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Influence of soil constitutive models on settlement prediction of urban tunnelling

Influence des modèles constitutifs du sol sur la prévision du tassement des tunnels urbains

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ABSTRACT: The validity of material models is a major field of research in soil mechanics. Different constitutive models have distinct stress-strain behavior, which can affect the results of the predicted deformation, failure mechanism, and load-bearing capacity of a geotechnical structure. In this regard, in this contribution, the application of three constitutive models in a Finite Element Analysis (FEA) of a well-documented case study is presented. This case study - Arash-Esfandiar tunnel - is a particular under-passing tunnel in the north of Tehran, Iran, starting from Modares highway and running to Niayesh highway. The tunnel project has a total length of 1532 m and was constructed with shallow overburden. The results indicate the necessity of using axial and bending elements as tunnel support measures at the same time. According to the large span of the tunnel and the geotechnical conditions, a combination of 4 different support elements was propose which includes, nails, micropiles, fore poling and, lattice girder. Various monitoring stations, including settlement points and geodetic points, have been installed as part of this project, providing extensive records of subsidence and tunnel deformation. The main goal of the numerical simulations is to investigate the influence of the material models on the results of accumulated subsidence for the stage construction method. The analysis outputs have been validated on available monitoring results of this actual tunnelling project. The results show a significant better performance of the hardening soil model when simulating the tunnel construction effects on the deformations of the excavation area and comparing them with the measurements results.

RÉSUMÉ: La validité des modèles de matériaux est un domaine de recherche majeur en mécanique des sols. Différents modèles constitutifs ont un comportement contrainte-déformation distinct, qui peut affecter les résultats de la déformation prévue, du mécanisme de rupture et de la capacité portante d'une structure géotechnique. À cet égard, dans cette contribution, l'application de trois modèles constitutifs dans une analyse par éléments finis (FEA) d'une étude de cas bien documentée est présentée. Cette étude de cas - tunnel Arash-Esfandiar - est un tunnel souterrain particulier dans le nord de Téhéran-Iran, partant de l'autoroute Modares et allant jusqu'à l'autoroute Niayesh. Le projet de tunnel a une longueur totale de 1532 m et a été construit dans un déblais peu profound peu profond. Les résultats indiquent la nécessité d'utiliser simultanément des éléments axiaux et de flexion comme mesures de soutènement du tunnel. Compte tenu de la grande portée du tunnel et des conditions géotechniques, une combinaison de 4 éléments de soutènement différents a été proposée : clou, micropieu, avant-pieu et poutre en treillis. Diverses stations de surveillance, y compris des points de règlement et des points géodésiques, ont été installées dans le cadre de ce projet, fournissant des enregistrements détaillés de l'affaissement de surface et de la déformation du tunnel. L'étude de l'influence des modèles de matériaux sur les résultats d'affaissement cumulé pour la méthode de construction d'étage est l'objectif principal des simulations numériques. Les résultats de l'analyse ont été validés sur les résultats de surveillance disponibles de ce projet de tunnel réel. Les résultats montrent une performance significativement meilleure du modèle de sol durcissant lors de la simulation des effets de la construction du tunnel sur les déformations de la zone d'excavation et en les comparants aux résultats des mesures.

Keywords: Tunnel; constitutive soil models; FEM, instrumentation.

1 INTRODUCTION

Any major cities worldwide require underground transportation systems, especially those grappling with issues related to population density and traffic congestion. The construction of tunnels and underground spaces may potentially impact the ground, leading to ground movement and settlement. These effects can be critical enough to disrupt the functionality of nearby structures. Consequently, one of the foremost concerns in tunnel construction revolves around ensuring the safety of the construction process itself, as well as safeguarding nearby structures, particularly in urban areas.

Geotechnical engineering is an evolving field focused on enhancing the precision of numerical analysis tools employed in simulating the interaction between soil and structures under complex load conditions. A critical aspect of this improvement is the development and validation of constitutive models that accurately represent the soil behavior. This paper endeavors to tackle the challenges associated with the selection of appropriate soil models for conducting realistic design analyses. In this regard, a specific case study has been chosen to examine the application of three different constitutive models (including: mohr-coulomb, hardening soil and hardening soil model with small strain) within a Finite Element Analysis (FEA) framework and to corroborate the findings with the data obtained from on-site monitoring.

