كلية الهندسة بشبرا
FACULTY OF ENGINEERING AT SHOUBRA
ERJ
PRINT ISSN 3009-6049
ONLINE ISSN 3009-6022

ENGINEERING RESEARCH JOURNAL (ERJ)
Volume (54) Issue (2)
April. 2025, pp:20-26
https://erjsh.journals.ekb.eg

Verification of Green Field Settlement of Cairo Metro Line 3-Phase 3 Using Numerical and Analytical Methodology

Ahmed Samir Ahmed*[1];Naser M.Saleh[1];Nesreen Elsayed Elfaris[2] ;Waleed A.Dawood[1]
[1] Department of Civil Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt
[2] National Authority for Tunnels, Cairo, Egypt
* Corresponding Author.
E-mail: ahmed.samir@feng.bu.edu.eg; na_sa_64@hotmail.com; yasmina_bosy@yahoo.com; walid.dawoud@feng.bu.edu.eg.

Abstract: . Urban areas develop as a consequence of rapid growth in population. One approach to solving transportation problems in more ancient towns is the construction of tunnels. One potential technique for constructing tunnels in urbanization is the utilization of tunnel boring machines (TBM). During the tunnel's construction, this technique of work caused surface settlement, which creates risks and should be precisely anticipated to prevent its negative effects.
In this study, the various phases of the TBM tunnel construction in Cairo metro line 3 phase 3 were simulated using a 3D finite element model with the program Plaxis 3D. The model's output was then compared with the actual measured data at the study region. The findings demonstrate that the FEM and the measured actual data correspond well. Additionally, the impact of the initial ground water table was examined, and it was discovered that ground surface settlement decreases with increasing ground water level and increases by 34% when the ground water table is removed.

Keywords: Tunnel, Green field, Settlement, Greater Cairo Metro, Ground water level.

1. INTRODUCTION

Due to the increasing number of populations that lead to high congestion in cities and causes a lot of traffic issues, the use of shield method of tunneling has become more convenient and demanding [1]. Shield tunnels have a minimal impact on surface traffic and typically have a circular cross-section [2]. The main risk and problem issues for using the shield tunnel is the surface ground settlement and predicting of this induced settlement is the major challenge in urban development [3]. To investigate ground surface settlement in a greenfield area there are three major methods that can be used (1) physical model and centrifuge test, (2) Analytical method, (3) Numerical modeling.
The centrifuge model tests were done before to get the ground surface settlement of the tunnels in the laboratory using physical models [4]. Loganathan et al. [5] conducted three centrifuge model tests in clay to get the ground surface settlement due to tunneling and its effect on the adjacent piles. In addition, the test results were verified with empirical and analytical methods. Centrifuge tests also was used to get the surface settlement of dense dry sand and the piles settlement at various distance and located at the zone of influence of the tunnel [6].For sandy soil centrifuge tests were conducted to get the ground surface settlement and this test results were verified using empirical and traditional methods[7].At the same time several analytical approaches were conducted to predict the ground surface settlement in both clayey and sandy soil [8].
Analytical approaches to get the deformation in an elastic soil was derived considering uniform radial displacement and shape of tunnel [9]. In addition to the previous the ground surface settlement was predicted in undrained clay soils based on empirical methods and it was found that this method gives good prediction of surface settlement in stiff clay soil and overpredict the settlement in soft clay [10].
As finite element modelling become a vital and valid way to simulate the geotechnical problems, several modeling techniques, including 2D Finite Element (FE) models and 3D FE models using commercial software like PLAXIS,

ABAQUS, and FLAC, can be employed to conduct numerical investigations of tunneling methods such as TBM, mechanized tunneling, or NATM [11] [12] [13].Despite the longer run time required for analysis, 3D FE models are commonly used and available due to its high accuracy and ability to deliver results in all three dimensions. [12] [13]. Prior research has compared the effectiveness of various tunnel construction techniques by examining ground surface settlement due to tunneling methods using the 3D FE methodology [14]. They reported that open-face approaches resulted in the highest volume loss and tunnel cavity distortion, whereas the closed-face EPB method produced the lowest values.

