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NUMERICAL ANALYSIS OF TUNNEL BORING MACHINE IN SOFT GROUND

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ABSTRACT

In this paper, it is planned to use numerical modeling to investigate the ground movement due to tunneling construction in soft ground. The proposed method is used for analyzing the under construction tunnel of Cairo Metro–Line III. Most of the length of this line will be constructed by Tunnel Boring Machine (TBM). Two and three-dimensional numerical analyses are applied to simulate this tunnel and approach for prediction of the settlement due to tunneling in soft ground by using Plaxis program. The resulted settlements of these analyses will be compared with the measured values which be gained from the field data in the site. Reasons for any differences are explained. The results of these models are promising; help to minimize the construction cost and help the decision maker to choose the optimum solution for the other phases and other lines in the future.

KEYWORDS

Tunnel Boring Machine (TBM), Numerical Modeling, Shallow tunnel, Deep tunnel

1. INTRODUCTION

Tunnels design requires a proper estimate of surface settlement and internal 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, Shabna PS, Dr.Sankar, 2016). The problem of tunnel excavation and support is an extremely complicated three dimensional one. Modeling of ground conditions is quite difficult due to its heterogeneity and complexity especially in front of the excavation face. Numerical analyses are very helpful tools to assess the ground response to tunneling and consequently to have an effective and economical

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design (Nakai, et al., 2000). Darabi et al. (2002) presented an appropriate model to predict the behavior of the tunnel in Tehran No. 3 subway line. They employed empirical methods to determine the variation of radial displacements along the longitudinal direction of a tunnel.

Tunneling in Egypt has been activated in the last thirty years where Greater Cairo Metro lines, road tunnels and wastewater tunnels network were all under construction. It is expected that this specialized construction activities will continue at a similar rate during the next ten years to complete the exiting plans of new infrastructures. The Greater Cairo Metro includes a regional line (line I) and two urban lines (line II and line III). The tunneling part of the first line was constructed using the Cut and Cover Method. Line II was constructed by Tunnel Boring Machine (TBM), which is used also to construct line III. (Zaki, M., Abu-krisha, A., 2006). Figure 1 shows the greater Cairo metro network and detailed route of line III.

El-Azhar road tunnels were also constructed using the same TBM of line II. For shorter lengths and unseemly shapes, for example junctions and underground stations, tunnels are typically excavated by hand with or without a shield and a sprayed concrete rimary lining is used which is often a cost efficient solution. The amount of resulting surface settlement depends partially on which methods, if any, are being applied to control the ground movements ahead of or around the excavation.(El-Kilany, M. El., 2000, Abu-Krisha, A., 2002, Mazek SA., Almannaei H.A. 2013).

In this paper, numerical simulation techniques are employed to investigate the current construction method for Cairo Metro-Line III as a representative of a range of practical configurations. Most of the length of this line will be constructed by the TBM method. Two and three-dimensional numerical analyses are used for the prediction of the settlement due to tunneling in soft ground by using Plaxis program. The resulted settlements are compared with the measured values obtained from the site. The deformations occurring during tunnel construction by TBM are predicted with good accuracy using a phased excavation scheme in two and three dimensional finite element calculations.

Numerical analyses are very helpful tools to assess the ground movement due to tunnelling and consequently having an effective and economical design. The purpose of the numerical simulation is to analyze both methods to get the deformation and stresses in the tunnel vicinity and to check tunnel stability and the suitability of the construction method. Additionally, the method of strengthening the ground to ensure more safety for NATM application has been investigated using numerical modeling. The results of these analyses are promising and will help in minimizing the construction cost and may help the decision maker to choose the optimum solution for tunnel construction in the future. (Mroueh, H., Shahrour, I., 2007, Ezzeldine, O.Y., Darrag, A.A., 2006).

The tunnel analysis 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 tunnelling is critical for the safety and integrity of surface structures. Tunnel excavation and support is an extremely complicated three dimensional problem. (Brinkgreve, R.B.J., Vermeer, P.A., 2001).

Based on the conducted analysis which was produced by (El-Mossallamy and Stahlmann, 1999), it could be conc1uded that the stress path dependent model (The Hardening Soil model) could detect the performance of tunnels better than the elastic - perfectly plastic model (The Mohr - Coloumb model). Brinkgreve, R.B.J., Vermeer, P.A. (2002).

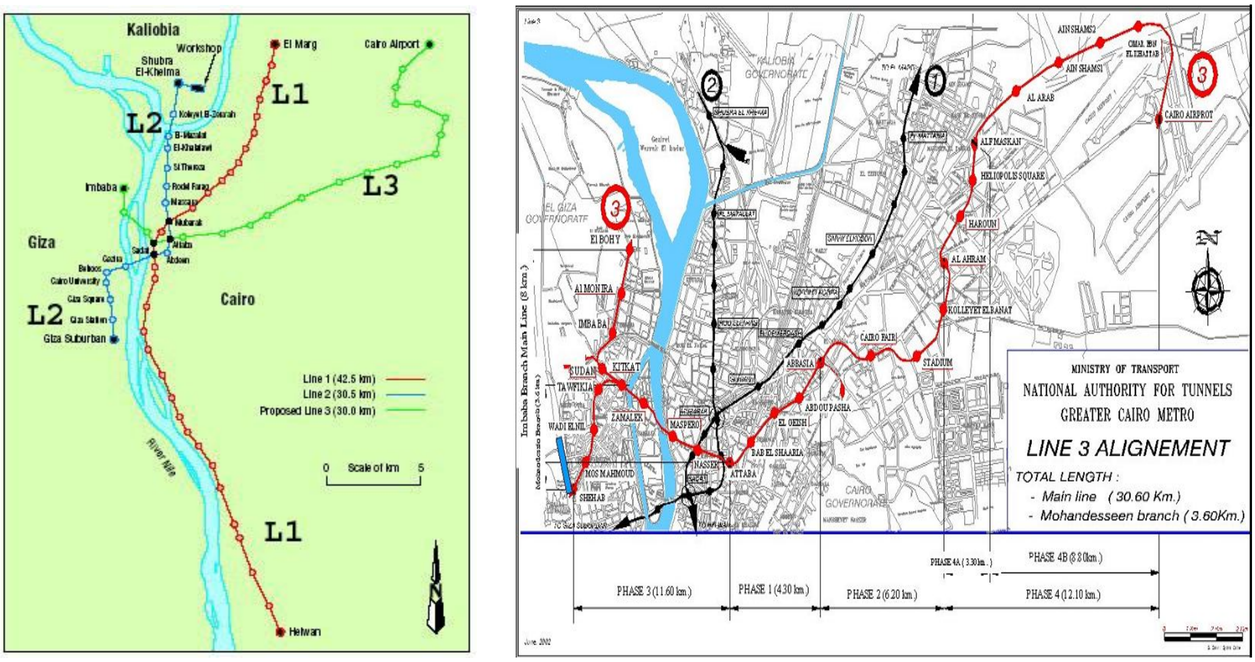


Figure 1: Greater Cairo Metro Network and detailed route of line III (after NAT.2009)