2 SOIL CONSTITUTIVE MODELS

Material constitutive models range from simple elastic perfectly plastic models (Drucker and Prager, 1952 and Mohr-Coulomb, by Jaeger and Cook, 2009) to models using critical state concepts models using multi-yield surfaces (Prevost, 1977), and double hardening models (Lade, 1977), to name a few.

In this research Mohr-Coulomb model (MC) is chosen from the available models due to its simplicity and widespread use in practical applications. Numerical modelling of the tunnelling with MC has proven inaccurate due to the lack of ability to properly simulate the phenomenon of unloading and the lack of distinction between the hardships of initial loading and unloading/reloading (Schanz et al, 1999). To overcome that disadvantage the Hardening Soil model (HS) selected as second model. HS is an advanced elastoplastic constitutive model that is used for simulating both stiff and soft soil behaviors (Schanz et al, 1999). HS also relates stiffness parameters to the stress-level and simulates the development of plastic strains under compressive loading. HS can distinguish between loading and unloading path.

The third model used is the hardening soil model with small strain stiffness (HSS). This model is an extension of HS considering increased stiffness for small strains (Benz, 2007). At low strain levels, most soils exhibit a higher stiffness, and this stiffness varies non-linearly with strain.

3 CASE STUDY

In this research, an underground tunnel located in the northern region of Tehran, the capital of Iran, will be examined. This tunnel, known as the Arash-Esfandiar-Niayesh Tunnel, is situated within the third district of Tehran Municipality. It is constructed to facilitate east-to-west connectivity in this locality, connecting East Arash Street with the starting point of Niayesh Highway. (Figure.1). The current study is modified after Salehi et al (2023).

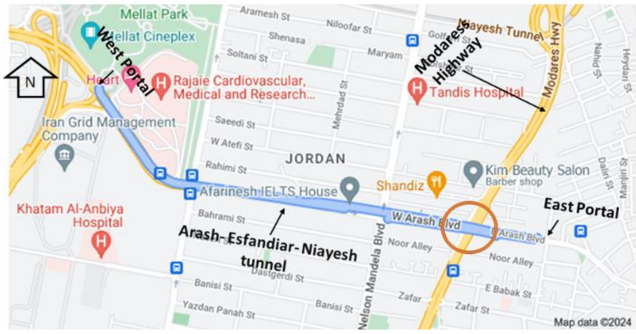

Figure 1. Plan of Arash- Esfandiar tunnel.

This project is constructed by New Austrian Tunneling Method (NATM). NATM was introduced in Austria during 1957-1965 by Rabcewicz. The idea of this method is to allow a certain amount of deformation in the surrounding rock or soil to reduce the stresses acting on the final support of the tunnel, (FHWA, 2009).

3.1 Soil Condition

The geological and geotechnical characteristics of the different soil types were established through laboratory assessments conducted on numerous samples obtained from seven boreholes and four test pits. For this study, we focused on four boreholes, each with a depth of 50 meters, and one test pit with a depth of 19 meters, all located within the project area. There was no sign of water table level up to the end of borehole (50m). After conducting laboratory tests and on-site investigations, the soil types were classified cemented granular and as follows: medium dense silty gravel up to 3.5 m depth, very dense silty sandy gravel and dense clay sand (located beneath the gravel layer). (found at depths of -3.5 to -50 meters),

Table 1 presents an overview of the key geotechnical parameters essential for our research and based on each constitutive soil model. Shear strength parameters are extracted from in situ shear, direct shear and triaxial tests. Stiffness parameters are extracted from pressuremeter test and plate load test is carried out to investigate the ratio of loading and unloading. Instead of using the Young's modulus as a stiffness parameter, alternative stiffness parameters were used (Eoed and G) and the young's modulus calculated automatically. Oedometer modulus (Eoed) is obtained for 90 kPa stress level to account to the tunnel depth at the top of the excavation.

