement due to metro tunnelling in urban areas, by studying and utilizing PLAXIS3D TUNNEL software, an attempt has been made to demonstrate what parameters and to what extent can influence settlement, which ones are important and which ones are irrelevant or insignificant. Additionally, FLAC3D software has been utilized for validation and to obtain more precise results. How soil and tunnel interact during mechanized full-face tunnel drilling stages? What is the behavior and interaction of soil and structures in underground spaces? How does soil and full-face tunnel drilling interaction impact groundsettlement? And what are the maximum displacement values?

3. Previous Studies

Groundsettlement evaluation methods are classified into three groups including empirical, analytical, and numerical.

Table 1. Prediction methods for settlement caused by tunnelling.

No.	Method	Year of appearance	Method type	Advantages	Problems
1	Pek	1969	Empirical	Easy to use, requires few parameters	Not considering water pressure and surface loads
2	Attwell and Farmer	1974	Empirical	Easy to use, requires few parameters	Not considering pressure applied to the benchface
3	Atkinson and Potts	1977	Empirical	Easy to use, requires few parameters	Not considering the inhomogeneity of the environment
4	Ottaway	1979	Empirical-Analytical	Easy to use, requires few parameters	Not considering water pressure and inhomogeneity of the environment
5	O'reilly and New	1982	Empirical	Easy to use, requires few parameters	Not considering pressure applied to the benchface
6	Meyer	1983	Empirical	Easy to use, requires few parameters	Not considering water pressure and surface loads
7	Sagaseta	1987	Analytical	Considering ovality phenomenon	Not considering the inhomogeneity of the environment
8	Verojit and Booker	1996	Analytical	Considering radial displacement and ovality	Not considering surface loads
9	Loganathan and Poulos	1998	Analytical	Using Gap parameter	Not considering the inhomogeneity of the environment
10	Bobet	2001	Analytical	Considering the drilling environment and water pressure	Limited to tunnels with proportions >1/5 H/R
11	Park	2004	Analytical-Numerical	Considering the drilling depth	Limited to undrained conditions

4. Volume Loss

During drilling, an unmaintained ground or a ground that is partially maintained beside the tunnel, causes stress release by moving toward the tunnel. Therefore, it will be necessary to drill a greater volume of soil than theoretically required. This additional volume drilled is referred to as volume loss or land loss and is described in terms of the length of drilling progress (i.e., cubic meters per meter of progress). In other words, the cross-sectional area divided by the land loss multiplied by 100 is a term commonly used for VL. Displacement size leading to loss of volume is a function of soil type, tunneling progress, tunnel diameter, drilling technique, shape and strength of the initial and temporary retainer. In mechanized tunneling conditions, distinct factors which contribute to volume loss include:

1. Reduction of pressure in the tunnel’s benchface, remove the rotating cutters of the material shield from benchface. During this continuous process, the face ground protrudes in the impacted front area and the drilling face’s surrounding area, leading to face loss.
2. Tunnel drilling slightly larger than the main section in front of the shield, for facilitating shield progress. At least two results are obtained from the slight over-drilling beside the shield: firstly, production of cutterheads with slightly larger diameters to reduce the likelihood of the shield getting stuck, and secondly, over-drilling in the face of the

shield, facilitates shield navigation for turning around bolts or even directing it towards the desired path. After the passing tabs, the ground has the opportunity to move radially inward.

3. Depending on the rate of soil deformation compared to the progress rate, the drilling environment may come very close to the shield within the shield's range.
4. Lining, slightly smaller in diameter than the shield, is installed inside the shield, and the space between the lining and the ground is immediately filled (usually with grout injection). Consequently, another opportunity arises for the ground to converge towards the lining. This process continues until the void is sufficiently filled with grout and firmly set to withstand ground pressure.

In mechanized tunneling, if the tunnel face is properly pressurized, the face loss is greatly limited, and radial loss can easily be controlled by sufficient grout injection with proper pressure and precise design of grout composition, through injection lines that are continuously maintained and repaired to prevent grout lines from clogging. In most ground, the surface settlement volume (V_S) will be approximately equal to the volume loss (V_L) at the tunnel depth. According to Cording et al. (1975) [25], in tunneling under drained conditions such as in dense sands, V_S is generally less than V_L due to dilation. The extent of volume loss or decrease, V_L, basically depends on the type of soil and tunneling method. Recent experiences in mechanized tunneling with closed-face tunneling generally indicate that settlement can be well controlled in sands and gravels, resulting in minimal volume loss (typically less than 5% of V_L). However, in soft clays, regardless of long-term settlement, the volume loss will range between 1 to 2 percent.

5. General Equations of Surface Settlement

Longitudinal settlement along the tunnel axis. General equation of surface settlement for drilling tunnels in a homogenic environment is (extended equation for surface settlement, Atwell and Woodman, 1982 [25]):

$$.S = \frac{V_S}{(\sqrt{2\pi}).i} . e^{\left(-\frac{y^2}{2i^2}\right)} . \left\{ G\left[\frac{X - X_i}{i}\right] - G\left[\frac{X - X_F}{i}\right] \right\}$$

Where S denotes the surface orthogonal settlement in (x, y) position, Y,[m] denotes the distance of the assumed point and the tunnel axis, X,[m] denotes the longitudinal position of the assumed surface point, V_S,[m] denotes the settlement volume for each meter of tunnel progress, [m^3/m] is defined as a percentage of V_L, X_i denotes the initial position or the beginning section of the tunnel, X_F,[m] denotes the position of the tunnel face, [m] is the pit width stated as $i=kz_0$, where k is a dimensionless constant depending on soil type, and z_0 is the depth of tunnel axis beneath the surface.