Recently 3D finite element modeling was conducted to investigate the water and tunnel interactions and It was discovered that changing the drainage boundary conditions from completely impermeable to permeable results in a 25.6% increase in the maximum axial force and a 14% increase in the bending moment [14].In addition ground surface settlement and the parameters affecting it was studied and investigated before using finite element methods and numerical modelling [15] [16].The 2D and 3D finite element numerical modelling were used to simulate the tunnel excavation techniques[17].In this modeling there were assumptions considered as elastoplastic sub-loading in the soil model and it was found that the ground surface settlement can be predicted using 2D and 3D models however 3D models should be used to get the induced forced on the tunnel lining . The finite element modelling can be used and gives good results for static and dynamic loading. Also, 3D finite difference models were used to investigate the tunnel advance. The Finite difference model was created using two constitutive models, plastic hardening and linear elastic and it gives accurate results compared to the actual measurement [18].

The objective of this study is to perform 3 D finite element modelling using plaxis 3D to simulate all the construction stages for the TBM passing under the greenfield area and validate the output results with the actual measured data for an area at a location of Cairo metro line 3 phase 3. Also to get the effect of changing the groundwater table on the ground settlement.

2. Characteristics of Cairo metro line 3 phase 3

The Greater Cairo Metro is an important rapid transit system in Egypt.Cairo metro Line 3 is divided into 3 phases: A, B and C with a total length of about 17 km. The below figure shows the proposed route of Line 3 phases A, B, and C. The current study is limited to Phase 3A which has a length of about 4 km and will be constructed entirely underground. Phase 3A starts from the existing Attaba Station to the diversion structure just after Sudan Station.

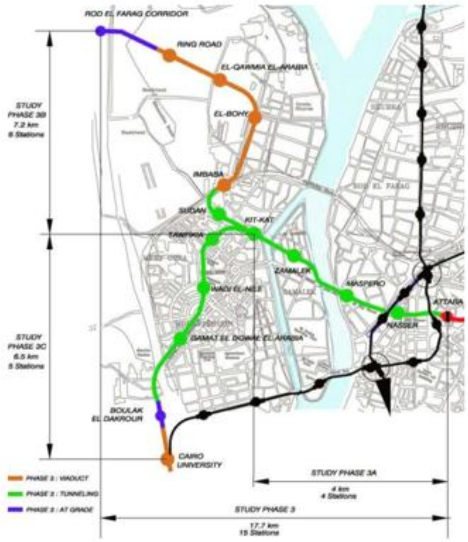

FIG 1. Route of Cairo Metro Line 3 Phase 3

Cairo metro line 3 tunnel has been constructed using earth pressure balance EPB-TBM with a tunnel internal diameter equal to 8.35 m and with a lining thickness of 0.40 m. The shield tail diameter is 9.45 m and the tunnel overcut diameter is 9.15 m. Geologically, the major soil types at the line are Fill, Clay & Silt, Upper Sand, and Lower Sand. The study area is at a location before Zamalek station. The study area is at KP25.520 and the geological profile in the area is shown in figure 2. The depth of the tunnel in this area is 18.70 m from the ground surface.

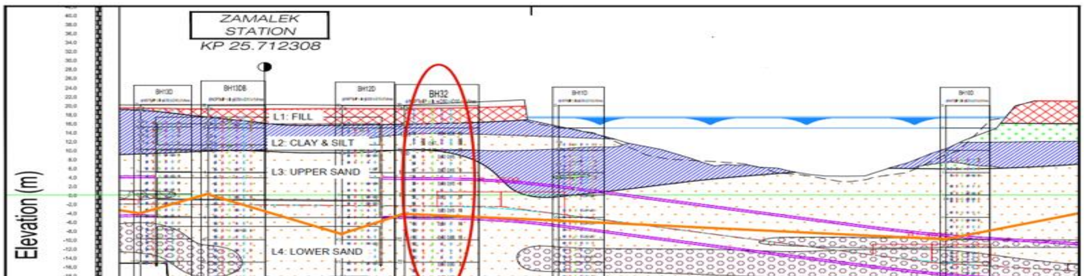

FIG 2. The Geological Profile for the Cairo metro line 3 phase 3 at the study area