Table 1. Geotechnical parameters.

First layer (0 to -3.5)	Second layer (-3.5 to -50) m
$\varphi = 30^{\circ}$	$\varphi = 37^{\circ}$
$c = 9.8$ kN/m^2	$c = 24$ kN/m^2
$\gamma = 17$ kN/m^3	$\gamma = 18$ kN/m^3
HS and HSS specified parameters	
$\nu_{ur} = 0.2$	$\nu_{ur} = 0.2$
$E_{ref\,(50)} = 4.0$ e04 kN/m^2	$E_{ref\,(50)} = 7.0$ e04 kN/m^2
$E_{ref\,(oed)} = 4.0$ e04 kN/m^2	$E_{ref\,(oed)} = 7.0$ e04 kN/m^2
$E_{ur(HS)} = 12.0$ e04 kN/m^2	$E_{ur(HS)} = 21.0$ e04 kN/m^2
m= 0.5	m= 0.5
$G_{0\,(ref)} = 5.856$ e04 kN/m^2	$G_{0\,(ref)} = 11.7$e 04 kN/m^2
$\gamma = 0.1$ %	$\gamma = 0.1$ %
M – C specified parameters	
$\nu = 0.2$	$\nu = 0.2$
$E_{oed} = 4.0$ e04 kN/m^2	$E_{oed} = 7.0$ e04 kN/m^2
G = 1.15 e04 kN/m^2	G= 2.625 e05 kN/m^2

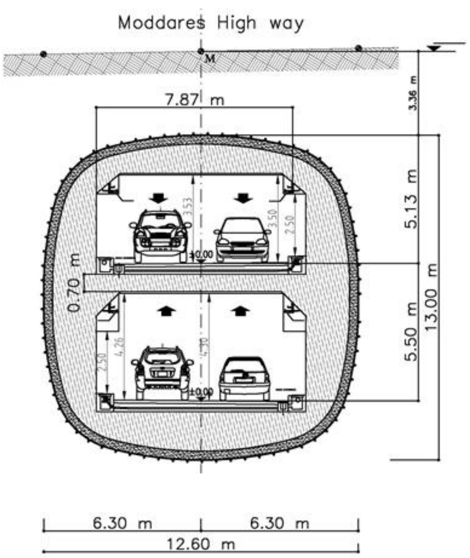

Figure 2. Modares two-level tunnel section

3.2 Tunnel Geometry

On one hand, there was a need to establish multiple entry points to access the project site from West Arash Street and Esfandiar. On the other hand, project constraints made it necessary to employ various geometric configurations during construction. To address the requirement for a two-way traffic option beneath Modares Highway, despite limited available space, the decision was made to implement a two-level tunnel. Thus, the Modares two-level tunnel became a component of the Arash-Esfandiar-Niayesh tunnel project. The tunnel section measures 12.2 meters in width and 13 meters in height, as shown in Figure 2. Given the shallow depth of the tunnel and its passage beneath major urban arteries close to tall buildings, the New Austrian Tunneling Method (NATM) was chosen as the construction method for this project.

3.3 FEM Model

The tunnel structure and the surrounding soil have been simultaneously simulated using the PLAXIS 2D finite element program. The construction stages and the continuous implementation of tunnel excavation were incorporated into the model to align with the actual construction process. To represent the various layers of the ground, 15-node triangular elements were employed, as shown in Figure 3. To comprehensively assess the extent impacted by the construction of underground structures, a model with a width of 80 meters and a height of 40 meters was created, which is 10 times the tunnel's diameter in width and 3 times in height. The tunnel's overburden within the investigated sections is a minimum of 4 meters, which has been considered in the geometric definition of the model. In this paper, the stress reduction or relaxation method is utilized to simplify the model and simulate the 3D problem. The relaxion factor are estimated based on previous research concerning this project (Golshani et al., 2018),) according to a 3D model and the Vlachopoulos and Diederich (2009) methods. The relaxation factors (RF) for each excavation phase are as follows: 35% in Top (Stage I to III), 20% in Bench (Stage IV to IX) and 15% in Invert (Stage X to XII).

