
NUMERICAL SIMULATION OF NEW AUSTRIAN TUNNELING METHOD
A CASE STUDY: ELHOSANIA CROSSING, ZAGAZIG, EGYPT

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ABSTRACT

Numerical modeling is considered a useful tool for the evaluation and quantitative interpretation of field data for assessing the original design or construction method. In this paper, numerical modeling is used to investigate the optimum construction method for a tunnel proposal to underpass the railway tracks at Elhosania crossing in Zagazig city, Egypt. A relatively short length is suggested here to be constructed by the NATM (New Austrian Tunneling Method) instead of the traditional cut and cover method. This is the first time that the application of NATM is considered in Egypt. The purpose of the numerical simulation is to analyze both methods to determine the deformations and stresses in the tunnel vicinity and to check tunnel stability and the suitability of the construction method. Additionally, the way of strengthening the ground to ensure higher safety for NATM has been investigated using numerical modeling. The numerical results are promising; they help to minimize the construction cost and also help the decision makers to choose the optimum solution for other tunnels and other lines in the future.

KEYWORDS

New Austrian Tunneling Method (NATM), Soilcrete jet grouting, shotcrete lining, soilcrete slab, numerical analysis.

1. INTRODUCTION

The design of tunnels requires a proper estimate of surface settlement and structural forces in lining. In urban tunnels, an accurate prediction and control of the magnitude and distribution of ground displacements due to tunneling is critical for the safety and integrity of surface structures (Sozio 1998, Netzel & Kaalberg 2000). Tunnel excavation and support is an extremely complicated three dimensional problem. Modeling of ground conditions is quite uncertain due to its heterogeneity and complexity and especially ahead of the excavation face its behavior is not easily predictable.

Numerical analyses are very helpful tools for assessing the ground response to tunneling and consequently having an effective and economical design.

The fundamental philosophy of the technique commonly referred to as NATM (New Austrian Tunneling Method) is to avoid or minimize the ground load than to resist it. Any kind of ground condition can be handled safely by following appropriate incremental excavation/support and/or pre-support approach (Zaki, M., Abu-Krishna, A. 2006). On one hand, deformation should be kept to a minimum so that the primary state of stability and compressive strength of the ground are not compromised. On the other hand, geomechanically controlled deformations are necessary to the extent that the ground formation itself will act as an overall ring like support structure. This creates a new state of equilibrium at an early excavation stage and thus minimizes costs of excavation and support (Karaku, M., Fowell, R.J. 2004).

The choice of cross section dimensions of the tunnel should be designed to be suitable for serving roadways utilization as shown in Figure 1. This method is highly recommended to reduce interruption due to tunneling operations in connections which pass a congested zone having traffic jams in congested urban areas. Additionally, the existence of a complex of bridge intersection and a lot of main utilities needs special attention. The NATM technique will serve to achieve this goal compared to the traditional cut and cover method.

The suggested dimensions of cross section of the tunnel include a clear height of the excavated cavity of about 5.0 m and a clear horizontal width of about 8.0 m. The cross section of the tunnel is designed to have double lanes and to be suitable for NATM tunneling. Two critical sections (shallow and deep) are chosen for investigation according to the geotechnical conditions shown in Table 1. The material parameters of the soilcrete and shotcrete were assumed from a similar research (El-Mossallamy and Stahlmann, 1999) which was based on the conducted laboratory and in-situ tests as well as on experience gained in similar projects.

2. GEOLOGICAL CONDITIONS

The subsoil mainly consists of a few meters of fill material followed by stiff clay, silty sand and medium sand (see Figure 1). The tunnel is located in the silty sand and medium sand. The groundwater table lies about 6.0 m below the ground surface. The material properties are shown in Table 1.

Table 1: Material Properties and Geotechnical soil parameters and the interfaces

Parameter	Symbol	Unit	Fill	Stiff. clay	Silty sand	Med. sand
Thickness	h	m	1.5	1.5	3	29
Dry unit weight of soil	γ_{dry}	kN/m ³	15	16	17	19
Wet unit weight of soil	γ_{wet}	kN/m ³	17	18	19	21
Permeability	K_x, K_y	m/day	1.0 E-3	1.0E-5	1.0 E-3	0.50
Young's modulus	E	Mpa	2.5	20	40	60
Poisson's ratio	ν	--	0.3	0.3	0.3	0.3
Cohesion	C	Kpa	5	100	-	-
Friction angle	ϕ	°	25	20	30	38
Dilatancy angle	Ψ	°	0	0	0	8
Triaxial secant stiffness	E_{50}^{ref}	Mpa	20	40	50	70
Oedometer tangent stiffness	E_{oed}^{ref}	Mpa	20	40	50	70
Unloading / reloading stiffness	E_{ur}^{ref}	Mpa	60	120	150	210
Unloading / reloading Poisson's ratio	ν_{ur}	--	0.2	0.2	0.2	0.2
Power in stiffness law	m	--	0.5	0.5	0.5	1.0
Coefficient of earth pressure at rest	K_o^{nc}	--	0.58	0.4	0.66	0.37
Failure ratio	R_f	--	0.9	0.9	0.9	0.9
Interface permeability	Perm	--	Natural	Natural	Natural	Natural

3. CONSTRUCTION SEQUENCE

The clear height of the excavated cavity is about 5.0 m and the clear horizontal width is about 8.0 m. The overburden height reaches about 3.0 m above the tunnel crown.