And the soil properties at this location is shown in the table below

TABLE 1. Soil properties at the study area

Layer	Fill	Clay / Silt/ Sand	Upper Sand	Lower Sand
Top level (msl)	20.22	16.5	9.6	-2.1
Bulk Density γ (kN/m3)	18.0	19.1	19.3	20.6
Undrained Cohesion c_u (kPa)	-	58	-	-
Poisson Ratio	0.30	0.35	0.30	0.30
Undrained Modulus of Elasticity E_u (MPa)	-	16.1	-	-
Angle of Internal Friction ϕ' (°)	27	27	38	40
Drained Cohesion c' (kPa)	0	0	0	0
Drained Modulus of Elasticity E' (MPa)	5	14	90	250
Coefficient of lateral earth pressure, KO	0.54	0.65	0.38	0.36

The ground water table is at level +16.8 M.S.L.

3. NUMERICAL MODELLING

The principal aim in this section was to present 3D numerical analyses, based on the F.E. technique. Finite element modelling was done using plaxis 3D program to simulate the tunnel construction using tunnel boring machine and to get the tunnels surface settlement.

A plain strain model is used for the study and the dimensions of the model have been considered more than 10 times the dimeter in both X and Y directions. These dimensions were chosen to decrease the boundary effects [19]. Ninety-three simulation steps were considered in the model to simulate all the construction stages of the tunnel (tunnel lining, grout pressure, tunnel face pressure, jack thrusting and tail void grouting) so that realistic results and findings can be achieved.

3.1. Size of the Model

To minimize the boundary effect the dimensions of the models are considered more than 10 times the diameter of the tunnel in the two directions x and y directions. The model extends more than two times the diameter of the tunnel below the bottom of the tunnel. The dimensions of the model are 200 m, 200 m and 50 m in length, width and depth (shown in figure 3) and these dimensions match the suggestion of the model dimension by Peck [20].

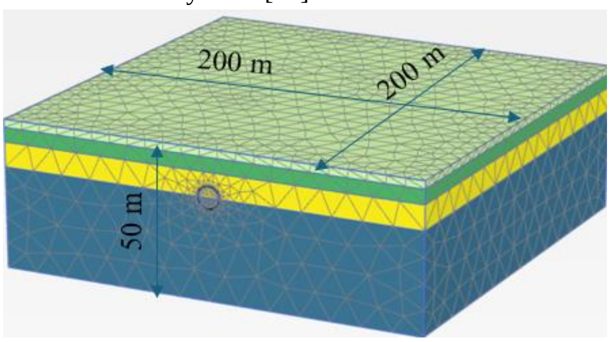

FIG 3. Plaxis 3D Model after meshing

3.1. Soil Layers

All the soil layers are modelled as elastoplastic soil constitutive Mohr–Coulomb model and the input data are according to table 1.

3.2. Modelling of the TBM Shield

In the model, the TBM (tunnel boring machine) is represented by plate components and is estimated to be 10.5 m long to accommodate seven standard slices in the study [21]. The segment thickness is 0.4 m, and the segmental tunnel lining is modeled as shell pieces and the effects of the joints through the line segments were considered. The equivalent reduced thickness used in the model is 0.32 m and this reduced thickness was calculated through Muir Wood (1975) [22] equation. The equation calculates the equivalent reduced moment of inertia I_e

$$I_e = I_j + \left(\frac{4}{N}\right)^2 . I$$

Where, I_j is the moment of inertia of the joints, N is the number of joints in the ring(N=7), I is the moment of inertia of the ring without joints.

3.3. Surface Contraction

The cone-shaped TBM requires the addition of a soil-structure interaction on the exterior of the tunnel. In our case, TBM’s tail has a cross-sectional area that is 0.3% less than its front.