3.4 Support System

Within the New Austrian Tunneling Method (NATM), various elements are employed to provide both temporary and permanent support for tunnels. Shotcrete is a commonly utilized material for temporary support during tunnel excavation. This choice is primarily made because no other support method can effectively bond the ground surface, preventing it from deteriorating or loosening in the same manner that shotcrete does.

A rock bolt or nail serves as a supporting element to enhance the stability of rock excavations, often employed in tunnels or rock cuts. Its primary function is to shift the load from the less stable outer areas to the more solid and robust interior of the rock mass. Rock bolts function by essentially "knitting" together the rock mass, preventing it from moving significantly and potentially coming apart piece by piece, which could lead to instability or failure.

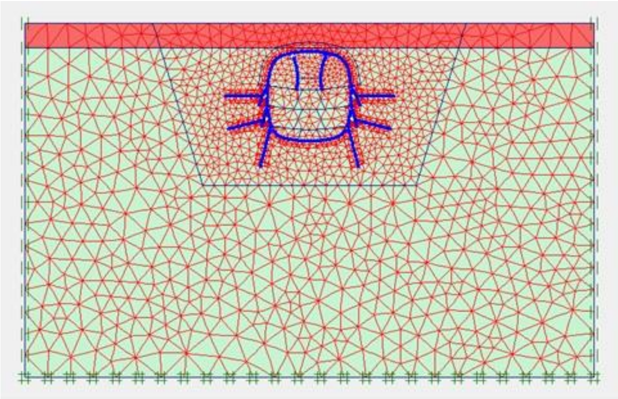

Figure 3. Meshing plot of Modares two level tunnel

One way to mitigate ground movements caused by tunneling is to employ in-tunnel support methods, such as the forepoling umbrella system. This system consists of steel pipes that offer structural support to the soil surrounding and above the tunnel excavation. Forepoling arches are specific tunnel heading reinforcements utilized to bolster the unsupported section of the tunnel heading during the excavation of tunnels in soft ground or loose soil conditions. In the current research according to the large span of the tunnel and the geotechnical conditions, a combination of 4 different support elements was proposed. A classification of the suggested support system and their combination is provided in Table 2.

In the two-level section, known as the Modares Tunnel, the primary walls will receive support through a combination of 35 cm thick shotcrete and lattice girder truss metal structures. In cases where additional support is needed, forepoling elements will be incorporated alongside micropiles and nails.

Additionally, the temporary walls will be reinforced with 25 cm thick shotcrete and lattice structures. In the numerical model, the shotcrete support is simulated with parameters corresponding to 7-day and 28-day settings, including Elastic Modulus values of 18.7+06 kPa and 23.4+06 kPa, respectively. The loading in this section is primarily static and results from the overburden of the tunnel. Additionally, the model takes into account the load imposed by the traffic on Modares Highway, which amounts to 20 KN/m per meter.

The initial lining of the tunnel was constructed with thicknesses of 35 cm and 25 cm, using shotcrete of class C25 and lattice girder steel bars of type III. In the modeling process, the lining structure was represented using plate elements, and a linear elastic behavior was assigned to the reinforced shotcrete material. Once stable initial conditions were established, and traffic-related loads were activated, simulations of the excavation and stage stabilizations is proceeded. It should be mentioned that the term “top” refers to stages 1 to 3 of excavation, “bench” refers to stages 4 to 9 and “invert” refers to stages 10 to 12, presented in Figure. 4.

Table 2. Classification of the examined support systems in Modares two-level tunnel.