Factors that affect the tunneling design are geological conditions and deformation requirements.

The tunnel is situated in a relatively high permeability cohesionless soil with the groundwater table at about 6.0m below the ground surface. The tunneling process must fulfill the serviceability requirements of a tunnel proposal under railway at a level crossing Elhosania, Zagazig, Egypt regarding the total as well as the differential settlements. According to experience with similar conditions (El-Mossallamy and Stahlmann, 1999) the maximum allowable settlement on the ground surface was defined as 5.0 cm. Due to the relatively small tunnel length of about 400 m the New Austrian Tunneling Method (NATM) with special measures was considered as the most economical solution.

Figures 1 and 2 illustrate the construction sequence and the applied special measures to control the accompanying deformations. Tunnel driving was conducted in two main stages. The top heading of the tunnel above the ground water level was first excavated along the entire tunnel length. This stage was conducted under the protection of a soilcrete Jet grouting forming an "arch like" structure to prevent the collapse of the cohesionless sand. The basic parameters of the soilcrete are as follows:

- Cement/water ratio = 1.0
- Jet pressure = about 500 bar
- Velocity of retraction (withdraw) = 0.3 m/minute

Table 2: Material properties of soilcrete and temporary lining

Material	Elastic modulus for short term condition (MN/m²)	Material strength for short term condition (kN/m²)
Soilcrete jet grouting at tunnel top heading	1000	500
Soilcrete jet grouting at tunnel invert	500	250
Temporary shotcrete lining	15000	Elastic