G is a function defined as:

$$G(\alpha) = \frac{1}{\sqrt{2\pi}} . \int_{-\infty}^{\alpha} e^{-\frac{\alpha^2}{2}} dx$$

If G(0) = 0.5 then $\alpha = (x-x_i)/i$ where $x=x_f$ (upper point of tunnel's face),

G(1) = 1 where $(x-x_i)$ ➔

G is calculated for different values of $(x-x_i)/i$ and it is available in a table. The parameters V_S and K depend on the soil type and ground conditions, while other parameters are geometric. There are two ways to select these parameters: the first is to use empirical relationships, and the second is to use numerical analysis. In the depths between the tunnel crown and the ground surface, the settlement has a similar shape, but the values of i and S_{max} will change with depth z. In conditions where the ground consists of both cohesive and non-cohesive materials, the ground displacement section follows the sequence of these layers. On the other hand, it can be imagined that the shallower the tunnel, the more important the surrounding layers will play in controlling ground loss and transferring settlement to the surface. If the environment is not homogeneous and has layering, an equivalent K is used, which is calculated from the following equation [25]:

$$k_{eq} = \frac{((1-\lambda).(z_1k_1 + z_2k_2 + \cdots + z_mk_m) + \lambda.(z_{m+1}k_{m+1} + \cdots + z_nk_n))}{((1-\lambda).(z_1 + z_2 + \cdots + z_m) + \lambda.(z_{m+1} + \cdots + z_n))}$$

In this equation, the λ coefficient is considered above 50% for layers close to the tunnel (up to a distance of 1.5D from tunnel axis). The shallower the tunnel, the more important the surrounding layers will play in controlling ground loss and transferring settlement to the surface. The value of λ is generally considered at least 50% and at most 65%.

6. Settlement in Cross-Section Between the Initial Section and the Drilling Face

The magnitude of settlement in a cross-section which is far enough from the initial section and before the drilling face can be obtained using the general settlement equation. Thus, if $(x-x_i)/i > 3$ and $(x-x_F)/i < 3$, then:

$G[(x-x_F)/i] = 0$ and $G[(x-x_i)/i] = 1$

For a cross-section which is far enough from the initial section and distant enough before the drilling face, settlement is considered at its final amount and it can be calculated by:

$$S = S_{max}.\exp\left(-\frac{y^2}{2i^2}\right) = \frac{V_L}{i.\sqrt{2\pi}}.\exp\left(-\frac{y^2}{2i^2}\right)$$

The practical range of settlement impact is at 2.5i distance from the tunnel axis.

In general, the surface settlement caused by tunnel drilling can be effectively described as a Gaussian distribution curve with the equation below:

$S_v = S_{max} \exp(-y^2/2i^2)$

where S_v denotes the settlement, S_{max} denotes the maximum settlement on the tunnel axis, y is the horizontal distance from the tunnel axis, and i is the horizontal distance from the turning point of the settlement curve to the tunnel axis. At the location of i, about 60% of the maximum settlement occurs, so the volume of the created depression is calculated by integrating the equation as follows:

$V_s = (2\pi)0.5iS_{max}$

In saturated clay soils, considering the undrained conditions and constant volume, the volume decrease in the soil is usually equal to the volume of the settlement depth. However, in sandy soils under drained conditions, especially in dense sands, due to the phenomenon of dilation and the increase in soil volume, the volume of the settlement depth will be less than the volume decrease.

7. Settlement on Longitudinal Section Along the Tunnel Axis

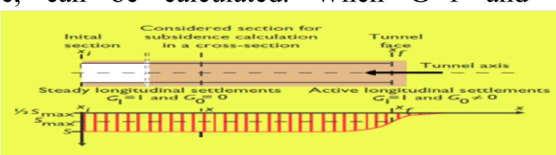
The surface settlement equation along the axis is as follows:

$$S = \frac{V_L}{(\sqrt{2\pi}).i}.\left\{G\left[\frac{X - X_i}{i}\right] - G\left[\frac{X - X_F}{i}\right]\right\} = S_{max}.(G_1 - G_2)$$

Based on the equation above, the settlement in front of the tunnel face will be about 50% of the total settlement, which is typical in traditional tunneling. Therefore, the empirical method will only be used to calculate the final settlement at sections far from the start section and the drilling face. The equation provided by Attewell and Woodman in 1982 for calculating the settlement depression along the tunnel axis, considering y=0, is as follows:

$$S = \frac{V_s}{(\sqrt{2\pi}).i}.\left\{G\left[\frac{X - X_i}{i}\right] - G\left[\frac{X - X_F}{i}\right]\right\} = S_{max}.(G_1 - G_2)$$

If the tunnel starts at X_i and the tunnel face is located at X_f, then the orthogonal displacement for various points located in front of ($X>X_f$) or behind ($X<X_f$) the face, can be calculated. When G=1 and G≠0,



longitudinal displacement is a percentage of S_{max}, where G_1-G_2<1.

Figure 1. Settlement depression along the longitudinal axis

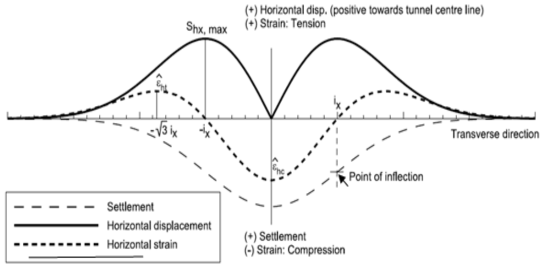


Figure 2. Horizontal displacements and strains

Horizontal displacements and strains: To predict horizontal surface displacements induced by tunneling, O'Reilly and New (1982) [25] proposed the following equations under the assumption that the movement vectors near the ground surface are oriented towards the tunnel axis:

$$S_h = \left(\frac{y}{z_0 - z}\right) S_y \text{ یا } S_h = \left(\frac{y}{z_0}\right) S_y$$

For the region beneath the surface, the horizontal strain on the surface is obtained by calculating the derivative of S_h:

$$\varepsilon_h = \frac{dS_H}{d_y} = \frac{S_{max}}{Z_0}.\left(1 - \frac{y^2}{i^2}\right).e^{\left(-\frac{y^2}{2i^2}\right)}$$

The maximum horizontal displacement occurs at the turning point, where horizontal strains reach their maximum at y = 0 (compression) and y = √3i (tension).

