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Improved Subsidence Assessment for a More Reliable Excavation Activity in Tehran

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Abstract: This paper presents a particular tunneling method or the new Austrian tunneling method (NATM) which plays an important role in reducing the subsidence of the surface and the damage to the structures in urban areas. It has a wide range of applications in shallow tunneling projects all over the world. In this study, numerical modeling of the third-line Metro tunnel in Tehran is under discussion which is designed and stabilized by NATM. The foregoing tunnel is excavated manually with a one-meter advancing step. In this project, the constructors used a lattice girder and sprayed concrete with 31 cm thickness as the initial lining. A suitable numerical software for this modeling is Plaxis 3D tunnel, which allows performing high-resolution finite element modeling (FEM) of the studied object. The performance of this method is investigated and compared with other NATM methods. As a result of numerical modeling, we give a value of 30.01 mm earth subsidence in the most damaged area of the settlement, in comparison with that of earth surface monitoring, which confirmed it with a dramatically low difference. Moreover, this tunnel was drilled and excavated with various methods, among which less settlement was obtained by the proposed method. The results are promising to continue the tunneling with this method to expand the subway line in the city.

Keywords: NATM; tunnel; FEM; earth surface subsidence; subsidence monitoring

1. Introduction

The development of the urban environment includes the reduction of further congestion. Where possible, underground structures are used to ease traffic problems. Before starting construction, it is important to have a thorough knowledge of the geological environment in order to encounter as few obstacles as possible during implementation. Continuously renewed methods are used during the data collection to reveal the detailed geological exploration results [1]. The design of tunnels is also becoming more and more complicated, because there is already a greater demand for super-large-section tunnels to meet the increased transport needs [2]. In many cities, we have reached the point where the underground tunnel networks are also crowded. The new tunnels often cross existing ones, the construction of which changes the geotechnical environment, and new technological methods must be used to solve the problems that arise [3].

Over the past several decades, subsidence has emerged as a significant issue affecting urban, coastal, and mining areas worldwide [4]. Tunnel construction particularly through weak materials may bring about undesired effects on existing structures due to ground deformation. Therefore, safe tunnel design and construction require stability, surface deformation, and effective supports; thus, the assessment of ground settlements and their effects on structures above the tunnel is essential for tunnel projects [5]. It is considered that the fundamental cause of land subsidence is stratum loss, which is the difference between the volume of excavated soil and the volume of the formed tunnel [6].

Tunnels should be driven full face whenever possible, although this cannot be done, particularly on bad ground, where it often becomes necessary to resort to heading and benching. In the most difficult cases, it may even be necessary to drive a top pilot heading before opening it out to the full section [7]. It is a well-known fact that a pile supports the load of the superstructure by transferring

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it to the ground resulting in the generation of stresses surrounding the pile. On the contrary, tunneling is a stress relief process which results in ground movements (which propagate through the soil to the ground surface) around the tunnel [8,9]. To meet the needs of large projects in hydraulic engineering, transportation engineering, etc. and to improve the utilization of underground space and reduce backfilling, large-scale noncircular tunnels are becoming very common currently. The sequential excavation of the cross-section, usually performed via the drill and blast method, is then employed in a large-scale tunnel construction to reduce the impact of excavation on the surrounding rock. The entire cross-section is divided into several sections in the sequential excavation, and each section is excavated at different times [10–13].

The NATM is a construction method, which is very adaptive according to changing subsoil conditions and changing shapes of cross-sections. Interacting with the subsoil the primary function of the shotcrete membrane is to form an arch around the tunnel, which is capable of carrying. With a favorable shape of the tunnel's cross-section and an adequate sequence of construction stages, it is possible to avoid or at least minimize bending moments and shearing forces in the shotcrete membrane. Thus, large underground openings can be supported by relatively thin shotcrete membranes. With an adequate design also the subsidence on the surface can be limited to relatively small values. Stability analyses, in which the interaction of the subsoil with the support is modeled in a realistic way, however, serve as a prerequisite for a successful tunnel heading using this method. The authors are convinced that this is possible only by numerical computation methods. Stability analyses, therefore, should be carried out generally using finite element codes [14].

In 1964, Rabcewicz wrote a paper "The New Austrian Tunneling Method" (NATM) that, he represents a cross-section of NATM for the first time (Figure 1), which was associated with a tunneling project in Austria. In many countries, tunnels in soils and rocks are constructed using the NATM. This is mainly due to its flexibility to adapt to different ground conditions and the use of simple equipment [7].