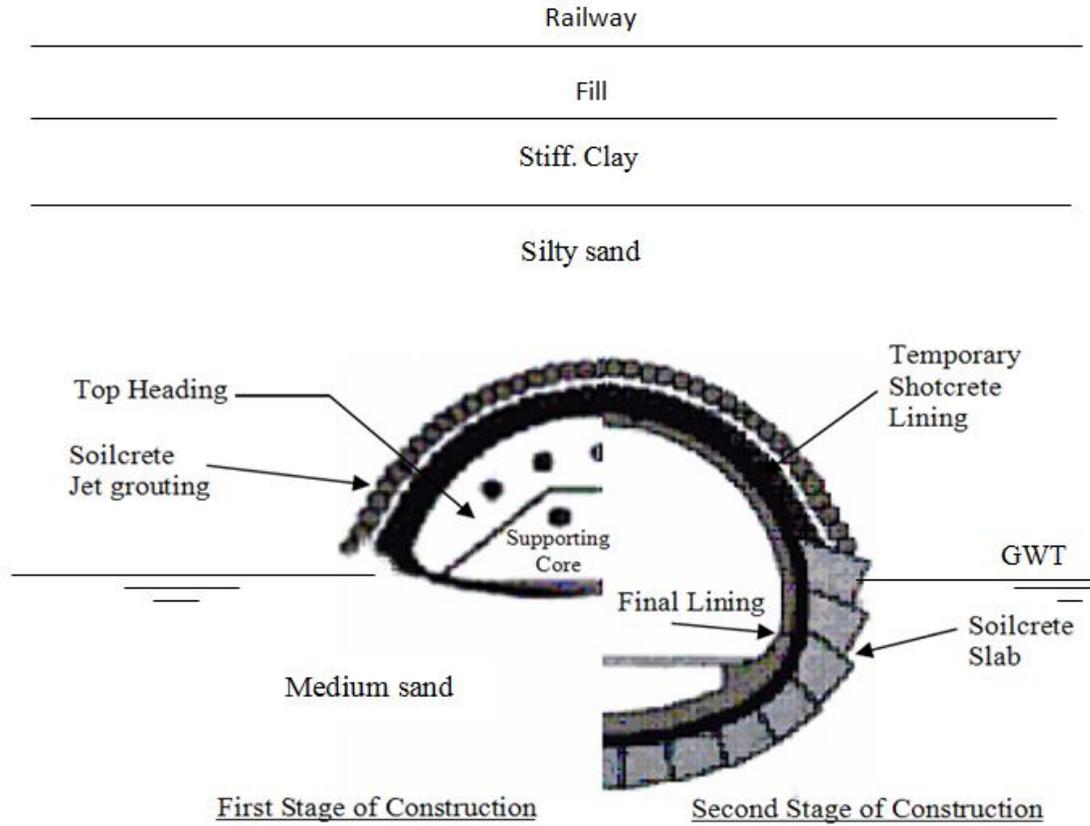


Figure 1: Layout of the tunneling system and soil stratigraphy

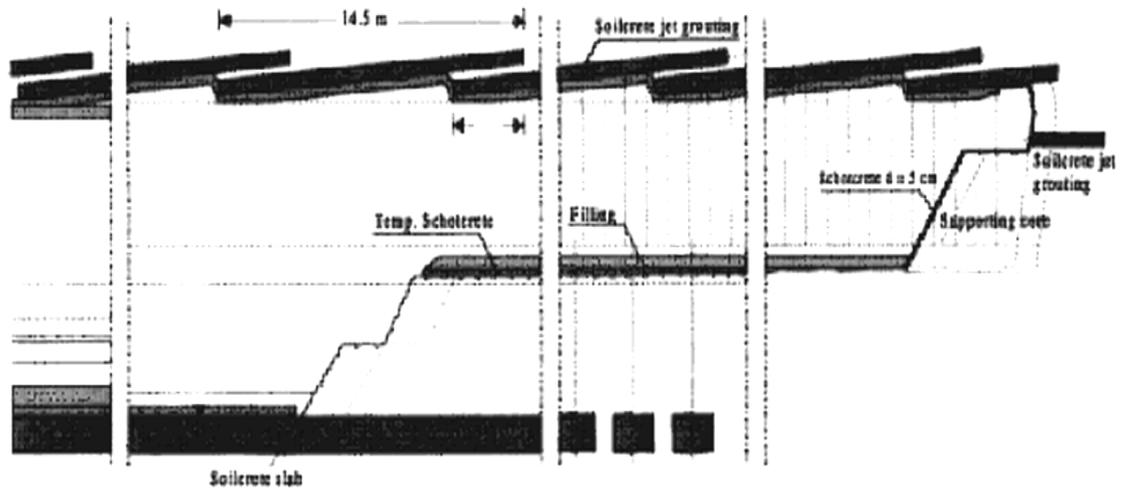


Figure 2: Construction stages of NATM

The horizontal soilcrete columns were designed with a length of 14.5m, a diameter of 0.75 m and a distance between the holes around the tunnel crown of about 0.6m to provide an adequate overlapping of the soilcrete columns. These soilcrete columns were installed at an inclination of 5% to the tunnel section in an outward direction forming the so-called umbrella shape. The tunnel excavation sections were 11m in length to enable an overlapping of the protection cover of 3.5m. The top heading excavation was conducted for segments with length of 80cm followed directly by a temporary shotcrete lining with two layers of welded wire mesh and U-shaped steel arches. Inclined micro piles (Figure 1) were installed under the benches of the top heading to increase its stability and to reduce the associated deformation. The tunnel face was stabilized by additional horizontal soilcrete columns in combination with a supporting core. The tunnel is driven from both tunnel portals.

In the second stage, a bottom seal was installed by means of secant jet grouting columns to provide a watertight inverted arch against the upward flow of water into the tunnel excavation. The excavation of the tunnel bench and invert was then conducted after breaking out the base slab of the temporary shotcrete of the top heading. The temporary shotcrete lining of the whole section was then closed. The construction of the permanent tunnel body (the inner shell) was followed with a tunnel crown of 50 cm thick and a tunnel invert of 80 cm thick.

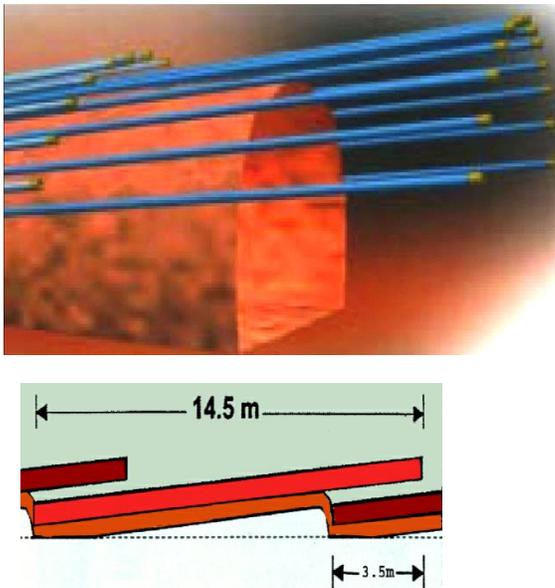


Figure 3: The Overlapping between Soilcrete Columns



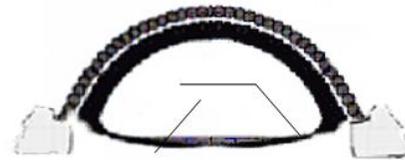
Figure 4: Operation of shotcrete lining

4. NUMERICAL SIMULATION

A two-dimensional finite element analysis was conducted to model the tunnel behavior using isoparametric linearly strain triangular elements with 15 nodes using program Plaxis (Brinkgreve, R.B.J., Vermeer, P.A. 2002). The soil was idealized using different constitutive laws to check their reliability. Elastic-perfectly plastic analysis using the Mohr-Coulomb model was carried out to detect the tunnel performance and the accompanying deformations. Additionally the Hard Soil model without and with cap was also applied to detect the sensitivity of a stress path dependent model. Figure 5 shows the used finite element mesh. Calculation of the stresses and deformations of the support elements and the surrounding soil was based on nonlinear FEM. The calculation was performed with several loading steps (Figure 5) to simulate the construction sequence as follows:



Step 1: Soilcrete jet grouting of the tunnel top heading.



Step 2: Excavation of the top heading and Installation of the secondary shotcrete lining.



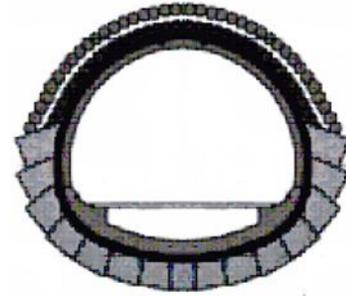
Step 3: Soilcrete jet grouting of the sealing base slab.



Step 4: Excavation of tunnel benches/invert and closing the temporary shotcrete lining.



Step 5: Installation of the Final lining.



Step 6: Construction of tunnel body.