8. Longitudinal GroundSettlement Caused by Tunnel Drilling and Soi-Machinery Interaction

In 1986, Atwell [25] proposed a theory stating that fifty percent of the total settlement in tunnelling occurs in front of the tunnel face. Meyer and Taylor [10], in 1997, suggested that the deformation of the ground surrounding underground spaces due to tunnel drilling with closed shields, is caused by the following factors, which result in stress redistribution in this area and ultimately lead to ground settlement: a) Movement of the ground towards the face due to stress release. b) Radial movement of the ground towards and along the shield due to its conical shape. c) Radial movement of the ground towards the drilled space behind the shield due to the presence of space between the shield and reinforced surface. d) Radial movement of the ground towards the reinforced surface and consequently its deformation.

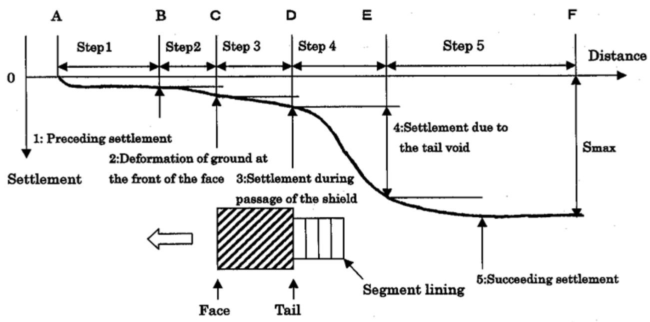


Figure 3. Settlement in mechanized tunneling with shield-Longitudinal settlement due to movement of the shield in the tunnel.

9. PLAXIS 3D TUNNEL Software

PLAXIS 3D TUNNEL is a 3D finite element software which is utilized to analyze deformations and investigate stability of various types of tunnels in rocks and other materials [1]. The simple graphical input method enables users to quickly generate complex finite element models, and the software output displays the computational results in details. This program performs calculations entirely automatically and is based on powerful numerical methods. Although it offers specific options for shield and Austrian tunneling methods, it also has the capability to model other types of tunnels and geotechnical issues.

10. FLAC3D Software

FLAC is an explicit finite difference software capable of modeling the behavior of soil, rock, and other materials that may undergo plastic flow when reaching their yield limit. Materials are represented by elements or zones forming a mesh, allowing users to create the desired structure to be modeled using this mesh. Each element behaves according to predefined linear or nonlinear stress-strain laws and responds to loads or boundary conditions.

11. Case Study

The Tehran Metro Line 7 starts from Amiralmomenin Town in the east of Tehran, and after passing through Basij Highway, extending along Shahid Mahallati Highway, connecting to Qiam Square, extending along Molavi and Helal Ahmar Streets, and connecting to Shahid Navab Safavi Highway, its route changes to north-south direction along the Navab Highway. After intercepting Jalal Al Ahmad Highway, its route extends along Nasr Street until reaching Kaj Square.

12. Separating and Describing Engineering Geology Units

The soil layers along the tunnel route have been classified into six engineering geological units [17]: a) Engineering Geological Unit ET-1: This soil unit consists of gravel sand and, in some areas, sand gravel. b) Engineering Geological Unit ET-2: Similar to unit ET-1, this soil unit is categorized as coarse-grained soils and consists of gravel sand along with silt and clay. c) Engineering Geological Unit ET-3: This unit comprises sandy clay with gravel, and sandy clay and silt. d) Engineering Geological Unit ET-4: Considered as coarse-grained soils, this unit is composed of sandy clay with gravel. e) Engineering Geological Unit ET-5: The particles forming this soil unit consist of silt, clay and sand. f) Engineering Geological Unit ET-6: The particles in this unit are primarily composed of sandy silt.

13. Modeling with PLAXIS 3D TUNNEL Software

Base Model: Due to symmetry, the model only covers one half of the tunnel. The tunnel overburden extends 21.6 meters from its crown, and the groundwater table is located above the tunnel crown. The model dimensions are 50×50×80 (width × depth × length). The dimensions are chosen to minimize the influence of unrealistic boundary conditions. The tunnel drilling process is modeled with drilling stages. Interface elements are used to model the interaction between the drilling machine and the soil. Standard clamping boundary conditions are applied at the model base, rollers are placed at the vertical sides of the model, and rotational clamping is considered at the tunnel end. As mentioned, interface elements are used to model the interaction between the soil materials and the tunnel covering.

The specifications of these elements are modeled using the Rinter parameter as a proportion of the specifications of the main materials, such that:

$\tan \varphi_{inter} = R_{inter} . \tan \varphi_{soil}$ & $c_{inter} = R_{inter} . c_{soil}$

By qualitatively determining the size of the meshes, the meshing of the environment is performed automatically by the software. In this analysis, a combination of medium-sized meshes around the tunnels and larger meshes with increasing distance from them is used. Volume elements with 15 nodes are used for meshing. Considering the 10-meter length of the shield, a thickness of 3 meters is assumed for the advancing sections, and the stages include 3 drilling and advancing stages, one grouting injection stage, and the four segment installations, comprising a total of 47 stages. In other words, each stage consists of several steps, for example the first stage of 3-meter drilling consists of 4 steps, and the total number 47 stages also include these steps. Phase 1 of modeling consists of 4 steps, phase 2 consists of 3 steps, phase 3 consists of 3 steps, phase 4 which is the grouting stage consists of 5 steps, phase 5 which is the first segment installation stage by the tunnel drilling machine consists of 6 steps, phase 6 which is the second segment installation stage (installation of row 2) consists of 8 steps, phase 7 which consists of the third segment installation stage consists of 8 steps, and phase 8 which is the fourth segment installation stage in the modeling, consists of 4 steps. In general, all points considered in the modeling play a role, and the displacement of these points is determined by the software.