3.4. Modelling of TBM face pressure and grouting pressure

Several loads influence the construction of the bored tunnel, including the face pressure that keeps the excavation stable. The face pressure is predicted to be equal to the hydrostatic pressure and operates in the horizontal direction. The face pressure is essential to maintain tunnel stability and decrease surface settlement [21]. The face pressure is calculated according to Dutch Centre Underground Bowen (COB) recommendations [23]. The face pressure adapted for the 3D finite element model is calculated to be 250 kN/m^2

Overcutting leaves a gap between the liner and soil that must be filled. The grouting pressure is used to fill this gap. When grouting, the grout pressure needs to be greater than the hydrostatic pressure outside the liner. The backfill grouting pressure is often calibrated to be 50–100 kN/m^2 greater than the slurry pressure [21]. The grouting pressure shall be considered as 300 kN/m^2.

3.5. Construction Stages of the model

After the initial stage the tunnel is defined to be advanced already by 21 m in the ground to simulate the movement of TBM inside the ground. After that Face excavation is applied, face pressure is activated and the soil inside the excavation is deactivated at the same time the cluster volume inside the excavation is set to dry state. Next the same steps are applied but only the surface contraction is applied till continuing the construction stages of the TBM(7stages).

3.6. Output from the model

Generally, the maximum settlement at the ground surface occurs directly above the tunnel and is increasing with the advancing of the tunnel. The maximum surface settlement reaches 7.50 mm above the line axis while it decreases at the area away from the axis. At the same time there is small value of heave happened after this area. Figure 4 shows the ground surface settlement at the ground.

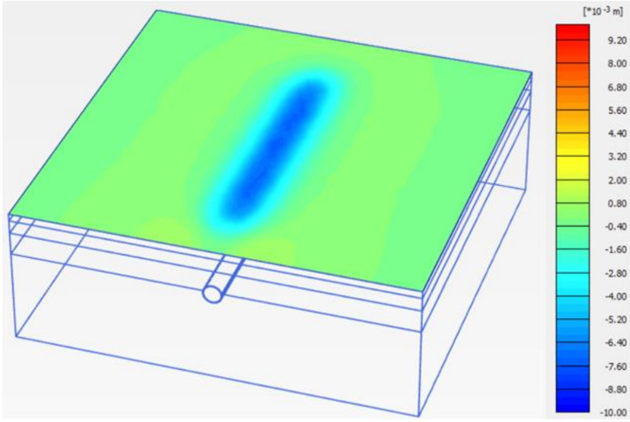

FIG 4. Maximum ground surface settlement from Plaxis 3D Numerical Modelling

3.1. Model Verification and Discussion

The settlement after TBM advancement in Cairo metro line 3 phase 3A at the study area (KP25.520) was measured and has been used to validate the FE numerical model.

Figure 5 shows the location of Elevation Reference Points (ERPs) regarding the tunnel route and the maximum settlement was 7.6 mm near tunnel CL.