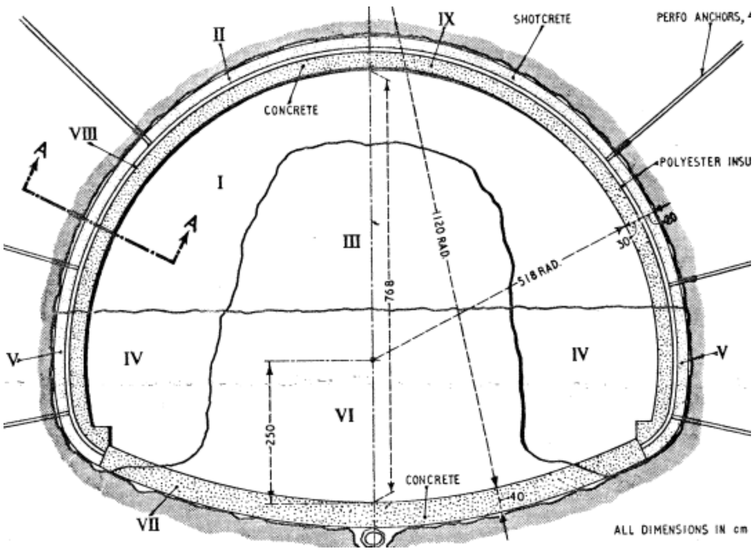

Figure 1. Recommended excavation pattern by Rabcewicz [7].

The NATM method was often preferred due to its advantages, which are the advantages of interfering in tunnel support systems instantaneously, adapting and changing support types depending on the ground conditions, and revising support systems and implementing specific support configurations in compliance with the encountered ground types [15]. At the same time, experience shows that it is important to be aware of its shortcomings and limitations, which may require revision, as it may not be used well in all geological environments [16].

A significant percentage of the final stabilized settlement is induced before face passage. This can only be adequately reproduced in 3-D analyses. Important aspects such as load transfer in the longitudinal direction due to soil arching cannot be represented in 2-D analyses. However, for a

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proper displacement forecast an appropriate constitutive model is also of utmost importance. The tunnel support lining is the most relevant single factor analyzed in reducing induced settlements. The closer to face the lining is concreted, the smaller the displacements even if the support is not yet fully activated. Full activation with inverted closure also greatly reduces induced displacements [17]. Figure 2 was used as an optimized way of staged excavation in later and further analyses.

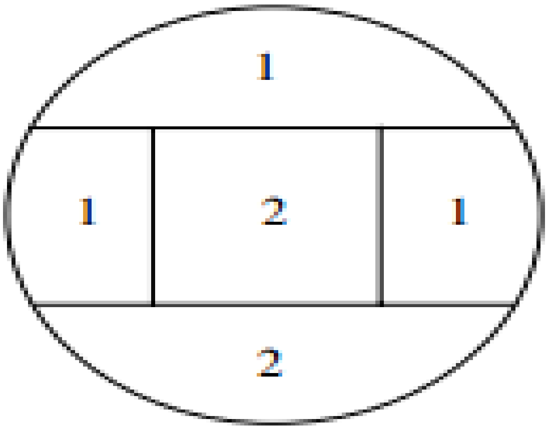

Figure 2. Recommended excavation pattern by Farias [17].

The available data are the input for adapting the driving parameters to ensure safety or/and to optimize the tunneling process [18].

From this follows that the support after NATM and the support after the Q-system differ only a little in good rock mass. Swelling rock mass conditions cause major differences in the choice of support between NATM and Q-system. In our opinion, the NATM allows more adaptable support in poor rock mass classes. Using the NATM it is possible to give a quick and a certain reaction on the several rock mass behavior types at each advance step [19].

The main issue of tunneling in urban environments, typically characterized by a low overburden thickness and the presence of surface infrastructure, is the control of settlements induced by tunnel excavation. The first step in the design of any protective measure reducing the tunnel impact on surrounding buildings is an accurate prediction of the tunneling-induced displacement field. It was shown that application of an advanced soil constitutive model, in combination with quality experimental data and 3D finite element analysis, may lead to accurate forward predictions of the displacement field induced by a tunnel with low overburden thickness [20].

"The field is fully covered by Kahrizak silts like in the north of Tehran", says by Iran's geology organization. Right now, this silt is slightly covered with Fine-grained sediments of current alluvium with no tidiness. The soil of the region is very old, and it is very compact because of the tectonic pressures. Also, Due to the experiments, the soil is pre-consolidated with a high over-consolidation ratio (OCR). The field has a lot of deep channels underground which have been destroyed and collapsed over the years. Also, the experiments prove that the area is flat and smooth even though its old rivers had been filled with soil [21]. The excavation procedures exhibit varying priorities depending on the in-situ stress levels, indicating a distinction relationship between design parameters and the prevailing stress conditions [22]. This observation underscores the gap for a dynamic and adaptive approach to excavation design which can be chosen by numerical modelling in this particular area.