14. Initiating the Drilling and Modeling in the Software

Considering the 1.9-centimeter space between the shield and the drilling section in the modeling (internal drilling diameter is 9.164 meters and external shield diameter is 9.126 meters), it has been modeled as a contraction equal to 0.9% of tunnel's surface area. Contraction is equal to (area of drilling section – area of shield's drilling section) divided by (area of drilling section), (i.e., $(A_{exc}-A_{shield})/A_{exc}$). Injection pressure at the tunnel's crown is equal to (face pressure + 50 kPa), and its increase is considered to be the same amount as the grout weight (12 KN/m^3). The first stage has been the modeling stage, and a 3-meter advance has been carried out in this stage using TBM. After the 3-meter advance, using the drilling machine, the settlement amount at the face has been determined. The maximum settlement at the face is 0.002223 meters.

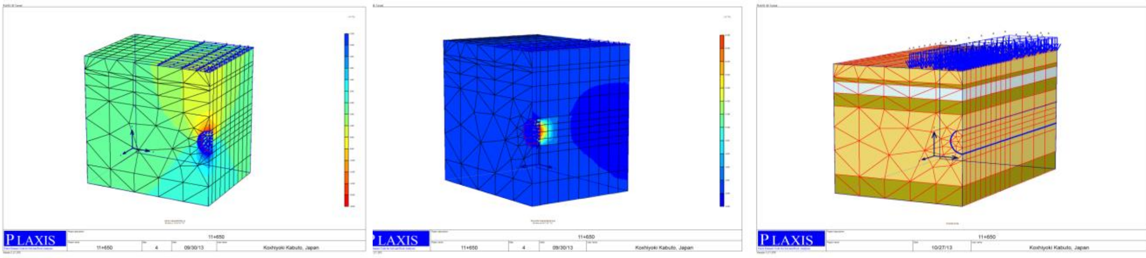


Figure 4. Drilling initiation and introduction of stress into the model created by PLAXIS

In the figure above, the displacement of 0.002217 meters is shown in front of the tunnel drilling face. Displacements in front of the tunnel face are up to three times the length of the drilled tunnel in the ground. In phase five of the modeling, after the injection process, the installation of a row of segments is carried out. In the image below, the injection process is depicted by forces (indicated by arrows) applied to the tunnel wall (applying load to the wall). In the injection phase, the displacement of all points is measured. At this stage, a total of 50 displacement values for the injection phase are considered for points and surfaces in the modeling, and the output is from the software.

In this stage, the software performs the loading operation on the ground, and with the grouting injection, the empty space between the drilling space and the segment section is filled to reduce the amount of ground surface settlement and minimize displacement. In this stage, the maximum displacement is related to point A, with a displacement of 0.02387 meters.

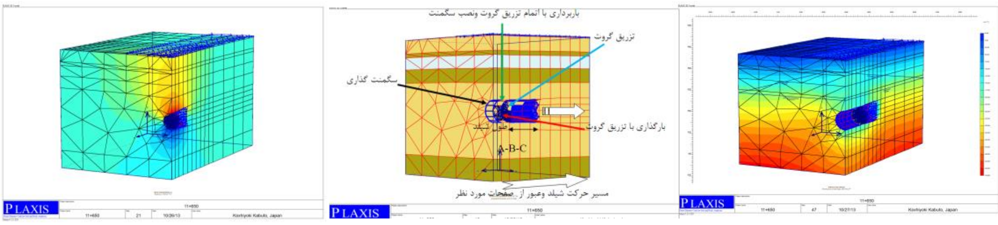


Figure 5. Impact of drilling, grout injection, and installation of segments after grout injection

In the fifth phase of the modeling, after injection operation and installation of one row of segments, the displacement is equal to 0.02334 meters. In the sixth phase of the modeling, the installation of the second row of segments is carried out. In this stage, the maximum displacement is again related to point A. The highest displacement occurs at the top of the tunnel during construction, especially at the end of the tunnel and from injection to segment installation. In the eighth phase of the modeling, the fourth row of segments is installed in the tunnel. In the eighth phase, the maximum displacement is related to point A, and the minimum displacement is related to points I and J. In the first step of the eighth phase, the maximum displacement was 0.03854 meters, which gradually decreased to 0.03838 meters as this phase was completed by the software. The highest amount of loss and displacement is related to the shield's end, which is in fact the grouting and lining positions. The highest stresses and deformations occur above the segments, which are installed immediately after drilling.