2. GEOTECHNICAL CONDITIONS

The geology formations along the tunnel route are typical Cairo Nile Alluvial Deposits. Geotechnical parameters are based on the geotechnical investigation report (NAT documents 2003). The values were similar to the corresponding ground formations encountered on the project of Cairo Metro Line II. The geotechnical soil profile which used in the current analysis for the shallow section and deep section was similar to the corresponding ground formations for Cairo Metro-Line III. Figure 2 shows the soil layers and thickness which had been used in the current analysis for the shallow section and deep section. The ground water was encountered in the boring and the water table was ranging between 2.0 to 6.0 m below the ground surface, taking an average depth in this study at a depth of 4.0 below the ground surface. The material properties are shown in Table 1.

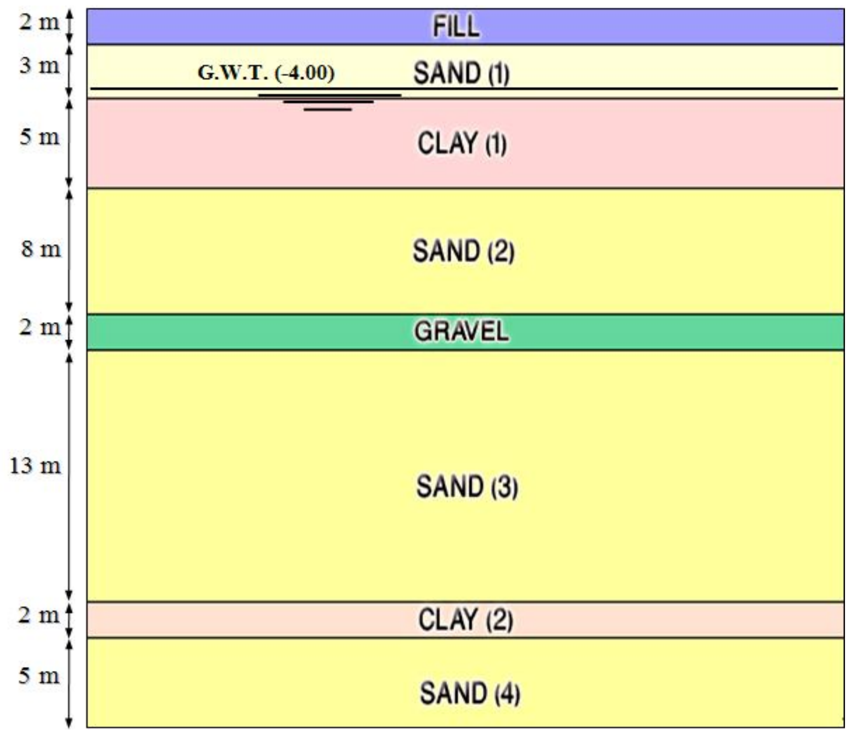


Figure 2: Geotechnical Soil Layers

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

Parameter	Name	Unit	Fill	Sand(1)	Clay(1)	Sand(2)	Gravel	Sand(3)	Clay(2)	Sand(4)
Layer Symbol	--	--	Layer A	Layer B	Layer C	Layer D	Layer E	Layer F	Layer G	Layer H
Levels	--	--	0--2	2--5	5--10	10--18	18--20	20--33	33--35	35--40
Dry Soil Wight	γ_{dry}	kN/m^3	15	16	15	17	18	18	16.5	17
Wet Soil Wight	γ_{wet}	kN/m^3	17	18	17	19	20	20	18.5	19
Young's modulus	*E*	*Mpa*	2.5	35	12	40	100	40	14	45
Poisson's ratio	*v*	--	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Friction angle	φ	°	25	37	20	39	42	38	20	40
Dilatancy angle	ψ	°	0	7	0	9	12	8	0	10
Cohesion	*C*	*Kpa*	5	5	75	5	1	5	150	5
Triaxial Secant stiffness	E_{50}^{ref}	*Mpa*	2.5	35	12	40	100	40	14	45
Oedometer Tangent stiffness	E_{oed}^{ref}	*Mpa*	2.5	35	12	40	100	40	14	45
Unloading / reloading stiffness	E_{ur}^{ref}	*Mpa*	7.5	105	36	120	300	120	42	135
Unloading / reloading Poisson's ratio	ν_{ur}	--	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Interface strength	R_{int}	--	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid	Rigid

A realistic simulation of the TBM tunneling dictates considering many factors. The machine advance, the machine stiffness, the grouting pressure, the slurry pressure at the machine face and the installation of the lining segments, among others, are factors to be considered in a step by step simulation. The material properties of the lining segments which used in the simulation are given in Table 2. This type of simulation is better performed by using 3D modeling. However, 3D modeling is always complex and requires experience for implementation and interpretation. This complicated analysis can be, and usually is, replaced by a much simpler, cross-sectional 2D analysis. With the help of 2D modeling, powerful, effective and easier solutions still can be attained provided that a proper assumption about the third dimension (near the tunnel face) is made. 2D axisymmetric models are not appropriate for urban tunnels as they assume symmetrical field stresses about the tunnel axis, thus neglecting the important effects of ground surface loads.

Table 2: Material properties of the Lining

Parameter	Name	Value	Unit
Type of behavior	Material type	Elastic	
Normal stiffness	EA	5.10E+07	KN/m
Flexural rigidity	EI	6.80E+05	$KN/m^2/m$
Equivalent thickness	d	0.40	m
Weight	w	10.0	KN/m/m
Poisson's ratio	ν	0.15	_

3. The 2D TBM Analysis Results

3.1 Displacements and Structural Forces for Shallow Section in 2D

The resulted final displacements and structural forces for shallow section along tunnel axis at 12.00 m below the ground surface are to be calculated according to taking different values of contraction ranging between 0.0% to 1.0% stepped by +0.25%. It can be noticed that the value of a contraction (volume loss) of 0.50% is the approximately value which should be taken in the evaluation of structural forces and settlements. The value of a contraction 2.0% is taken into consideration but it is not included because of long- range of its results to the sensible values. Figure 3 shows the maximum total displacement (-15.10 mm) at the tunnel crown, while the maximum vertical displacement at the ground surface (-12.33 mm) can be illustrated in Figure 4.