Figure 5: Modeling the different construction stages

4.1. Displacements and Structural Forces for Shallow Section by Mohr-Coulomb Model

The soil layers and the tunnel for NATM for the shallow section can be seen in Figure 6. The crown of the tunnel is at 3.00 m below the ground surface. The finite element mesh adopted for the analysis of the shallow section is shown in Figure 7.

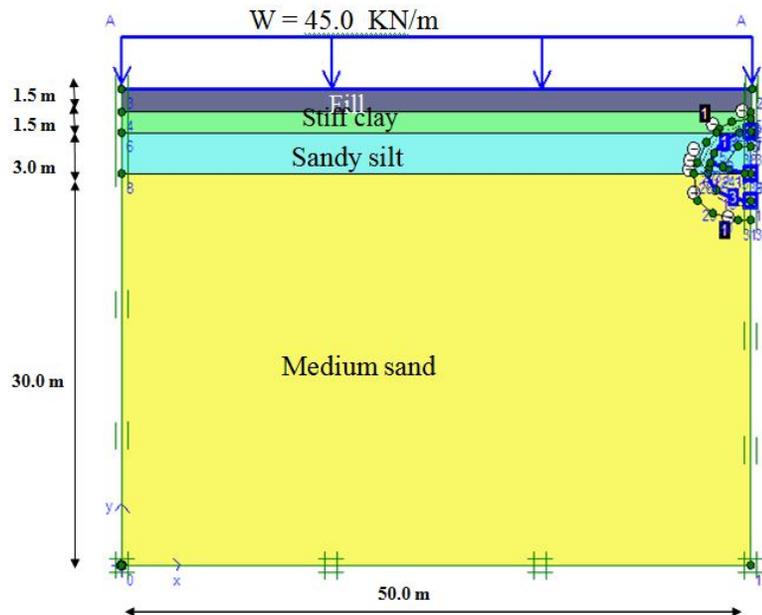


Figure 6: Soil layers and tunnel for the NATM

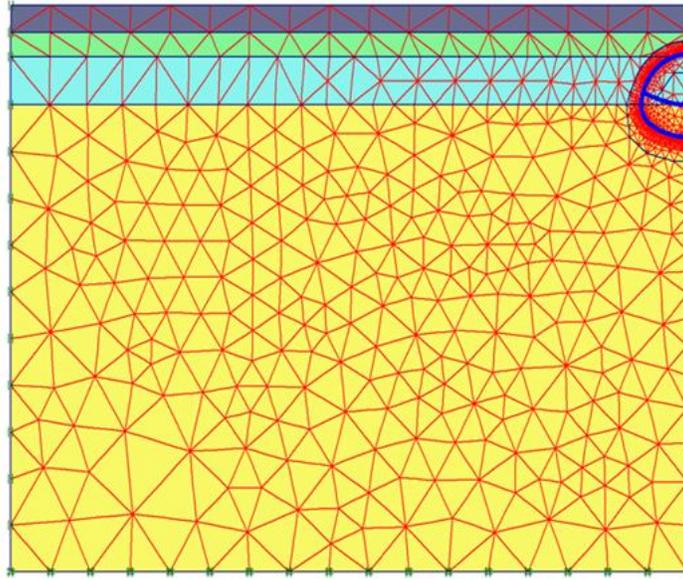


Figure 7: Finite element mesh adopted for the NATM

Figure 8 shows the deformed mesh at the final stage of construction. It is shown that the maximum total displacement occurs at the tunnel crown. The maximum vertical displacement (-25.42 mm at surface) is shown in Figure 9.

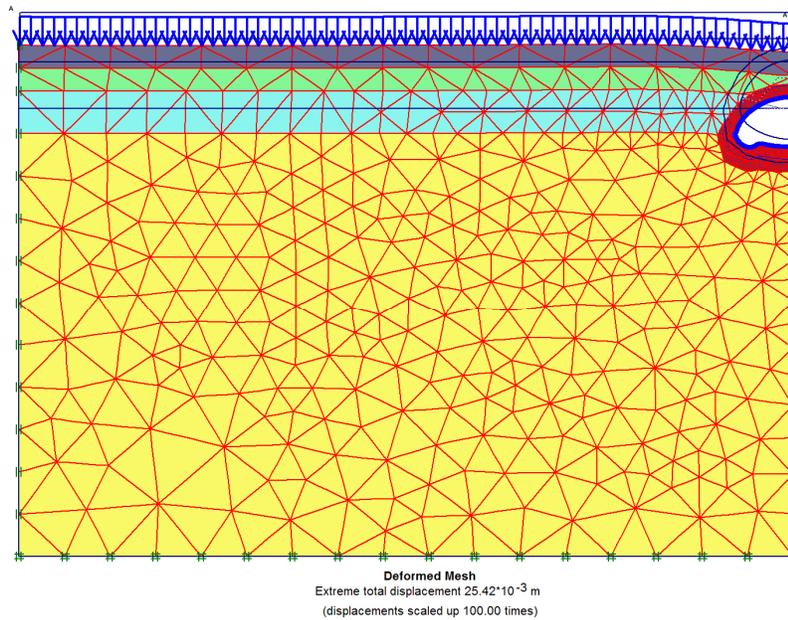


Figure 8: Deformed Mesh (Max.Total Displacement 25.42 mm)