Table 2. Considered phases, related planes and work cycles

No.	Point	Plane	Distance from planes	Machine position
1	A	Initial point	0.000	---------
2	B	Plane A	3/000	Phase 1
3	C	Plane B	6/000	Phase 2
4	D	Plane C	10/000	Phase 3
5	E	Plane D	14/000	Injection
6	F	Plane E	18/000	Segment 1
7	G	Plane F	22/000	Segment 2
8	H	Plane G	26/000	Segment 3
9	I	Plane H	30/000	Segment 4
10	J	Plane I	34/000	---------

Table 3. Considered phases and different drilling stages

No.	Considered work conditions	Machine condition	Drilling stages
1	TBM D1 – stage one of machine entrance	Entering of 3 meters of the machine into the ground	Phase 1
2	TBM D2 – stage two of machine entrance	Entering of 6 meters of the machine into the ground	Phase 2
3	TBM D3 – stage two of machine entrance	Entering of 10 meters of the machine into the ground	Phase 3
4	GROUT – Grout injection	Drilling and grout injection	Phase 4
5	Seg ins.1 – segment installation, row one	Drilling+injection, tunnel+ring installation	Phase 5
6	Seg ins.1 – segment installation, row two	Drilling+injection, tunnel+ring installation	Phase 6
7	Seg ins.1 – segment installation, row three	Drilling+injection, tunnel+ring installation	Phase 7

The highest amount of settlement has taken place in point A with a settlement magnitude of 0.03838 meters (38.38 millimeters).

Table 4. Maximum and minimum of settlement (m), various points in various phases after completion of modeling stages.

No.	Drilling stages	A	B	C	D	E	F	G	H	I	J
1	Phase 1-minimum	0.00309	0.00303	0.00228	0.00259	0.00224	0.00186	0.00149	0.00116	0.00088	0/00066
2	Phase 1-maximum	0.00596	0.00586	0.00558	0.00499	0.00427	0.00351	0.00278	0.00215	0.00162	0.00120
3	Phase 2-minimum	0.00789	0.00776	0.00738	0.00658	0.00559	0.00456	0.00359	0.00276	0.00206	0.00159
4	Phase 2-maximum	0.01184	0.01165	0.01110	0.00995	0.00489	0.00696	0.00552	0.00427	0.00322	0.00240
5	Phase 3-minimum	0.01363	0.01342	0.01280	0.01150	0.00984	0.00810	0.00645	0.00501	0.00380	0.00283
6	Phase 3maximum	0.01600	0.01576	0.01506	0.01356	0.01165	0.00962	0.00769	0.00600	0.00457	0.00341
7	Phase 4-minimum	0.01915	0.01888	0.01809	0.01637	0.01415	0.01174	0.00943	0.00738	0.00563	0.00421
8	Phase 4-maximum	0.02387	0.02356	0.02266	0.02066	0.01802	0.01507	0.01217	0.00958	0.00735	0.00551
9	Phase 5-minimum	0.02532	0.02502	0.02411	0.02209	0.01938	0.01631	0.01324	0.01046	0.00805	0.0606
10	Phase 5-maximum	0.02944	0.02915	0.02827	0.02622	0.02337	0.02000	0.01647	0.01316	0.01022	0.00776
11	Phase 6-minimum	0.02989	0.02953	0.02865	0.02661	0.02374	0.02035	0.01678	0.01341	0.01043	0.00793

12	Phase 6-maximum	0.03445	0.03422	0.03349	0.03169	0.02898	0.02551	0.02161	0.01767	0.01399	0.01079
13	Phase 7-minimum	0.03450	0.03427	0.03353	0.03174	0.02903	0.02557	0.02167	0.01772	0.01403	0.01082
14	Phase 7-maximum	0.03831	0.03813	0.03754	0.03603	0.03360	0.03025	0.02498	0.02189	0.01757	0.01365
15	Phase 8-minimum	0.03854	0.03837	0.03780	0.03631	0.03389	0.03056	0.02565	0.02216	0.01780	0.01383
16	Phase 8-maximum	0.03838	0.03822	0.03768	0.03629	0.03403	0.03093	0.02589	0.02310	0.01894	0.01505

Table 4 presents the results of modeling with Plaxis 3D software, according to which, with completion of the drilling and segment installation stages, the maximum ground settlement is at point A with a value of 0.03838 meters. The highest settlement occurs after the passage of the fully mechanized tunnel drilling machine and after the installation of the segments. The increase in settlement at this stage (from phase 3 to phase 4) is approximately 3 millimeters, which is actually a sudden drop. The main reason for the increase in settlement at that point is due to the gap between the drilled space and the space where the segments are installed.

15. Modeling with FLAC3D software

FLAC software has been used to validate and generate more accurate results.

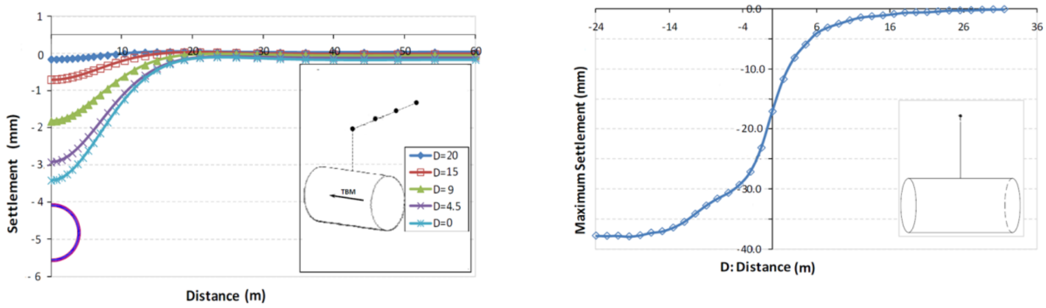


Figure 6. Longitudinal and lateral settlement of a point located on the center of the tunnel in FLAC modeling.

The amount of settlement at the end of the drilling stage is approximately 35 millimeters, which has been expressed in the software output as a graph. At distance D = 0, the maximum settlement is 45.34 millimeters, at D = 0.4, the maximum settlement is 58.29 millimeters, at D = 0.9, the maximum settlement is 69.19 millimeters, at D = 1.5, the maximum settlement is 11.7 millimeters, at D = 2.0, the maximum settlement is 43.1 millimeters. The maximum ground settlement is obtained at the top of the tunnel axis and gradually decreases. At a distance of 20 meters from the tunnel, the settlement amount approaches zero at the ground surface.