This paper presents a particular tunneling method or the new Austrian tunneling method (NATM) which plays an important role in reducing the subsidence of the surface and the damage to the structures in urban areas. In this study, numerical modeling of the third-line Metro tunnel in Tehran is under discussion which is designed and stabilized by NATM. A suitable numerical software for this modeling is Plaxis 3D tunnel, which allows performing high-resolution finite

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element modeling (FEM) of the studied object. The performance of this method is investigated and compared with other NATM methods.

2. Numerical Modelling

Plaxis 3-D tunnel (version 1.2) software had been used for this research which is a special purpose three-dimensional finite element computer program used to perform deformation and stability analyses for various types of tunnels in soil and rock. The program has special features for NATM and shield tunnels, but it can also be used for other types of geotechnical structures. In addition, since soil is a multi-phase material, special procedures are required to deal with hydrostatic and non-hydrostatic pore pressure in the soil. Although the modelling of the soil itself is an important issue, many tunnel projects involve the modelling of structures and the interaction between the structures and the soil. The Plaxis 3-D tunnel is equipped with special features to deal with the numerous aspects of complex geotechnical structures.

The Plaxis 3-D tunnel program offers a convenient option to create circular and non-circular tunnels composed of arcs and lines. Plates and interfaces may be added to model the tunnel lining and the interaction with the surrounding soil. Fully isoperimetric elements are used to model the curved boundaries within the mesh. Various practical methods have been implemented to analyze the deformation that occurs due to the construction of the tunnel. On top of that, the staged construction feature enables a realistic simulation of construction and excavation processes by activating and deactivating clusters of elements. Also, the application of loads allows for a realistic assessment of stresses and displacements as caused, for example, by an excavation of a tunnel or an underground construction [23].

2.1. Creating the Model and Generating the Mesh

The two-dimensional pattern of the tunnel which designed for the project is in Figure 3. According to the pattern, the height of the tunnel is 8.335 m and the width of it is 8.593 m. Also, the thickness of concrete which applied for this tunnel was 500 mm and the thickness of sprayed concrete (shotcrete) was 310 mm [24].

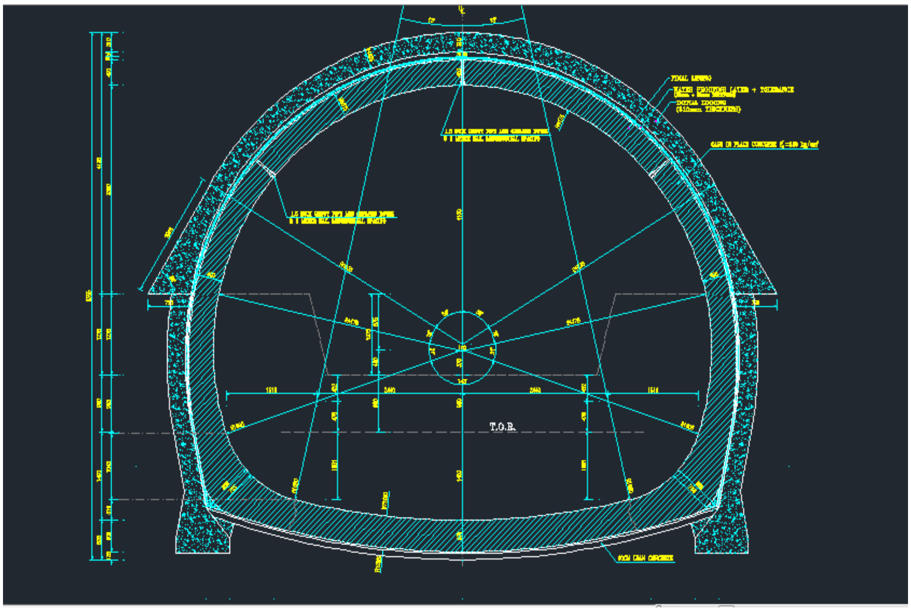

Figure 3. The two-dimensional pattern which was designed in the project.

After creation of the geometry of the model, a finite element model composed of 6-node triangles can automatically be generated, based on the composition of clusters and lines in the geometry model [23]. Due to the fact that geometry was symmetrical, only one-half of the model was created. Also, symmetry conditions are adopted at the center plane (Figure 4). The Mohr-Coulomb Model was

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accomplished because of the soil condition and of the region and it's assumed that its behavior is semi-continuous, hence the Mohr-Coulomb model had been considered for this region.