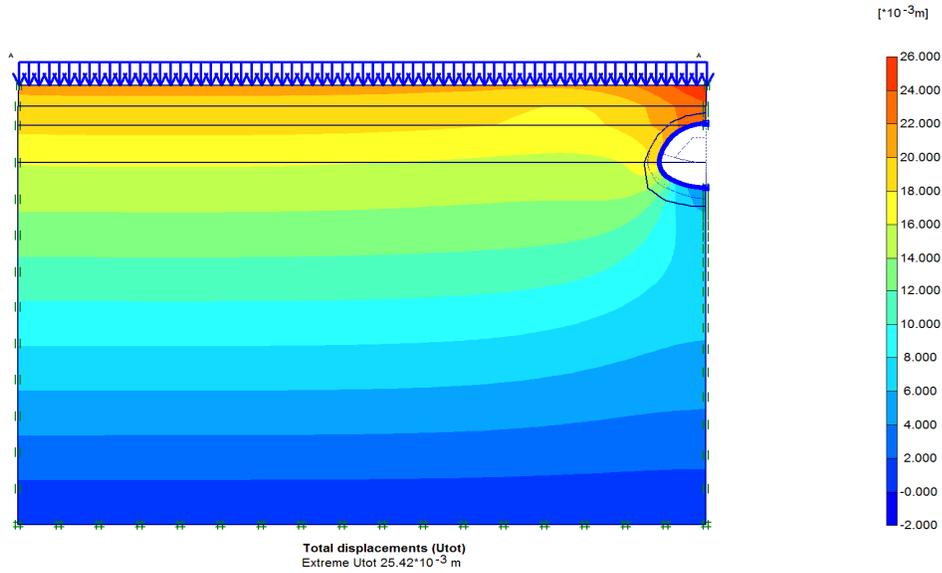


Figure 9: Vertical Displacement (At surface -25.42 mm)

It can be seen that the maximum settlement occurs at the final stage of construction and all surface settlements during the different stages of construction are considered allowable. Figure 10 shows the distribution of total stresses in the soil (Max.stress-724.96 KN/m²). The distribution of the pore pressure (Max. -289.07 KN/m²) is shown in Figure 11.

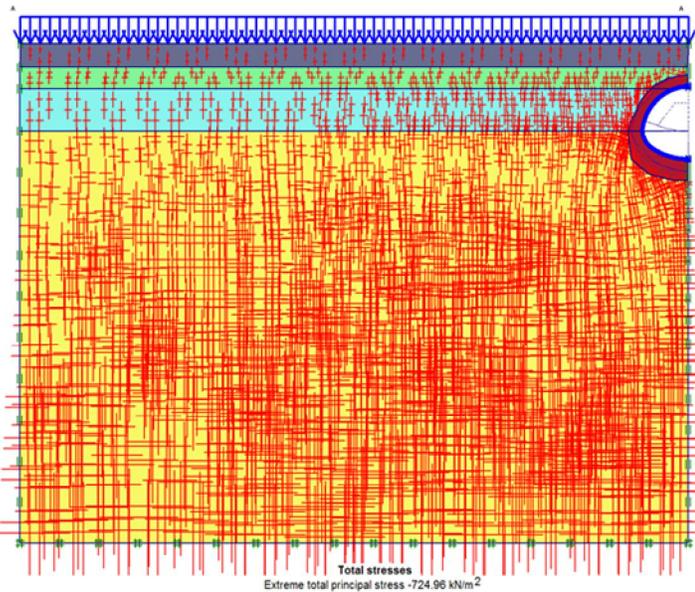


Figure 10: Total stresses (Max.stress: -724.96 KN/m²)

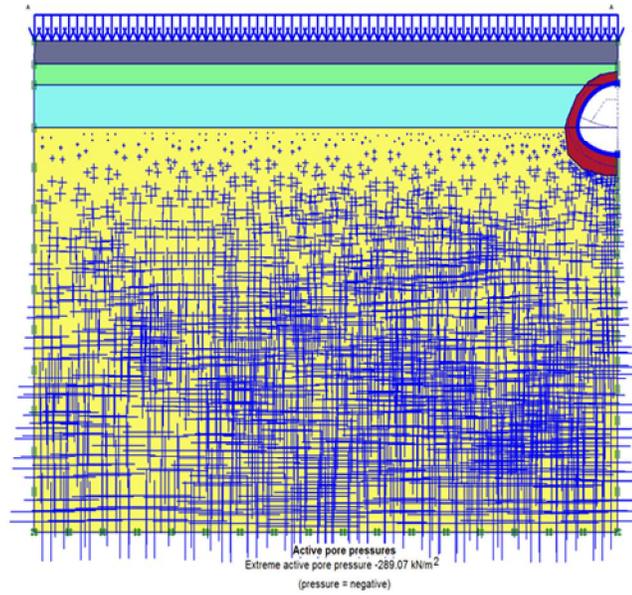
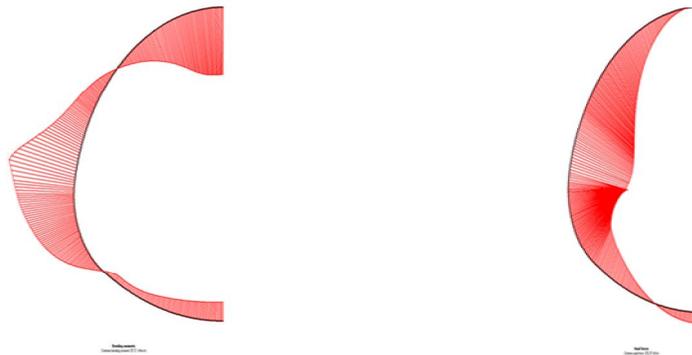


Figure 11: Active pore pressures (Max.: -289.07 KN/m²)

Figure 12 shows the critical values of normal forces (-252.97kN/m), and bending moments (-25.72 k.N.m/m) in tunnel lining for the shallow section.