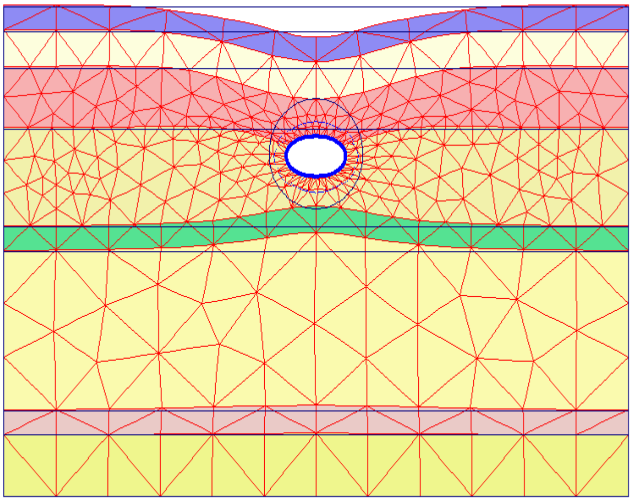


Figure 3: Deformed mesh
(Extreme total displ. -15.10mm)

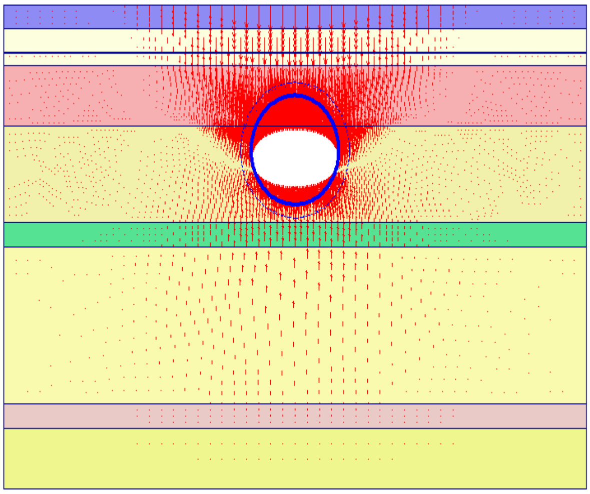
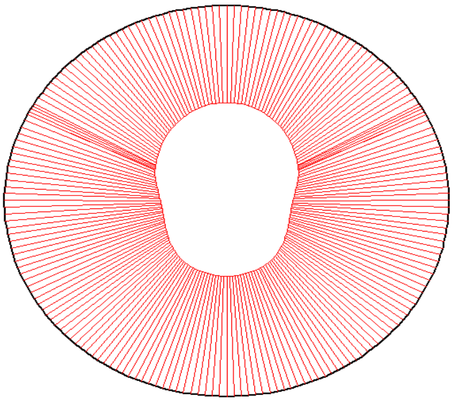
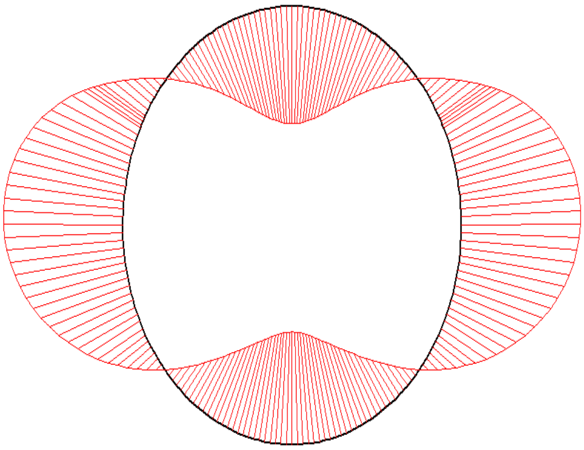


Figure 4: Vertical displ.
(At surface -12.33mm)



a) *Normal forces*
(Max: -584.64kN/m)



b) *Bending moments*
(Max: 79.25kN.m/m)

Figure 5: Structure forces of shallow tunnel section in 2D

Figure 5 illustrates the critical values of normal forces and bending moments in tunnel lining for the shallow section .Figure6 shows the relationship between the vertical deformation and depth with variation of contraction (volume loss) value ranged from 0.0% to 1.0%. The effectiveness of contraction on the surface settlement can be illustrated in Figure 7. Figure 8 shows that the 0.50% contraction curve is similar to the measured curve from site according to JOINT VENTURE G2 FOR CIVIL WORKS Report (JV) for shallow section.