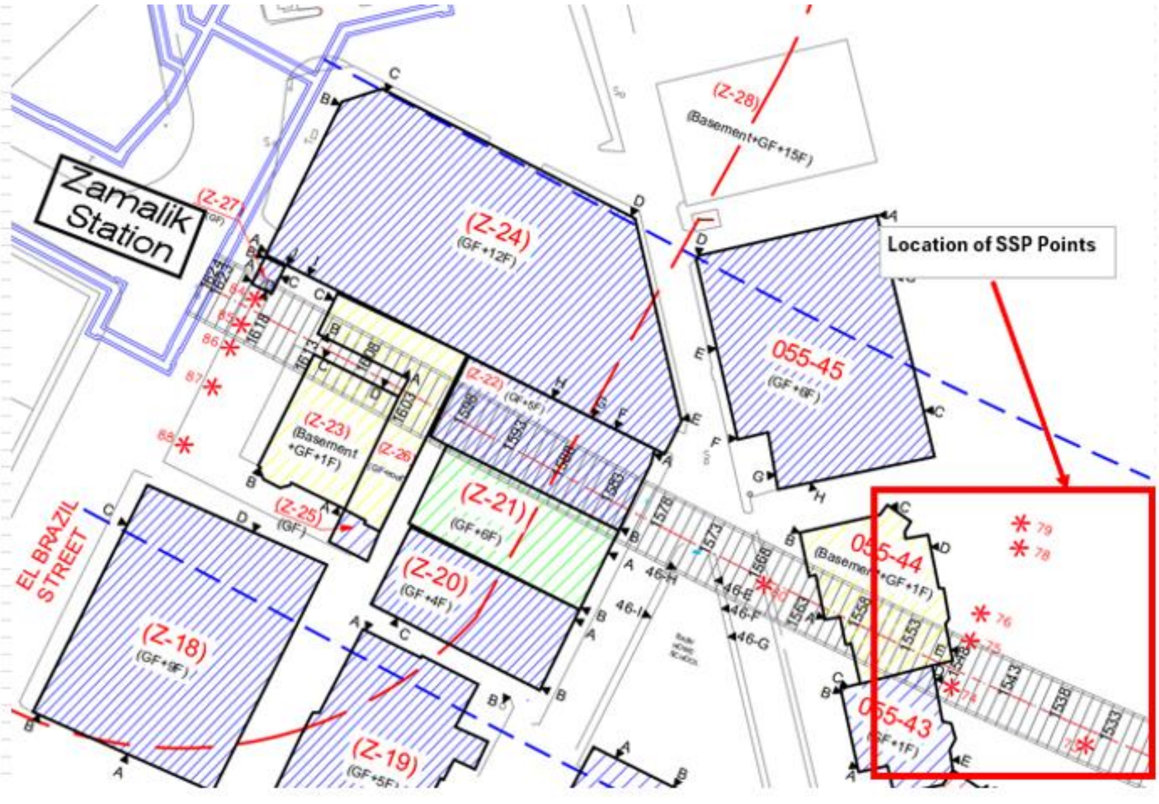

FIG 5. Location of ERPs regarding the tunnel route

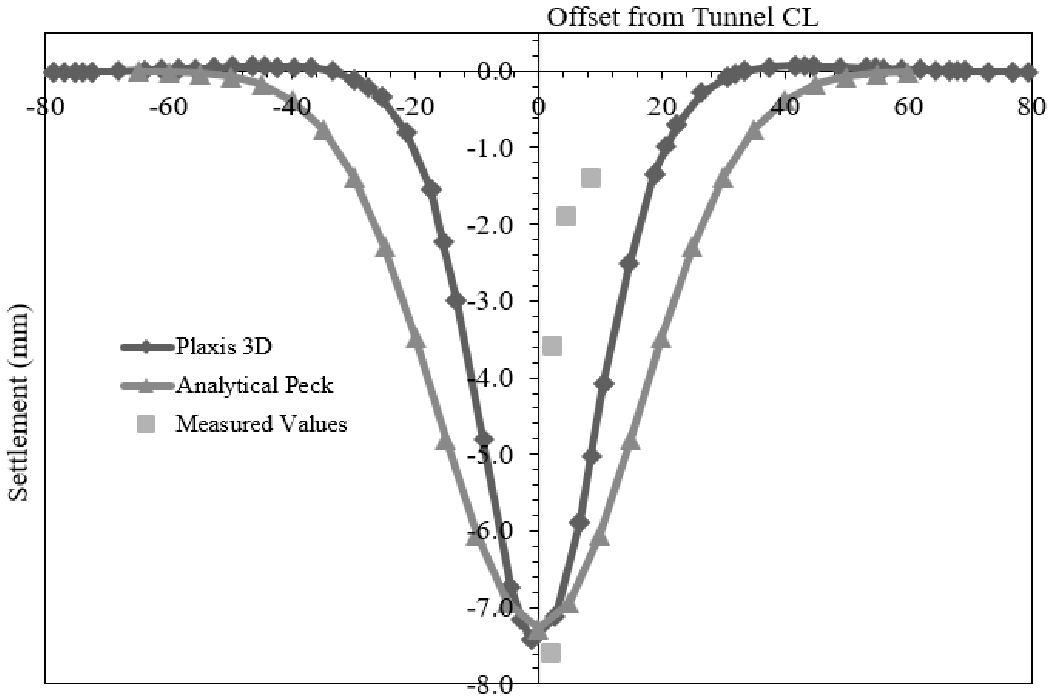

FIG 6. Ground Surface settlement using different methods

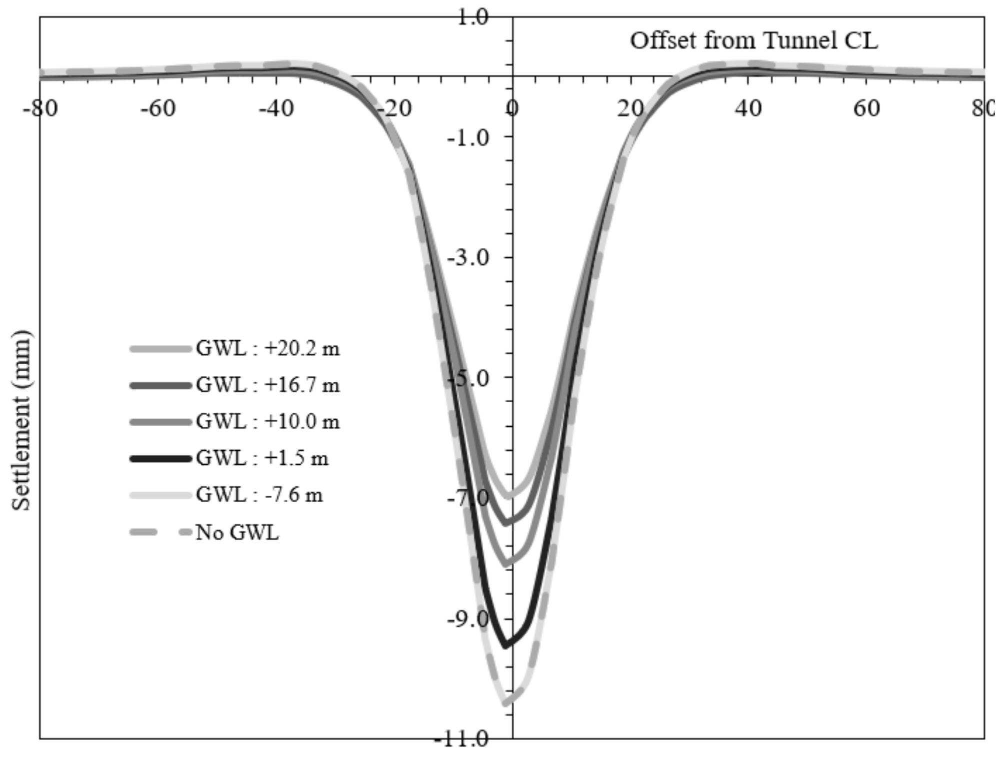

FIG 7. Transverse Ground Surface Settlement due to change in GWL

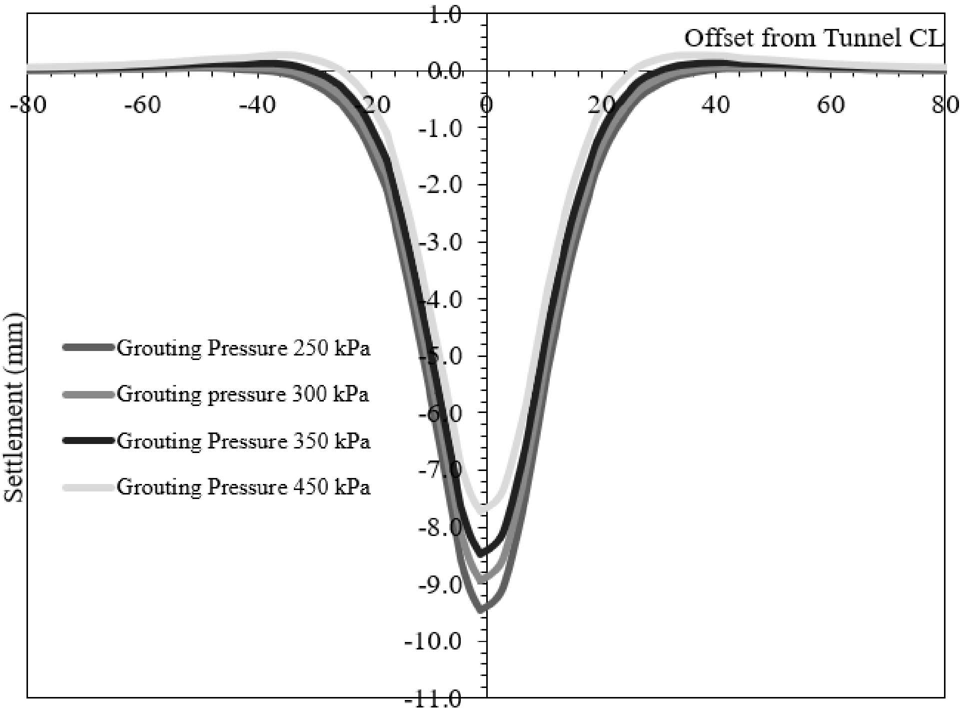

FIG 8. Ground Surface Settlement through different grouting pressure

The maximum measured settlement is 7.6 mm for surface settlement point SSP 73 which is located 2.1 m from the tunnel center line. The results with numerical model were validated with the measured settlement and with the results from the analytical methods as shown in figure 6. The numerical modelling results are in good agreement with measured values, and this confirms the numerical modelling accuracy.

3. Parametric Study

There are a lot of factors that affect the surface ground settlement due to tunnelling. The factors are composed of mechanical and geometrical factors. The ground conditions, way of tunnelling and tunnelling parameters are the main factors that affect this settlement.

This study is based on the data at station (KP25.520) at Cairo metro line 3 phase 3.