A) Bending moments
 (Max: -25.72 k.N.m/m)

B) Normal forces
 (Max: -252.97 kN/m)

Figure 12: Structure forces for NATM

4.2. Displacements and Structural Forces for Shallow Section Predicted by the Hard Soil Model

The resulted final displacements and structural forces along tunnel axis for the shallow section is 3.0 m below the ground surface by using the Hardening Soil model. Figure 13. shows the deformed mesh at the final stage of construction. It is shown that the maximum total displacement (-29.84 mm) occurs at the tunnel crown. The maximum surface settlement for the shallow section is (-29.84 mm) shown in Figure 14.

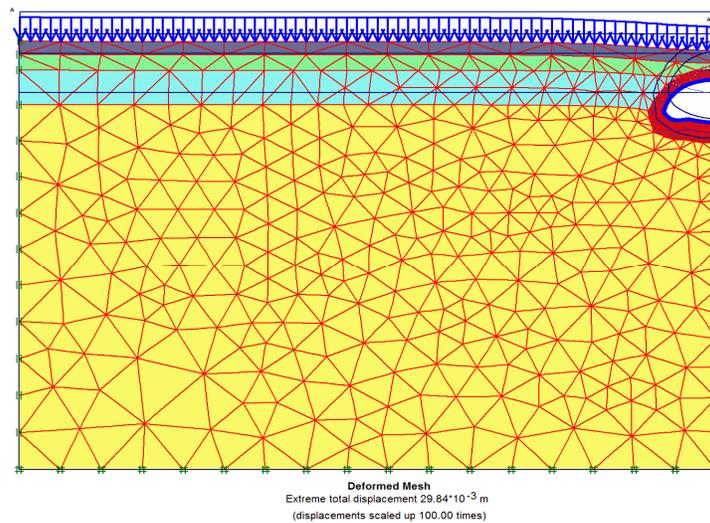


Figure 13: Deformed mesh (Max.Total Displacement 29.84 mm)

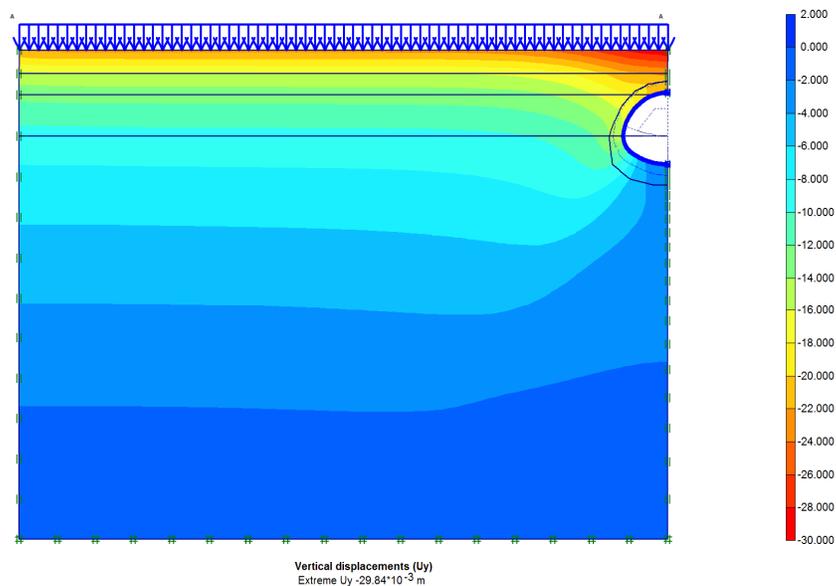


Figure 14: Vertical displacement (At surface -29.84 mm)

Figure 15 Shows the critical values of normal forces (-213.64 kN/m) and bending moments (-20.78 kN.m/m) in the tunnel lining for the shallow section predicted by using Hardening Soil model.

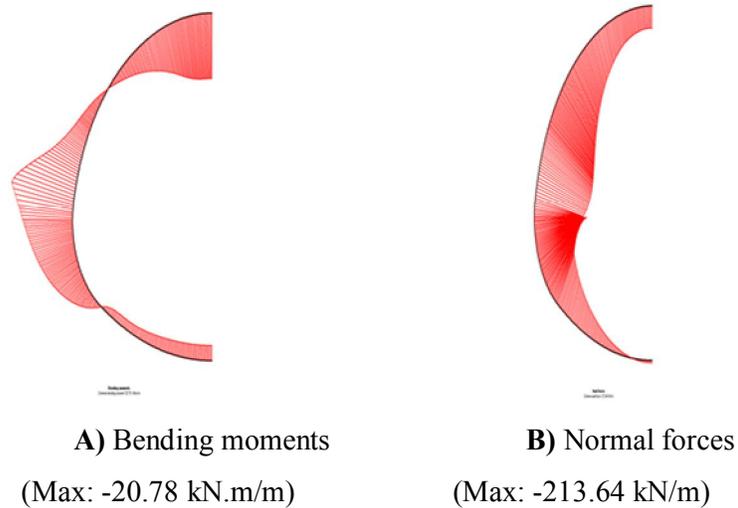


Figure 15: Structure forces for NATM

Fig.16. shows the surface settlement of the NATM cross section for the shallow section predicted using the Mohr-Coulomb and Hard Soil models. Fig.17. shows the vertical displacement for the shallow section (at final construction stage). It can be seen that the maximum settlements values occur at the final stage of construction and all surface settlements during the different stages of construction are considered allowable.