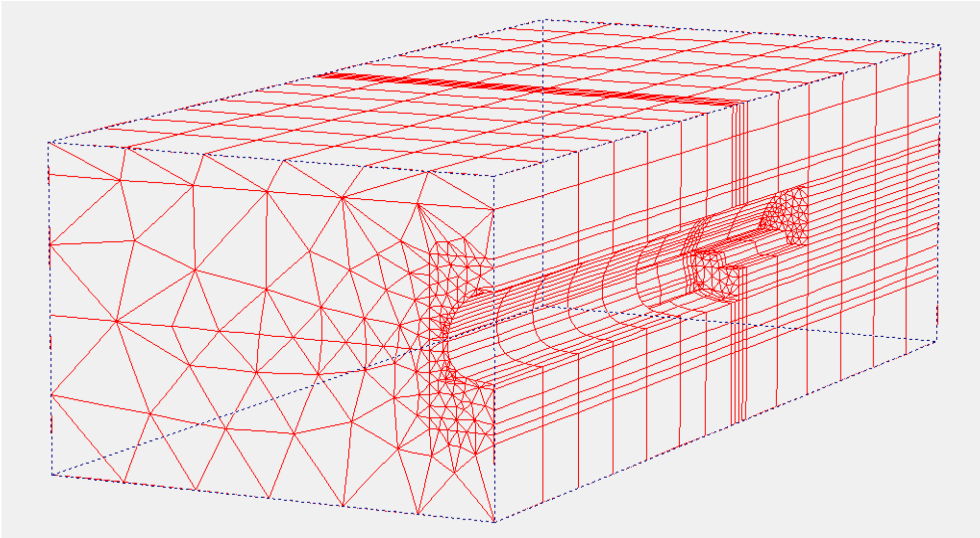

Figure 4. The geometry of the model with generated mesh in the software.

2.2. Material Parameters

There was some data about soil layers needed to input software. There were three soil layers and their parameters are presented in Table 1 [21].

Table 1. Parameters of soil layers.

	Upper layer (sand)	**Middle layer (clay with silt)**	**Bottom layer (clay with silt)**
E (kN/m^2)	**1.75*104**	**3.75*104**	**5.5*104**
8unsat(kN/m^3)	**16.9**	**16.9**	**16.9**
8sat (kN/m^3)	**20.250**	**20.250**	**20.250**
ψ(º)	**0**	**0**	**0**
φ(º)	**27**	**27**	**27**
ν	**0.35**	**0.35**	**0.35**
C (kN/m^2)	**40**	**40**	**40**
K0	**0.548**	**0.492**	**0.504**

Also, the data which is associated with first and final support has given in Table 2 [24].

Table 2. Material properties of temporary and final supports.

	E (kN/m^2)	**8unsat (kN/m^3)**	**ν**	**EA (kN/m)**	**EI (kNm^2)**	**d (m)**	**W (kN)**
Shotcrete	-	-	0.2	$6.103*10^6$	$2.215*10^4$	0.209	7.2
Final concrete	$2.387*10^7$	25	0.2	-	-	-	-

The definitions of these parameters are shown in Table 3.

Table 3. Definition of the parameters.

Parameter	Definition
E	Elasticity module
γ_{unsat}	Unsaturated unit weight
γ_{sat}	Saturated unit weight
Ψ	Angel of dilation
Φ	Internal friction angel
V	Poison's ratio
C	Cohesion
K_0	Coefficient of lateral earth pressure
EA	Normal stiffness (Axial rigidity)
EI	Flexural rigidity
d	Equivalent thickness
W	Unit weight

3. Subsidence Calculation due to the Excavation Procedure in the Project

At first, excavation pattern of the project modelled in Plaxis in order to get the subsidence then this subsidence had comparison with subsidence in the instrument report. According to the excavation method which had been made in the project, first the top part excavated then after 14 meters the bench part followed [25]. Figure 5 shows only half of the tunnel.

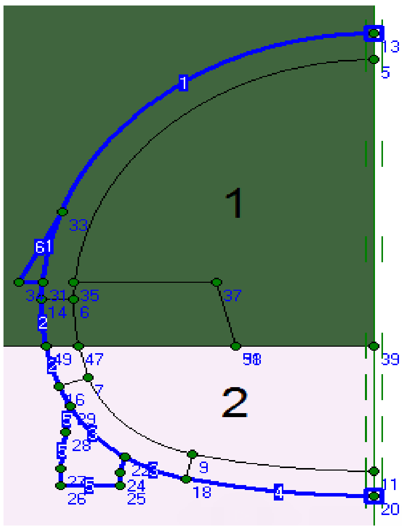

Figure 5. Excavation procedure which accomplished in the project.