Two parametric studies were done to get the effect of changing the ground water level on the ground surface settlement. The first parametric study was done by changing the original water level +16.7 m to levels +20.2 m, +10.0 m, +1.50 m, -7.60 m and dry soil conditions and by keeping the face and grouting pressure the same. The levels +1.50 m and -7.60 m were chosen as the tunnel crown and tunnel invert. However, level 20.2 m is the ground surface . The transverse ground surface settlement is shown in figure 7.

It was found that by lowering the ground water level the surface ground settlement increased and removing the ground water table (soil is dry) the ground surface settlement increased by 34 %. Also, if the ground water table is under the tunnel invert the ground surface settlement would not be affected by lowering the ground water table.

Another parametric study was done to study the effect of changing the grouting pressure on the ground surface settlement. The case that is studied is the water elevation +10.0 m and the face pressure was reduced to 170 kPa accordingly. The grouting pressure was changed to 250 kPa, 300 kPa, 350 kPa and 450 kPa. The ground surface settlement is shown in figure 8.

It is found that increasing the grouting pressure decreases the ground surface settlement.

4. Conclusion

This study is done to get the surface ground settlement in the green field area due to the TBM tunneling using 3D finite element program plaxis 3D.First the model was validated by actual measured data at study area KP25.520 at Cairo metro line 3 phase 3.Also the effect of changing the ground water table on the surface ground settlement was studied and the findings from this study can be summarized as follows :

- 3 D finite element model is applicable to analyze and predict the behavior of Cairo metro line3.
- The results of 3D finite element model are in good agreement with the field data and analytical calculation.
- Lowering the ground water level increases the effective stress thus the ground the surface settlement increases, considering constant face /grout pressure.

- Removing the ground water table increases the ground surface settlement by 34 %.
- Lowering the ground water level below the tunnel invert will not affect the results of surface ground settlement.
- The grouting pressure should be increased to prevent the increase in ground surface settlement due to lowering the ground water level.
- Face/grout pressure has a major effect on ground settlement and should be calculated adequately to limit the ground settlement.

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