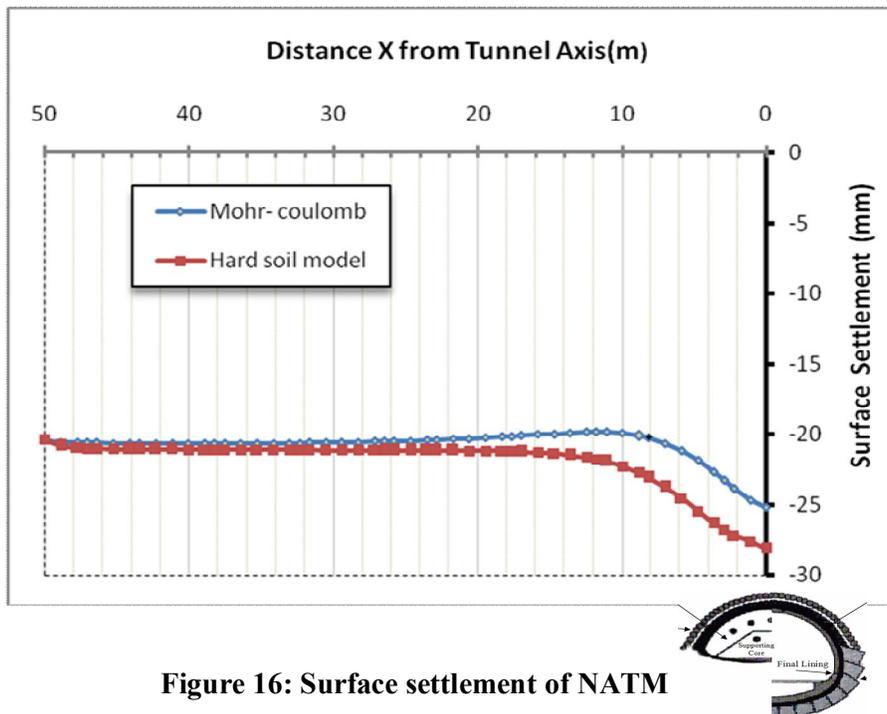


Figure 16: Surface settlement of NATM

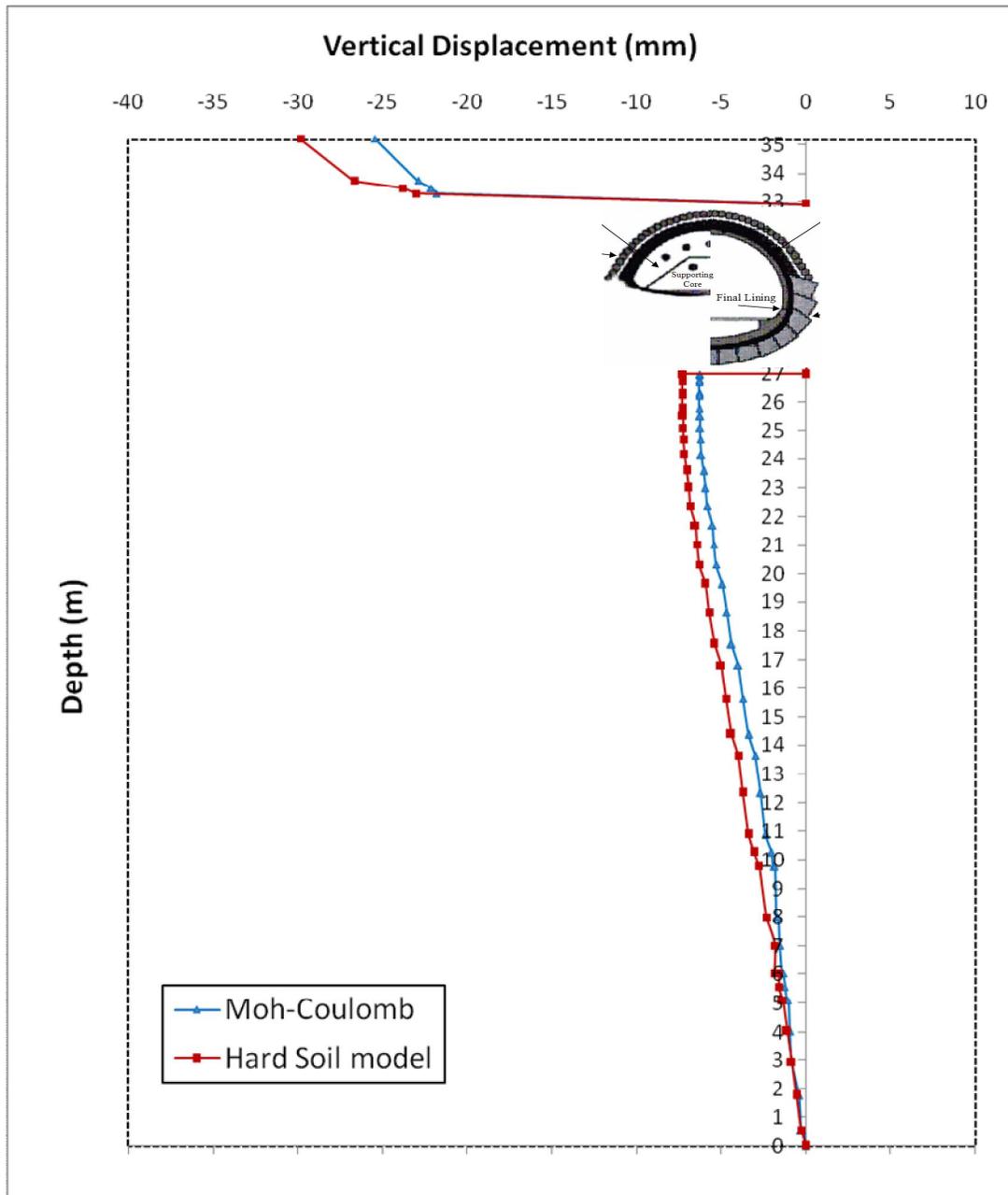


Figure 17: Vertical displacement of NATM

5. RESULTS AND ANALYSIS

The results obtained using the Mohr-Coulomb and Hard Soil models represent the expected upper and lower limits for the NATM tunneling section. The hard soil model is the most reliable model to simulate the tunnel behavior. That is due to its ability to characterize between unloading/reloading and primary loading conditions. Figures 16 and 17 present the expected vertical settlements for the shallow section at different levels at the final stage of construction. All the surface settlements are less than the allowable value of the National Authority for Tunnels (30.0mm).

Reviewing the settlement values of the tunnel at the surface during its construction indicates that the suggested construction sequence is safe. It is important to note that the main reason for introducing the grouting for the tunneling part is not only to control the settlements but also to ensure sufficient face stability in the sand.

Reviewing Figures 8 and 17 for the structural forces in the shotcrete lining for both shallow and deep sections after tunnel completion indicates that a concrete section with 40 cm thickness will be sufficient to resist the construction loads with a reasonable factor of safety. For the permanent lining, a concrete section with 50 cm thick is found to be more suitable for long term conditions.

It must be emphasized here that the above mentioned simulation is a trial to predict the deformations of the soil in the new method (NATM). Therefore, any disturbance in the shape of deformation would have no significant effect on the structural action of the temporary shotcrete lining because it is reinforced with two layers of welded wire mesh.

Finally, a new tunnel cross section was suggested to be suitable for NATM tunneling. A sequential excavation/support method was suggested for NATM tunneling and numerically simulated by FEM. Reviewing the settlement values during and after construction indicated that the suggested construction sequence is safe. The impact of soil strengthening prior to NATM tunneling operation in controlling soil deformations and increasing safety level is emphasized. More sophisticated analysis for tunnel face stability is recommended by using 3D modeling techniques. The use of powerful simulation techniques will encourage updating/optimizing modern construction techniques, minimizing construction cost and will help the decision makers to choose the optimum solution for the other phases and other tunnels projects in the future.

6. CONCLUSION

Numerical analysis is a powerful tool for the evaluation and for quantitative interpretation of field data for assessing the original design or construction. In numerical analysis techniques, the system is simulated in a numerical model based on a finite element discretization of the medium.