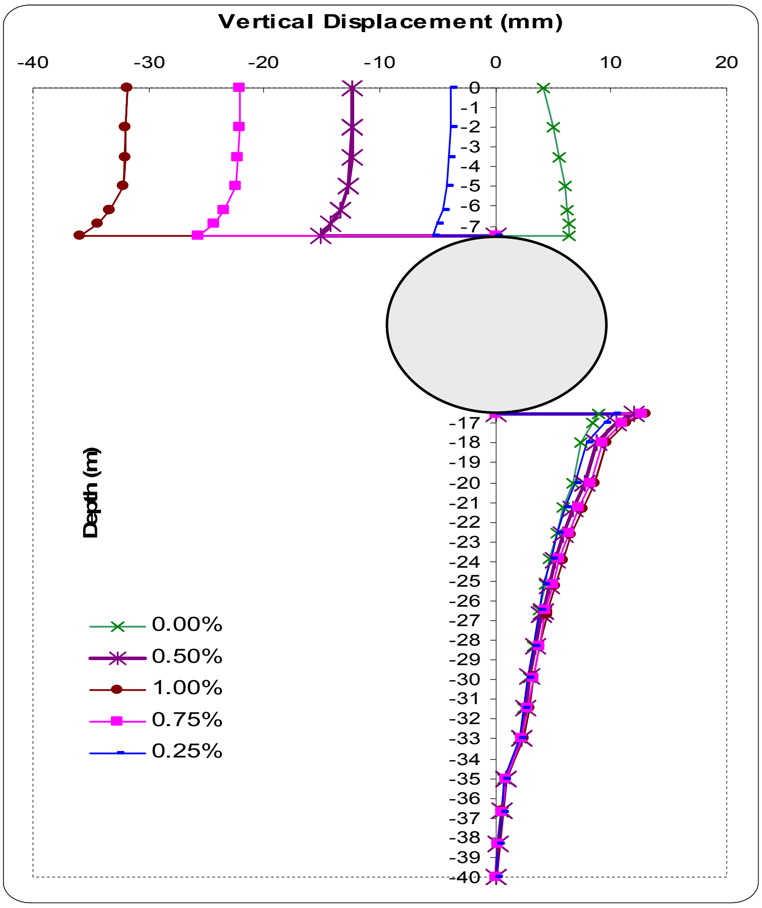


Figure 6: Vertical Displacements and depth changing with contraction value

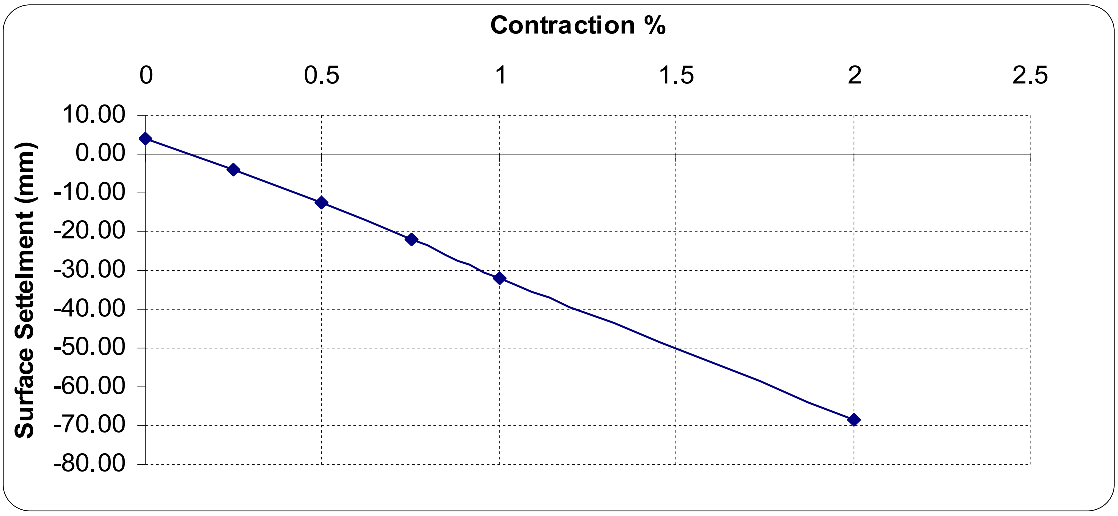


Figure 7: Surface settlements and contractions

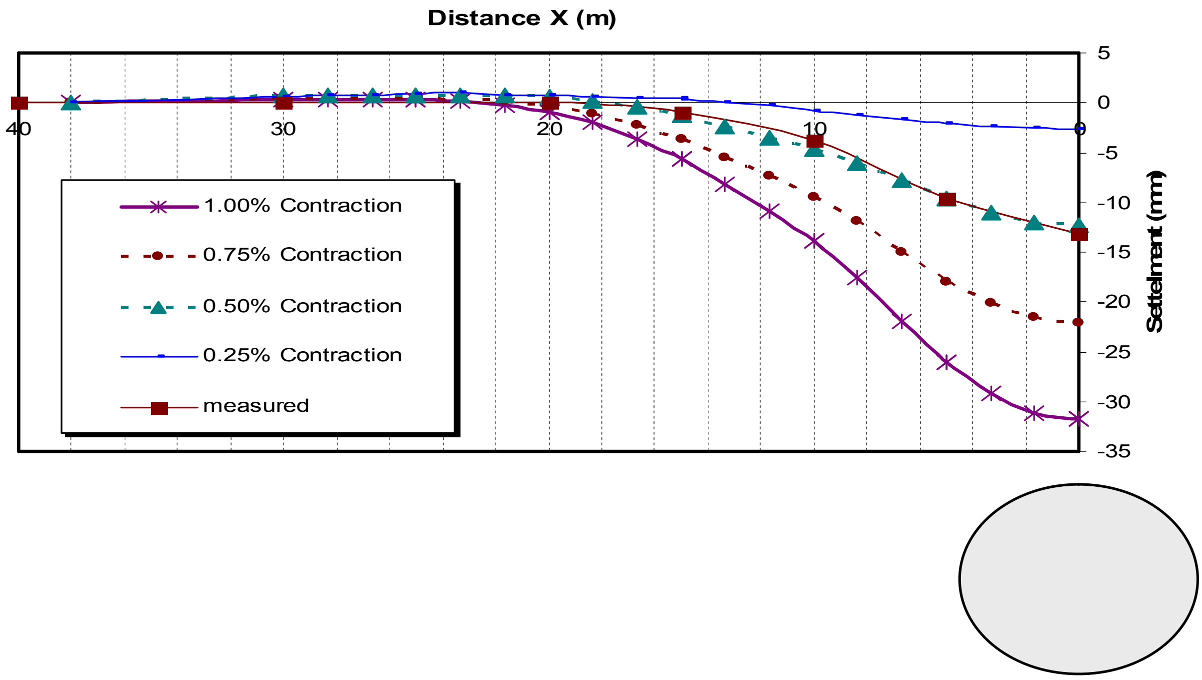


Figure 8: The Settlements through at the ground surface

3.2 Displacements and Structural Forces for Deep Section in 2D

The resulted final displacements and structural forces for deep section along tunnel axis at 25.00 m below the ground surface are to be calculated according to taking different values of contraction ranging from 0.0% to 1.00% stepped by +0.25%. It can be noticed that the value of a contraction (volume loss) of 0.5% is the approximately value which should be taken in the evaluation of structural forces and settlements, reason for this choice is to be illustrated later. Also, the value of a contraction 2.0% is taken into consideration but it is not included because of long- range of its results to the sensible values. Figure 9 shows the maximum total displacement (-16.69 mm) at the tunnel crown, while the maximum vertical displacement at the ground surface (-11.09 mm) can be illustrated in Figure 10.