Table 5. Maximum settlement amount in various points (mm)

No.	Point	A	B	C	D	E	F	G	H	I	J
1	The Amount of Settlement (mm)	37.84 *	37.43 -	37.08 -	35.78 -	31.89 *	29.45 -	23.56 -	20.00 -	14.21 -	11.89 *

The maximum settlement has been obtained as 37.84 mm according to modeling with FLAC3D software.

16. Calculation Methods (Empirical-Analytical)

Lateral settlement using empirical and empirical-analytical method: The calculation of final settlement will be carried out for lateral sections which are far enough from the starting section and distant enough from the drilling face, using the mentioned equations.

Table 6. Maximum and minimum amounts of k for geological layers along the tunnel path.

No.	Geological Unit	k_{max}	k_{min}
1	ET-1	0.40	0.35
2	ET-2	0.45	0.40
3	ET-3	0.50	0.45
4	ET-4	0.45	0.40
5	ET-5	0.50	0.45
6	ET-6	0.35	0.30

Table 7. Maximum and minimum amounts of k according to layering.

No.	Z_0	$K_{i(min)}$	$K_{i(max)}$
1	21.6	0.45	0.5
2	16.6	0.45	0.5
3	14.6	0.45	0.4
4	10.1	0.45	0.5
5	6.5	0.45	0.5

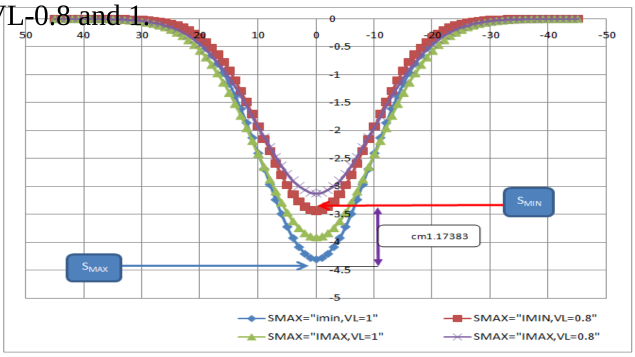
Table 8. Settlement amounts obtained by empirical calculations (Pek).

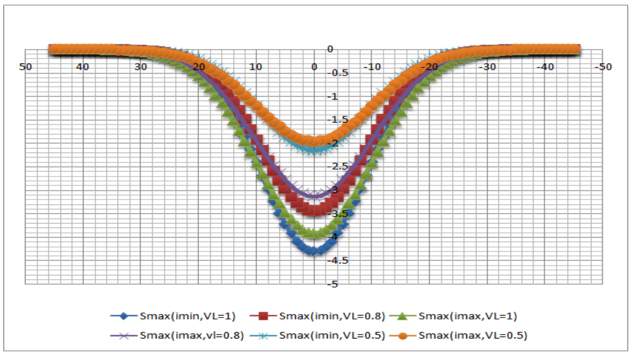
No.	i value	$V_L$value	Maximum settlement (cm)
1	9.265590778i_{min}	1V_L	-4.30563
2	9.265590778i_{min}	0.8V_L	-3.44451
3	10.19083507i_{max}	1V_L	-3.91472
4	10.19083507i_{max}	0.8V_L	-3.13177

Table 9. Settlement amounts obtained by empirical lateral settlement calculations (Pek)

No.	i value	$V_L$value	Maximum settlement (cm)
1	9.265590778i_{min}	1V_L	-4.30563
2	9.265590778i_{min}	0.8V_L	-3.44451
3	10.19083507i_{max}	1V_L	-3.91472
4	10.19083507i_{max}	0.8V_L	-3.13177
5	9.265590778i_{min}	0.5V_L	-2.152816
6	10.19083507i_{max}	0.5V_L	-1.95736

Table 7. Difference between maximum and minimum settlement in tunnel's cross-section, considering VL-0.8 and 1.





Prediction of settlement using Loganathan and Polous method is carried out via the equation below:

$$U_{Z=0} = \varepsilon_0 R^2 . \frac{4H(1-\vartheta)}{H^2+X^2} . exp\left\{-\frac{1.38x^2}{(Hcot\beta+R)^2}\right\}$$

Where ε_0 is the corresponding land loss which is $\varepsilon_0 = ((4\times R\times g) + (g^2)/4\times R^2)$. In this equation, R denotes the tunnel radius, g is the physical gap parameter, and H represents the ground depth from the tunnel. Thegap parameter can be expressed as $g = GP + U_{3D} + \omega$, where G_P denotes the physical gap representing the geometric distance between the outer shield shell and the lining, U_{3D} denotes the 3D elastoplastic deformation in the tunnel face, and ω is a factor considering the skill level of the workers. The maximum surface settlement using the Loganathan and Polous method is 0.03852 meters.

Settlement prediction using the Bobet method: Bobet's analytical method was proposed in 2001 [21]. It is used to investigate settlement and ground deformations caused by tunnel drilling in shallow areas and saturated environments. This method is utilized in areas where the depth-to-radius ratio is above 1.5. The maximum ground settlement using the Bobet method in this section is 0.04650 meters (δ_{MAX} = 0.04650).

Table 10. Settlement values obtained by empirical and analytical calculations.

No	i value	valueV_L	Pek (modified by Atwell and Woodman) Maximum settlement (cm)	Loganathan and Polous (cm)	Bobet (cm)
1	9.2655i_{min}	1V_L	-4.30563	-3.852	-4.650
2	9.2655i_{min}	0.8V_L	-3.44451		
3	10.1908i_{max}	1V_L	-3.91472		
4	10.1908i_{max}	0.8V_L	-3.13177		
5	9.2655i_{min}	0.5V_L	-2.152816	------	------
6	10.1908i_{max}	0.5V_L	-1.95736	------	------

Horizontal surface displacements: Since horizontal displacements are assumed symmetrical in both sides of the y-axis in Atwell and Woodman equation [25], we consider this diagram as symmetrical as well.