Although modeling all the boundary conditions and controlling the interaction between the ground and tunnels seems to be impossible, the proposed numerical modeling of the present work has yielded good results. These results confirmed the need for establishing a realistic construction procedure in the numerical model because it is considered as the main factor controlling the ground-tunnel interaction characteristics, especially by applying the NATM. This model is supposed to be equivalent to the real system. This equivalence means that the response of the numerical model should be as close as possible to that of the real system under the same conditions.

Most of the available studies have used the Mohr-Coulomb elastio- plastic model to represent the soil surrounding the tunnel as it is a simple model. In this paper, analyses were also carried out using the Hard Soil Model (HSM) to obtain a more accurate and reliable solution for the tunnel simulation.

The main conclusions can be summarized as follows:

1. Reviewing the surface settlement values during and after construction using the NATM indicates that the construction sequence is safe where these values satisfy the serviceability requirements of the National Authority for Tunnels. Thus, it can be said that there will be no risk in using this method in tunnel construction in Egypt.
2. The soil deformations for NATM can be controlled by using special soil strengthening around tunnel like grouting in cohesionless soil. This improvement also ensures a sufficient face stability of the tunnel.
3. It is highly recommended that NATM can be used instead of the Cut and Cover Method in tunneling construction in connections which have traffic jams in a congested urban area to reduce the interruption due to tunneling operations, where NATM technique will help in achieving this goal.

4. In relatively short tunnels, NATM can be used instead of the TBM in tunneling construction. The NATM is generally considered as an economical solution for tunneling.
5. The numerical investigation developed in this study has shown the possibility of simulating the tunneling excavation and lining phases using standard FEM commercial software. The use of powerful simulation techniques will encourage updating modern construction techniques, minimizing construction cost and helping decision makers to choose optimum solutions for future tunnels projects.

7. Recommendations for future work:

1. It is recommended to investigate the usage of the 3D modeling techniques in future research for tunneling analyses especially for NATM analysis in order to simulate the different stages of construction.
2. It is advised to study the failures occurred in tunnels accidents, especially for the NATM before applying this method in Egypt, to understand causes of failure and to avoid their occurrence during the execution.

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