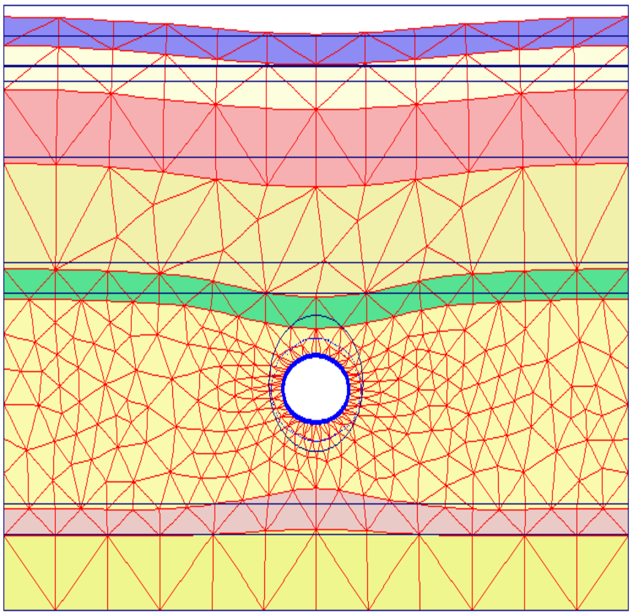


Figure9: Deformed mesh
(Extreme total displacement-16.69mm)

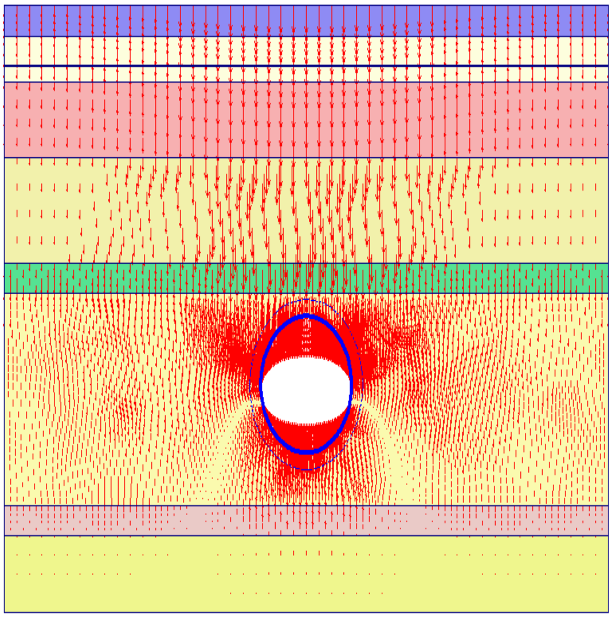
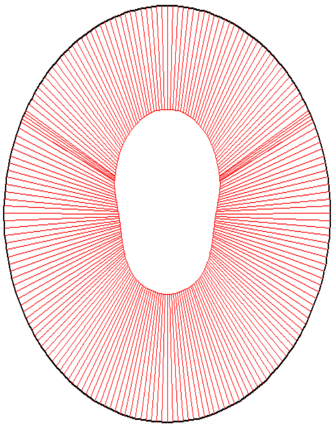
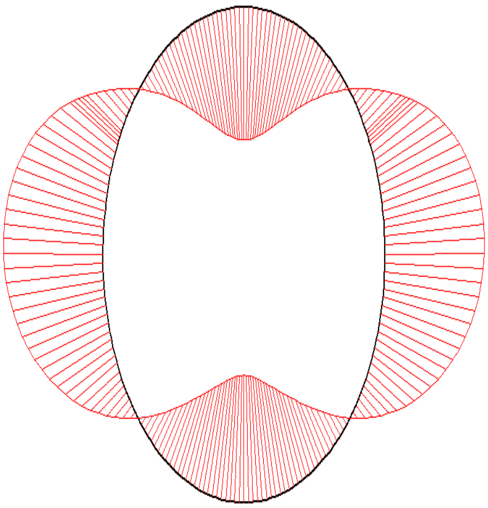


Fig.10: Vertical displacement
(At surface -11.09 mm)



a) *Normal forces*
(Max: -1390kN/m)



b) *Bending moments*
(Max:128.6kN.m/m)

Figure 11: Structure forces for deep tunnel section in 2D

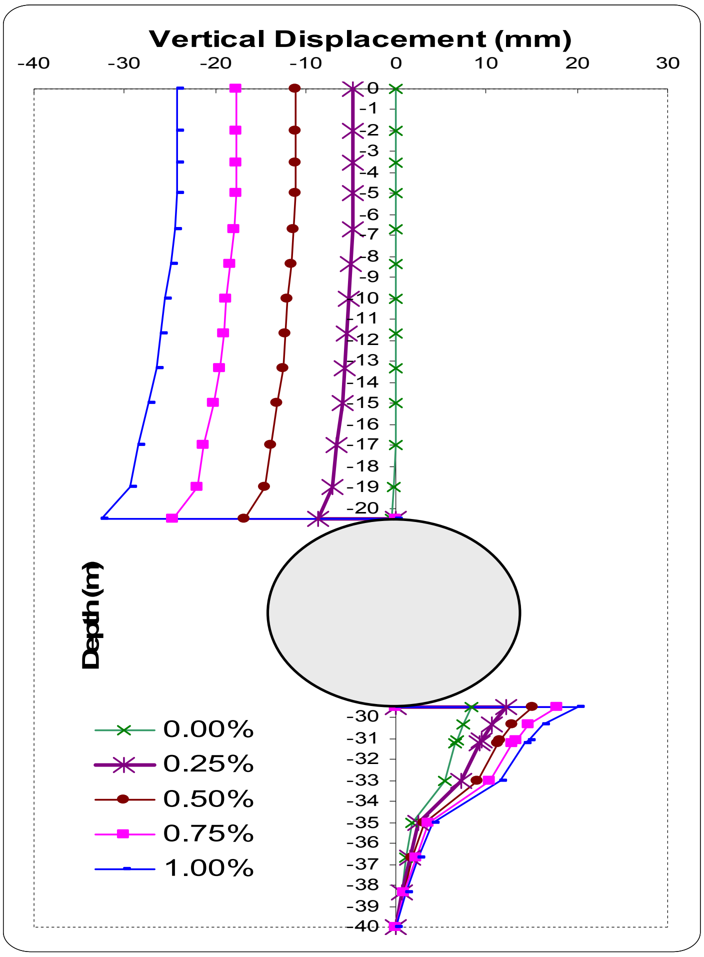


Figure 12: Vertical displacements and depth changing with contraction value

Figure 11 illustrates the critical values of normal forces and bending moments in tunnel segments for the deep section. Figure 12 show the relationship between the vertical deformation and depth with variation of contraction (volume loss) value ranged from 0.0% to 1.0%. The effectiveness of contraction on the surface settlement can be illustrated in Figure 13. Figure 14 shows that the measured curve from site according to (JV) Report for deep section is ranged between 0.25% contraction curve and 0.50% contraction curve but the surface settlement value along the tunnel axis approaches to the measured value at 0.5% contraction. Hence, it can be said that the lack of similarity of 0.5% contraction curve and measured curve belongs to differences in the geotechnical properties for deep section at the site.