We modeled because of the symmetry of geometry. After geometry creation mesh is generated then parameters input, also for having a realistic output model developed in the third dimension just like Figure 4.

After the calculation process, the output is represented as figures. Figure 6 shows a longitudinal profile where the vertical axis shows the settlement and its horizontal axis, the length of the tunnel, and Figure 7 shows the cross-section of the most subsided area where the vertical axis stands for the surface settlement also the horizontal axis indicates the distance from the zero axis which means the tunnel axis.

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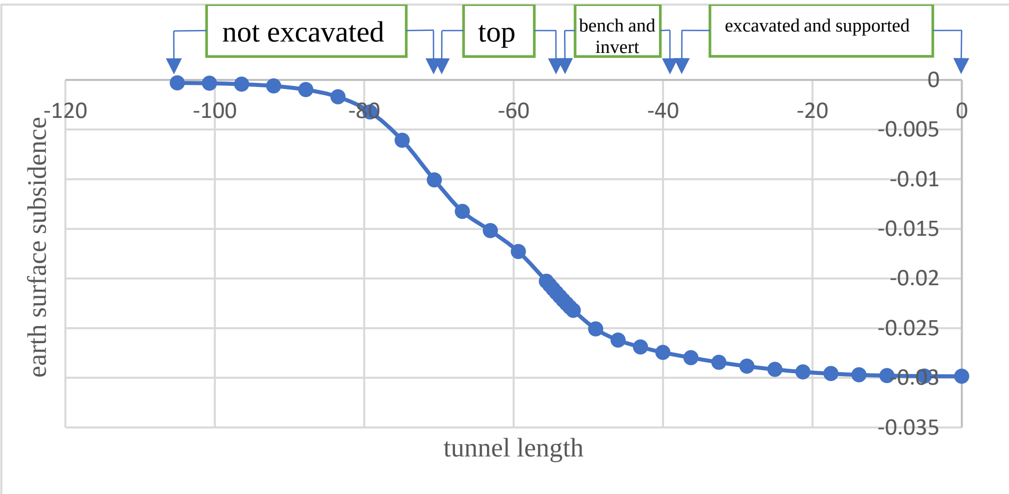

Figure 6. Longitudinal profile of surface subsidence.

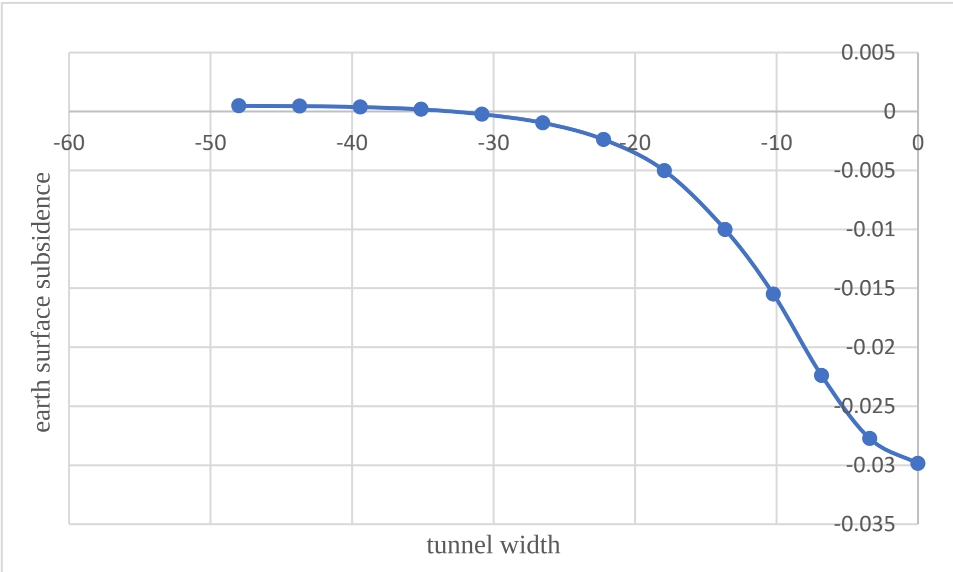

Figure 7. Cross-sectional profile of surface subsidence.