Horizontal strains: Horizontal strain in the surface is obtained by deriving S_h, while considering i maximums and minimums and V_L = 1, 0.8 and 0.5.

Table 11. Horizontal displacements obtained by empirical calculations

No.	i value	valueV_L	S_h (Horizontal displacement) (m)
1	9.265590778i_{min}	1V_L	0.0926322

2	9.265590778i_{min}	0.8V_L	0.0741058
3	10.19083507i_{max}	1V_L	0.0913984
4	10.19083507i_{max}	0.8V_L	0.0731188
5	9.265590778i_{min}	0.5V_L	0.0463161
6	10.19083507i_{max}	0.5V_L	0.0456992

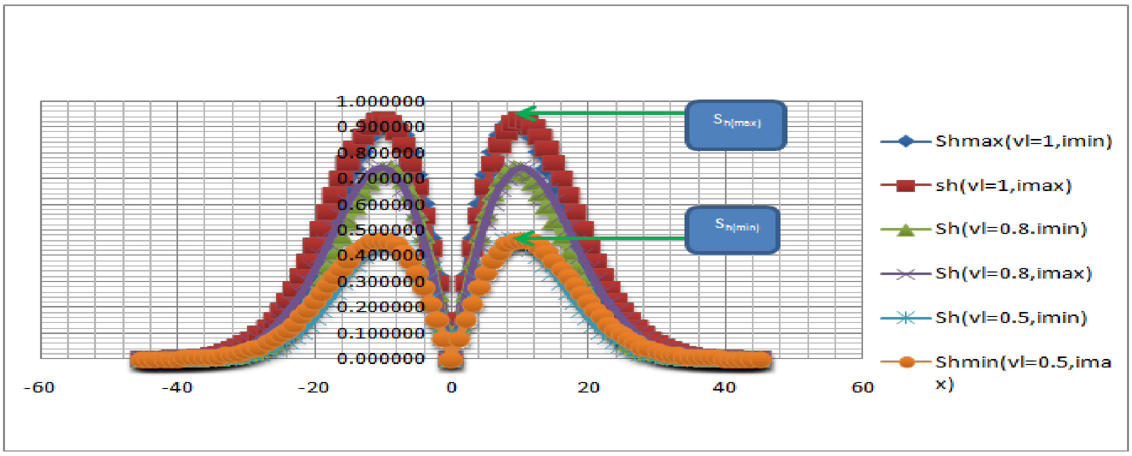


Figure 8. Horizontal surface displacements due to tunneling along the lateral section of the tunnel.

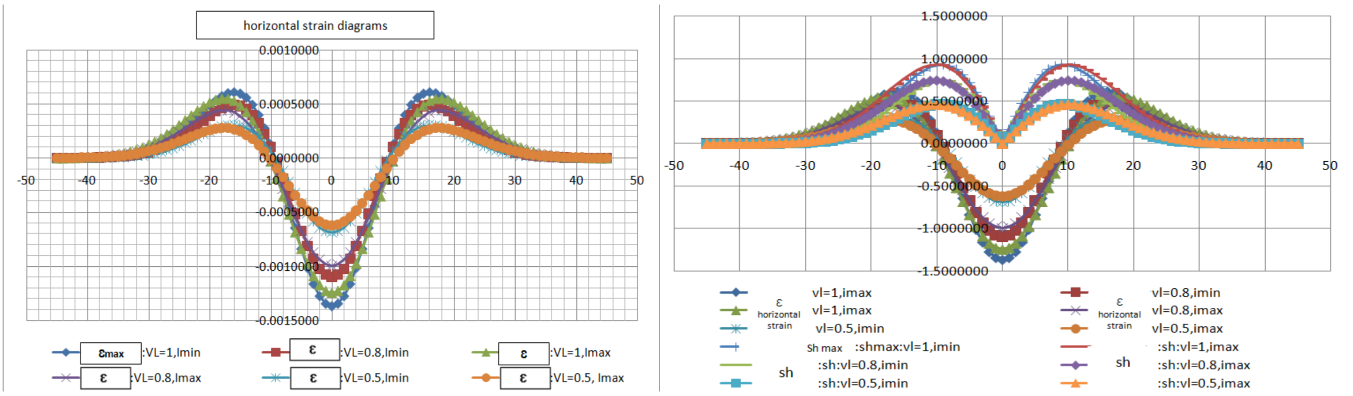


Figure 9. Horizontal strain due to tunneling along the lateral section of the tunnel in six states – and maximum and minimum horizontal strain diagrams.

17. Assessment of Results

Table 12. Comparing the results of numerical-analytical and empirical methods.

No.	valuei	V_L value	Pek (modified by Atwell and Woodman) Maximum settlement (cm)	Loganathan and Polous (cm)	Bobet (cm)	Modeling with PLAXIS software (cm)	Modeling with FLAC3D software (cm)
1	9.2655i_{min}	1V_L	-4.30563	-3.852 Without using I and V_L	-4.650 Without using I and V_L	-3.838 Without using I and V_L	3.784 Without using I and V_L
2	9.2655i_{min}	0.8V_L	-3.44451				
3	10.1908i_{max}	1V_L	-3.91472				
4	10.1908i_{max}	0.8V_L	-3.13177				
5	9.2655i_{min}	0.5V_L	-2.152816	------	------	------	-------
6	10.1908i_{max}	0.5V_L	-1.95736	------	------	------	-------

Table 13. Comparing settlement magnitude with instrumentation.