Support system	Class
Lattice+shotcrete	A
Lattice+shotcrete+forepoling	B-I
Lattice+shotcrete+micropile	B-II
Lattice+shotcrete+nail	B-III
Lattice+shotcrete+forepoling+nail	B-IV
Lattice+shotcrete+forepoling+micropile	C-I
Lattice+shotcrete+nail+micropile	C-II
Lattice+shotcrete+forepoling+nail+ micropile	D

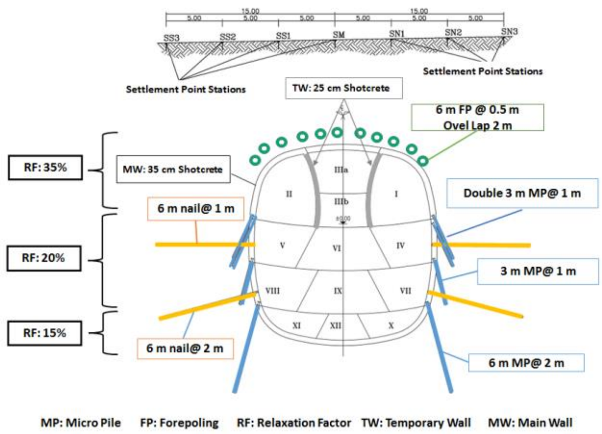

Figure 4. Excavation stages, initial support (Class D), and settlement points on Modares two-level tunnel.

3.5 Instrumentation

In the Arash-Esfandiar-Niayesh tunnel project, several measurement techniques were employed to monitor ground settlements and validate the numerical model across different profiles. In the two-level section of the project, a settlement measurement system was implemented to capture surface deformations, denoted as Settlement South (SS), Settlement Middle (SM), and Settlement North (SN). The layout of the instrumentation plan is depicted in Figure 4. It's important to note that the internal deformation is measured using optical reflectors, but since this research does not encompass internal convergence, it won't be discussed in this paper.

4 RESULTS

After solving the model, it was determined that using only shotcrete and lattice for temporary support would lead to develop a shear zone during the second bench excavation and tunnel will collapse. Consequently, to ensure a stable excavation process, 76 mm pipes with a 5 mm thickness were introduced for forepoling. However, despite the inclusion of forepoling in the model, structural instability resurfaced in tunnel excavation section VIII. To reduce the stresses from the initial support (shotcrete and lattice), additional axial elements were introduced. In this scenario, self-drilling nails with a 32 mm diameter (86 mm drilling diameter) and spaced 1 meter apart were chosen and implemented at two different heights.

Furthermore, the potential use of micropile elements was investigated as a meansof managing the vertical displacements. The calculations for the characteristics of micropiles resembled those of self-drilling nails. However, when micropiles were employed in isolation, the model once again exhibited instability during excavation in section X. As a result, the subsequent step involved investigating the combined use of forepoling and nails.

Given the project's sensitivity and its passage beneath a major urban traffic road, a decision was made to reinforce the tunnel using a class D support system. By combining axial and bending support structures, such as forepoling and nails, not only can displacement be minimized, but tunnel stability can also be ensured.

The overall pattern of recorded displacements aligns with the outcomes derived from the Finite Element calculations. The HS model oversestimates the displacements. In contrast, the MC and HSS models consistently produce results that underestimate the observed displacements. On the other hand, the absolute maximum settlement values align with the result of the numerical analysis. For example, when the temporary wall was removed, a measured settlement of 1 cm corresponded to the numerical results. It should be noted that in nearly all stages, there is a significant and immediate increase in settlements (a change in slope) in the FEM analysis results earlier than what's observed in the monitoring data. The results of the Finite Element Method (FEM) analysis indicate total vertical displacements of 2.7 cm, 2.1 cm, and 1.4 cm for the Hardening Soil, Small Strain Hardening Soil, and Mohr-Coulomb soil models, respectively.

In contrast, according to the settlement point records, the maximum vertical displacements at the ground surface were observed to be 2.6 cm as shown in Figure 5.