The maximum settlement of the surface was 32.9 mm according to the monitoring and instrumentation report (Monitoring and instrumenting of tunnel behavior, CVR consultant engineers, design consultant of Tehran third south subway line [24,25]. On the other hand, the subsidence obtained from PLAXIS was 30.01 mm regarding Figures 6 and 7, hence these numbers prove the validation and accuracy of modeling also reliability of the PLAXIS 3d tunnel for this region. (So, not only is the PLAXIS 3d tunnel reliable for this region but also these numbers are an approval for validation and accuracy of modeling with this software.)

4. The Comparison between Excavation Patterns of NATM

All patterns can be seen in Figure 8, pattern A is the one which they had applied in the project. Pattern B followed Rabcewicz recommendation. Case C was one of Farias's optimized patterns which has a rather similarity to case B. Although patterns D & E are almost equal, their difference is in their excavation priority. The last one had come from trial and error based on pattern C.

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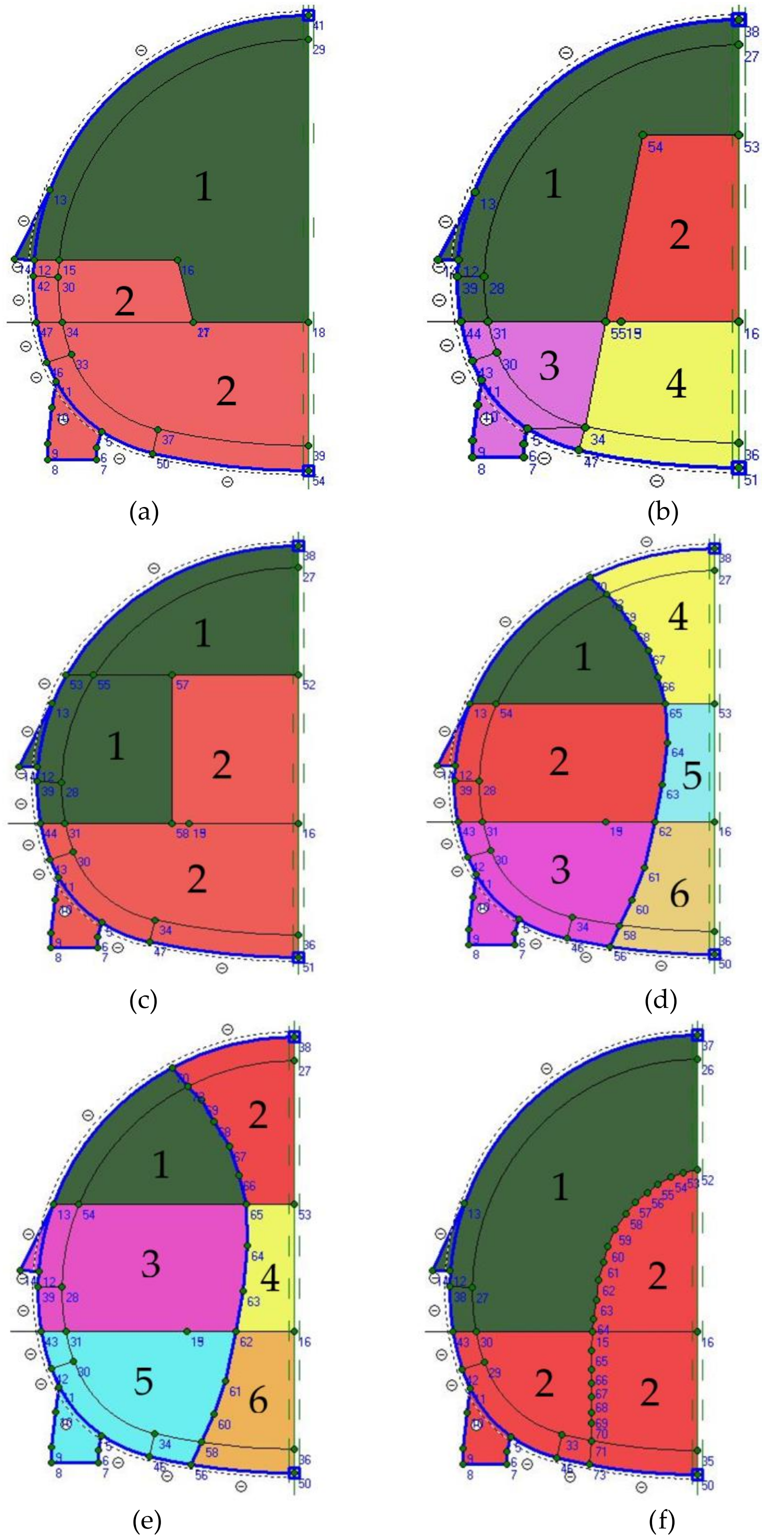

Figure 8. Varied excavation patterns of NATM: (a) project pattern; (b) proposed pattern by Rabcewicz; (c) Farias's optimized; (d) empirical pattern 1; (e) empirical pattern 2; (f) empirical pattern 3.