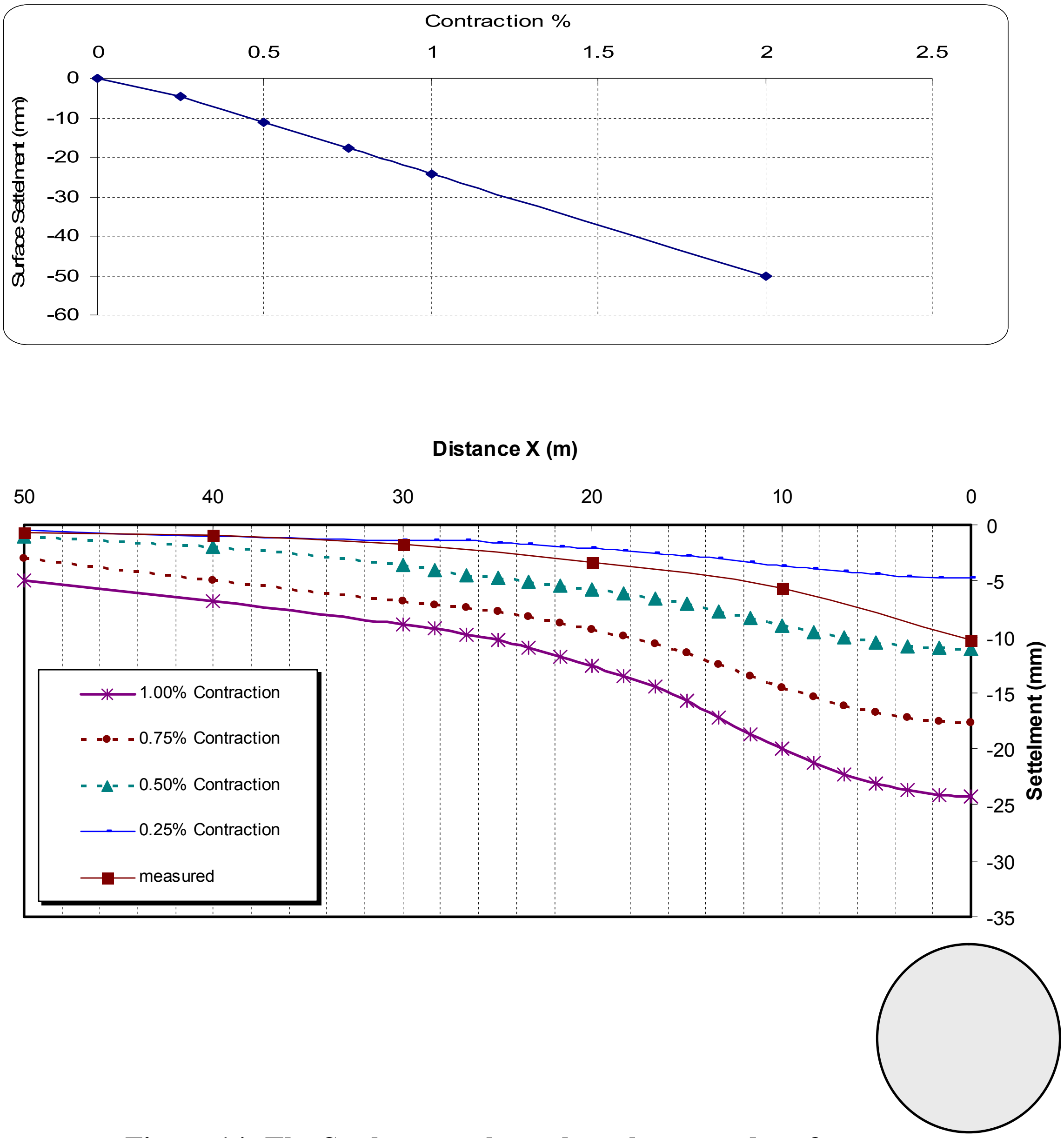


Figure 14: The Settlements through at the ground surface

3.3 Discussion of 2D Analysis Results

It can be noticed that the surface settlements which have been calculated according to taking different values of contraction ranging from 0.0% to 1.0% stepped by +0.25% is approximately similar to the measured curve from site at value of contraction of 0.50% for shallow and deep sections. It can be noticed that the maximum surface settlement for the shallow section is (-12.33 mm) for the deep section is (-11.09 mm). The values approximate to the measured values from site (-13.1 mm) for shallow and (-10.30) for deep section, thus it can be said that these values are in a good correlation with the

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monitoring system results performed before for Cairo Metro line III. Hence, it can be concluded that the value of a contraction (volume loss) of 0.50% is the appropriate value which should be taken into consideration. Therefore, in general the contraction (volume loss) was varied over the practical range 0.50% ± 0.2 should be taken in the 2D TBM analyses to simulate the iconicity of the TBM. The reason for this range refers to the type of soil. The resulted final settlement along tunnel axis for the shallow and deep sections can be illustrated in Figure 13 and Figure 14.

4. The 3D TBM Analysis Results

Displacements and Structural Forces for Shallow Section in 3D

The resulted final displacements and structural forces for shallow section along tunnel axis at 12.00 m below the ground surface are to be calculated according to taking different values of contraction ranging between 0.0% to 1.0% stepped by +0.25%. It can be noticed that the value of a contraction (volume loss) of 0.75% is the approximately value which should be taken in the evaluation of structural forces and settlements, reason for this choice is to be illustrated later. The value of a contraction 2.0% is taken into consideration but it is not included because of long- range of its results to the sensible values. Figure 15 shows the maximum total displacement (-21.1 mm) at the tunnel crown, while the max vertical displacement at the ground surface (-13.18 mm) above the tunnel axis can be illustrated in Figure 16.