Results obtained by different methods		Instrumentation results	Error percentage
Modeling by PLAXIS3D TUNNEL	38.38	34.45	10.23
Modeling by FLAC3D	37.84	34.45	10.01
Loganathan and Polous method	38.52	34.45	10.56
Bobet method	46.50	34.45	25.91

Pek empirical method	i_{min}	34.45	43.05	34.45	19.97
	i_{min}	34.45	34.44	34.45	0.02
	i_{max}	34.45	39.14	34.45	11.98
	i_{max}	34.45	31.31	34.45	****

Figure 14. Maximum horizontal strain in various planes within modeling.

No.	Considered planes	Maximum horizontal strain (m)	No.	Considered planes	Maximum horizontal strain (m)
1	Front plane	$114.42*10^{-5}$	7	F	$79.66*10^{-5}$
2	A	$113.26*10^{-5}$	8	G	$67.7*10^{-5}$
3	B	$111.78*10^{-5}$	9	H	$55.54*10^{-5}$
4	C	$105.61*10^{-5}$	10	I	$43.0*10^{-5}$
5	D	$98.96*10^{-5}$	11	J	$32.64*10^{-5}$
6	E	$90.32*10^{-5}$			

CONCLUSION

1. The maximum settlement occurs after the passage of the shield and during the installation of segments.
2. The injection of grout into the ground settlement has caused an increase in the slope of the settlement curve.
3. The settlement amount at the tunnel face is not completely consistent with Nomoto et al., and it also confirms this theory. Because based on modeling and calculations performed, the settlement amount has been obtained as 31% to 47%, which seems reasonable and justifiable considering the geological conditions, soil layering, and the characteristics of the drilling equipment.
4. It has been proven in this study that the settlement in front of the tunnel face is less than 50%, while it has been ranging between 31% to 43% in experimental and numerical-analytical modeling and calculations.
5. Based on the empirical relationship of Peck, the influence of V_L and i values on settlement has been investigated. For V_L=1 and minimum i, the highest settlement is obtained (5.43 mm).
   For V_L=1 and maximum i, the settlement is 14.39 which is close to the modeled values (38.38 mm in PLAXIS and 84.37mm in FLAC). The settlement results from modeling differ by approximately 1.5mm from both empirical and analytical equations (Loganathan and Peck).
6. Due to the varying layering of the considered cross-section, the equation provided by Selbye has been used to calculate the value of i which is approximately equal to the average of the relationships proposed by researchers for determining i. Also, considering the influence of soil layering on determining values for settlement calculation has led to better results.
7. In determining the settlement based on the empirical Peck relationship, the effect of V_L and i has also been investigated. This leads to considering different aspects in predicting the settlement. V_L=1 represents normal tunneling conditions, V_L=0.5 represents good conditions (good ground conditions and pressure control, and excellent tunneling conditions in all aspects), and V_L=0.8 represents in-between conditions, considering their closeness to normal tunneling conditions.
   For V_L=1 and i_{min}, maximum settlement has been obtained (4.3056 cm), and for V_L=0.5 and i_{max}, minimum settlement (4.9753 cm) has been achieved. However, the result closest to the modeling results is obtained for V_L=1 and i_{max}, where the maximum settlement is 3.9147 cm.
8. The difference in settlement between the minimum and maximum settlement amounts in the empirical method is approximately 2.3482 cm for input values (V_L and i), which is a relatively large number. It seems necessary to use different values of V_L (especially 1 and 0.8) in calculations to achieve conditions close to reality and to conduct more accurate assessments.
9. The maximum horizontal displacement due to tunneling and horizontal strain is associated with V_L=1 and i_{min}, and the minimum value is associated with V_L=0.5 and i_{max}.
10. The minimum induced horizontal displacement due to tunneling with shield, takes place on top of the tunnel's center, and it is equal to 0 in calculations. Also, maximum horizontal surface displacement is orthogonal to i_{min}(turning point). Moreover, the maximum strain value (in tensile conditions) is orthogonal to $\sqrt{3}i$.
11. Considering the results of numerical and empirical-analytical methods, relying only on empirical or numerical methods for analysis and obtaining results is insufficient, and both of them must be utilized in analysis simultaneously. This is because in empirical and analytical methods, calculations are made using some geological parameters and mathematical constants, without practically considering real-life drilling scenarios. In

numerical methods, real-life conditions are not modeled completely. For example, the presence of regional sewers at a point, operation type of machinery, personnel, etc., are factors which are not considered in modeling. Also, considering the complexity and variability of working conditions, the input data can be altered. As a matter of fact, simultaneous usage of several methods leads to obtaining various values and a comparison between results and actual ground settlement amount. In this study, the results obtained from modeling, along with analytical (Loganathan) and empirical (Pek based on input data) methods, were closer to the actual ground settlement amount. The modeling results were closely similar with each other.

12. Considering that generally, the settlement level is 50 millimeters for non-residential areas and 35 millimeters for residential areas, the obtained settlement values are below the accepted maximum settlement level specified in scientific sources.
13. The maximum settlement obtained in modeling with PLAXIS3D software is 38.38 millimeters, and in FLAC3D modeling, it is 37.84 millimeters. The results from both software indicate a close estimate of settlement levels through numerical modeling. The settlement values in the Loganathan and Pek methods were closer to the actual values, and the maximum settlement among empirical and analytical methods was obtained by Bobet’s method and it was equal to 46.50 millimeters.
14. Considering the settlement value obtained in software modeling, the average settlement in modeling is 38.11 millimeters, in analytical methods it is 42.51 millimeters, and in Pek’s empirical method it’s 36.985 millimeters. The average settlement obtained by analytical and empirical methods is 39.74 millimeters, and the overall average of settlement using various methods, is 38.92 millimeters, which is closely similar to the actual settlement value.

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