4.1. Comparison of Surface Subsidence between All Patterns

This comparison had managed to reach the best pattern. All these patterns were modeled in PLAXIS based on the exact situation of the project and all of the stages and excavation steps of the Tehran Third South subway line project were simulated precisely for all patterns by PLAXIS 3d tunnel that gave us longitudinal and cross-section profiles for each of the patterns that they merged

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in one longitudinal profile (Figure 9) and one cross-section profile (Figure 10) to get better view for comparison.

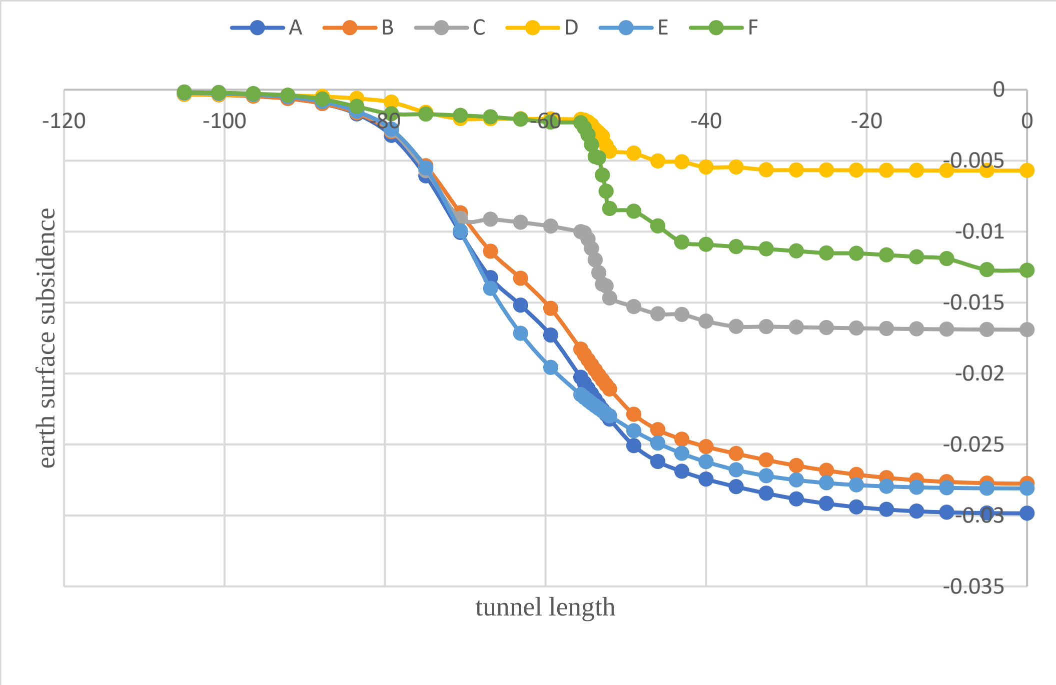

Figure 9. Longitudinal profiles of surface subsidence which belong to all the excavation patterns.

In Figure 9 profiles C & F & D have similar behavior which is sensible due to their priority of excavation according to Figure 8. Also, in this chart excavation faces are at the end of the top part and the end of the bench part. The excavation direction is from right to left and the vertical axis represents surface settlement meanwhile the horizontal axis shows tunnel length.

Figure 10 shows cross-section profiles of all the patterns simultaneously. Patterns B and E have similar behavior in the settlement that is justifiable due to their pattern and excavation procedure. In this chart, the vertical axis indicates subsidence and the horizontal axis distance from the tunnel axis. In both charts pattern D has the lowest amount of subsidence.