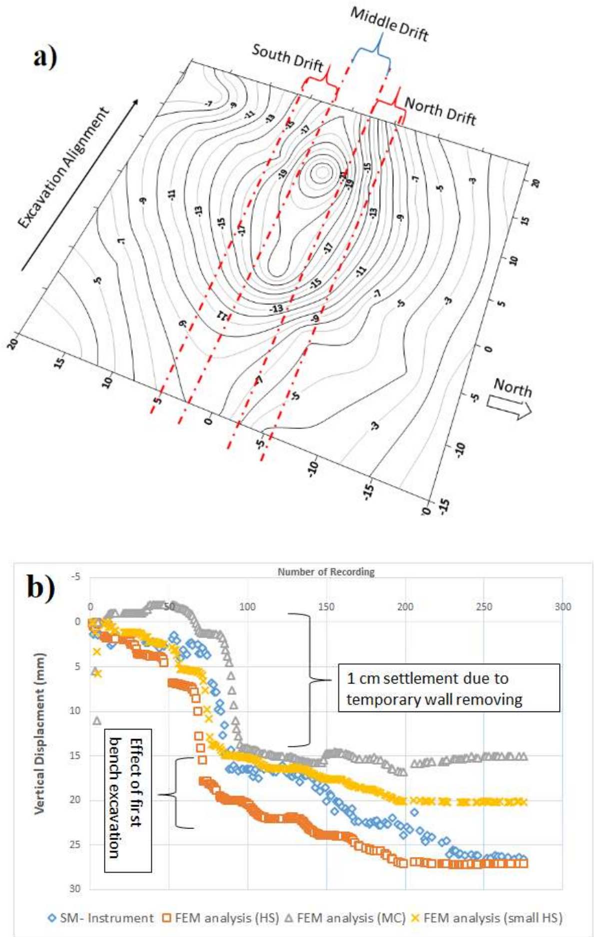

Figure 5. Surface Settlement: a) Normalized recording charts, b) Comparison of onsite measurements and FEM results in SM station (above the tunnel axis).

In Figure 5b, The horizontal axis is the number of instrument recordings (can be interpreted as time) in the construction site which is synchronized by the excavation and FEM model construction stages. The cumulative sum of settlements is selected to illustrate the progressive subsidence attributed to the excavation stages.

5 CONCLUSIONS

The findings from both the analysis and field data highlight the substantial influence of the tunnel's geometric shape on its stability and the distribution of stress. Prior to commencing operations, various options for stabilization methods were thoroughly reviewed and subjected to numerical modeling. The results obtained underscore the inadequacy of conventional support systems for shallow tunnels with an ovoid section. In such cases, relying solely on shotcrete and lattice girder elements, even in combination with forepoling, proves insufficient to ensure both structural and geotechnical stability of the tunnel. This limitation is primarily attributed to the significant height of the tunnel section and the high bending moment experienced by the beam elements. In addition to employing micropiles and forepoling to control surface settlement, the use of nails at two levels becomes imperative to alleviate stresses on the shotcrete and lattice and ensure the structural stability of the tunnel.

The results from the numerical model indicate that the incorporation of forepoling elements results in arching around the structure, leading to a decrease in surface settlements as well as a reduction in bending moments and shear forces. The minimum settlement achieved with the selected support system (type D) amounts to 2.7 cm at the surface.

The settlement monitoring records indicate a maximum vertical displacement of 2.7 cm at both the surface and within the tunnel. The absolute value of the final settlement in the numerical analysis method (based on the HS model) aligns with the measured data. However, there are some differences in the trends of the two diagrams (as shown in Fig. 5 (b)). In the on-site measurements, the slope in settlement curve becomes zero after the temporary lattice girders are removed, and despite the excavation of the first bench, the displacements exhibit a constant trend. In contrast, numerical model still show increase in displacements. This could be attributed to the application of relaxation factors during the excavation of the first bench. In practice, no increase in displacement was observed until the excavation of the middle part of the first bench (excavation section VI, Figure 4). This trend is also evident in the second bench excavation but with less impact. Furthermore, the final stage of excavation (invert) had minimal effect on surface displacements.

However, in complex situations with quasi-rectangular geometric sections, complicated support systems and high side walls, 3D modelling is required for accurate assessment. If the 2D method is used, simplification requires a more specific approach. In particular, the relaxation factor should be calibrated based on each soil constitutive model. This topic is an ongoing research in our team and results will be presented at the upcoming events.

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