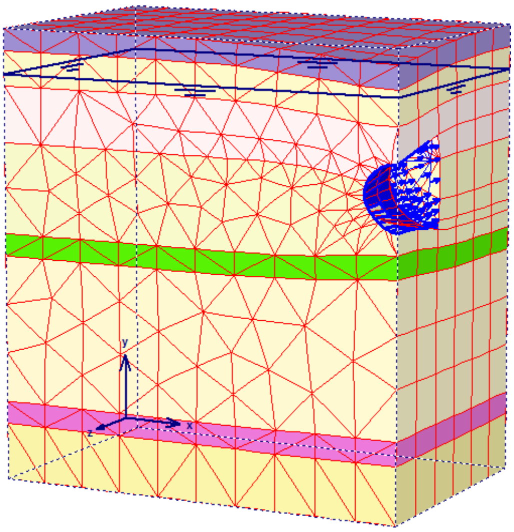


Figure15: Deformed mesh (Extreme total displacement -21.1 mm)

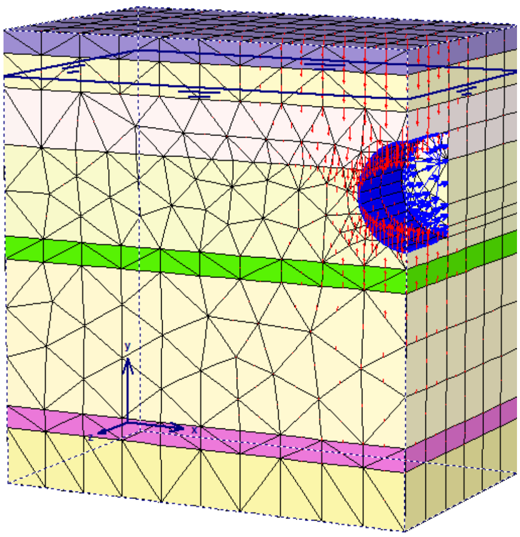
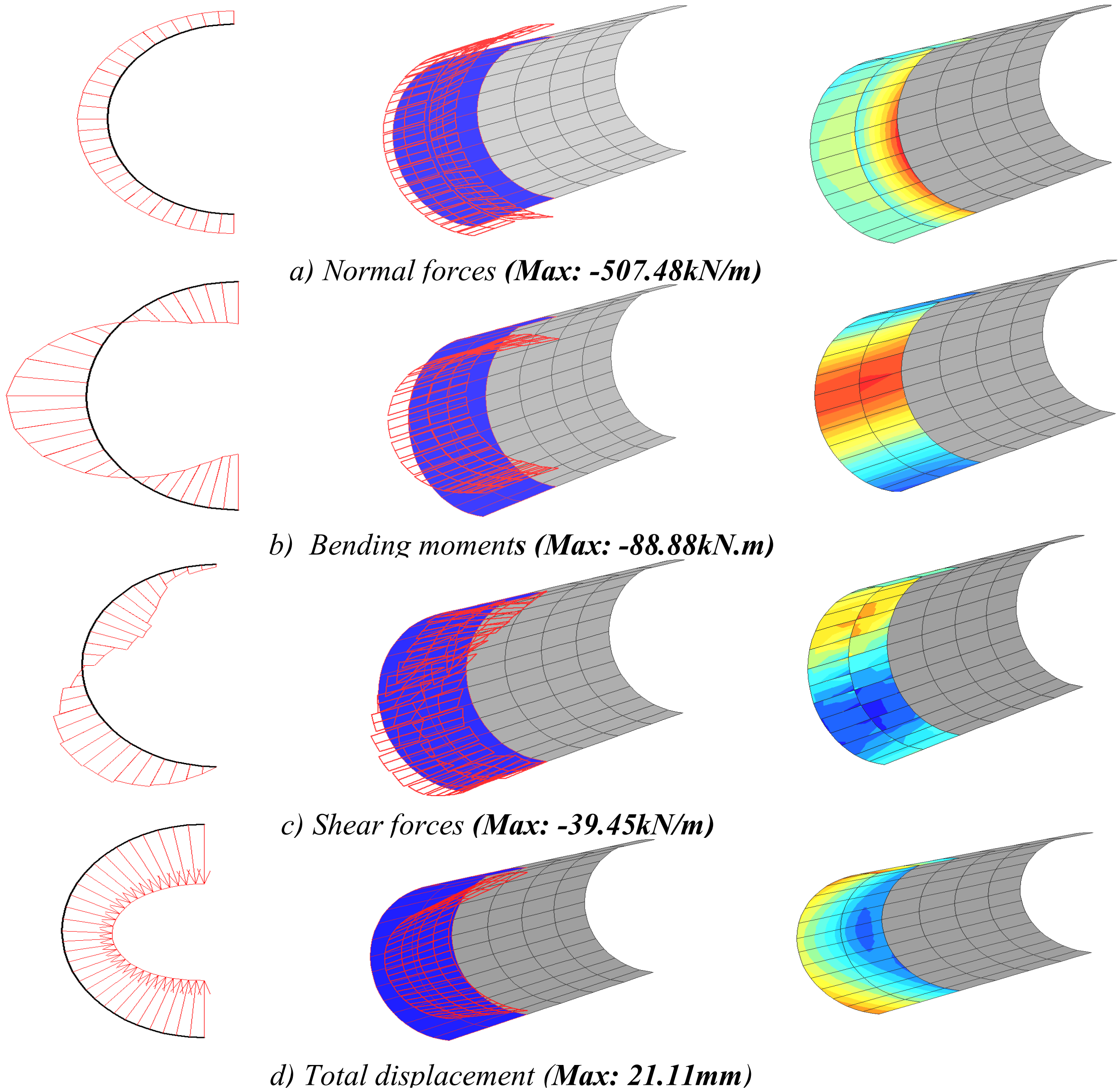


Figure 16: Vertical Displacement (At surface -13.18 mm)

Figure 17 illustrates the critical values of normal forces, bending moments and shear forces in tunnel lining for the shallow section. Figure 18 show the relationship between the vertical deformation and depth with variation of contraction value ranged from 0.0% to 1.0% and the maximum surface settlement is (-13.18 mm) according to taking the value of a contraction (volume loss) of 0.75% to simulate the iconicity of the TBM, and this value is considered allowable. The effectiveness of contraction on the surface settlement can be illustrated in Figure 19. Figure 20 shows that the measured curve from site according to (JV) Report for shallow section is ranged between 0.50% contraction curve and 0.75% contraction curve but the surface settlement value along the tunnel axis approaches to the measured value at 0.75% contraction. The surface settlements in the front of the face of TBM can be predicted in 3D analysis as shown in Figure 21.