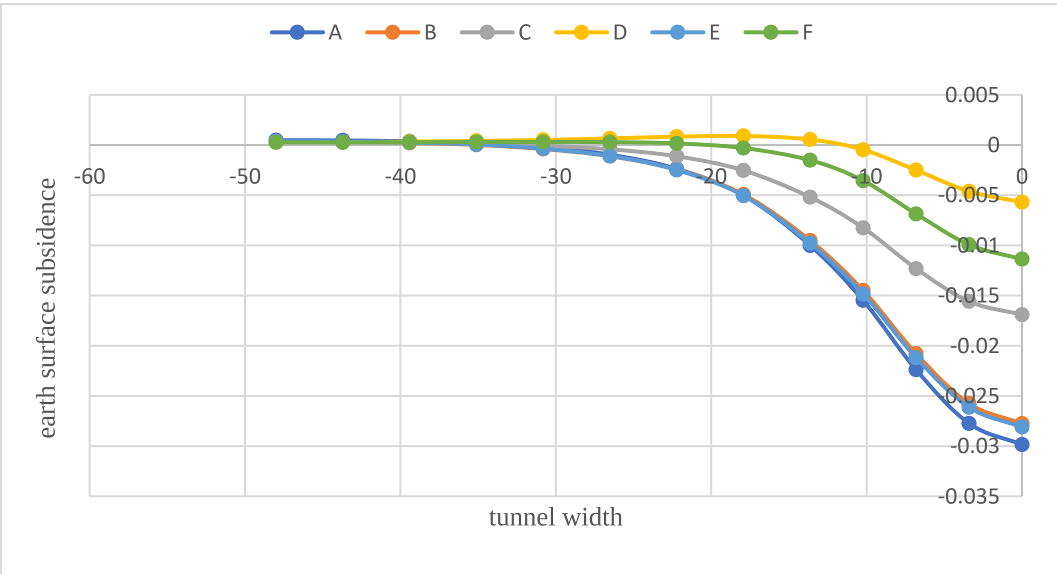

Figure 10. Cross-sectional profiles of surface subsidence which belong to all the excavation patterns.

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4.2. Comparison of Effective Mean Stresses of All Patterns

In addition to subsidence, a comparison of effective mean stresses of all patterns are accomplished in order to reach optimized patterns. Fortunately, the PLAXIS 3d tunnel provided the required data for this collation which is charted in Figure 11. As it can be seen from this figure pattern D has the least amount of effective mean stress.

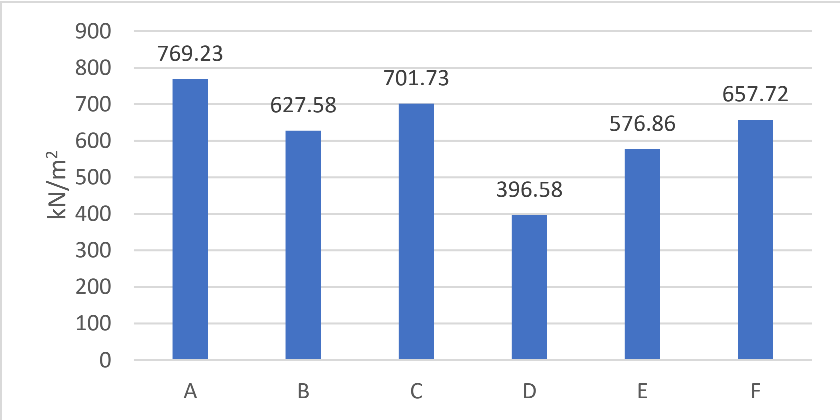

Figure 11. Effective mean stress of excavation patterns.

Considering Figures 9, 10 and 11 pattern D is the most suitable excavation procedure for this region also it could be used for similar geological conditions and in megacities with high traffic congestion in order to alleviate surface settlement as far as possible.

5. Conclusions

The maximum settlement of the surface was 32.9 mm according to the instrument report (Monitoring and instrumenting of tunnel behavior, CVR consultant engineers, design consultant of Tehran third south subway line. On the other hand, the subsidence obtained from PLAXIS was 30.01 mm regarding Figures 6 and 7, hence these numbers prove the validation and accuracy of modeling and also the reliability of the PLAXIS 3-D tunnel for this region.

Analyzing Figures 9, 10 and 11, it becomes evident that pattern D emerges as the most viable excavation procedure for the region under consideration. Moreover, its applicability extends to comparable geological conditions and mega cities grappling with high traffic congestion. Implementing pattern D not only addresses existing challenges but also strives to minimize surface settlement, offering an effective solution to complex urban environments. This strategic approach not only ensures optimal excavation outcomes but also underscores its potential for widespread application in regions facing similar infrastructural and geological constraints.

The conducted research underscores the significant impact of adopting specific excavation patterns and altering the priority of excavation on both surface subsidence and effective mean stress. The findings suggest that the choice of excavation pattern plays a crucial role in influencing these outcomes. By strategically modifying the excavation priorities, it is possible to observe substantial changes in surface subsidence and the effective mean stress experienced in the geological context under consideration. This recognition highlights the importance of thoughtful planning and decision-making in excavation methodologies, as they can directly contribute to minimizing surface subsidence and optimizing the distribution of effective mean stress during the construction process.

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Conflicts of Interest: The authors declare no conflict of interest.

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