a) Normal forces ***(Max: -507.48kN/m)***

b) Bending moments ***(Max: -88.88kN.m)***

c) Shear forces ***(Max: -39.45kN/m)***

d) Total displacement ***(Max: 21.11mm)***

Figure 17: Structure forces and settlements for shallow tunnel in 3D

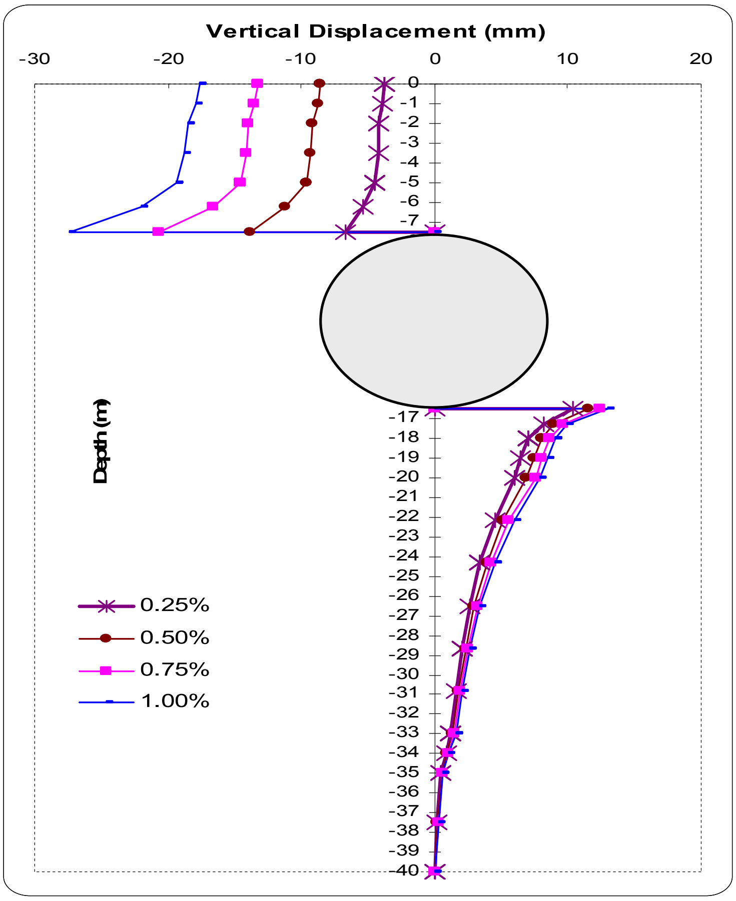


Figure 18: Vertical displacements and depth changing with contraction

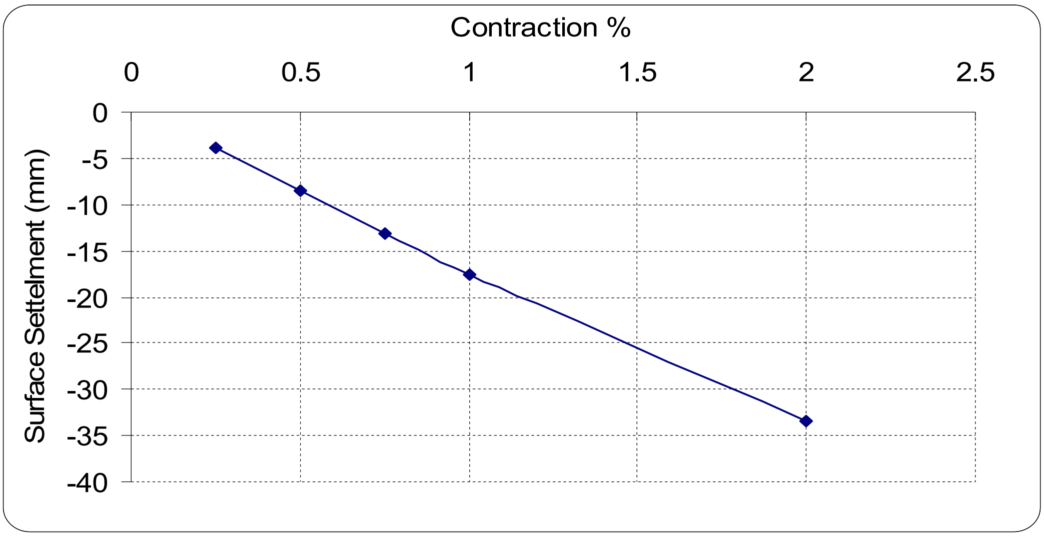


Figure 19: Surface settlements and contractions

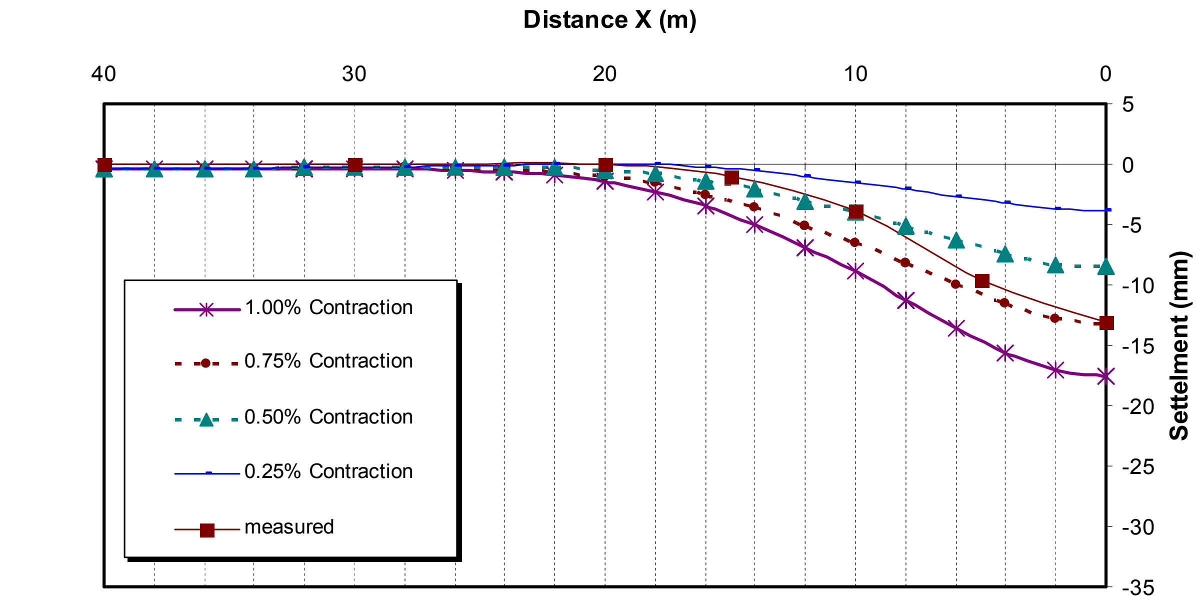


Figure 20: The settlements through at the ground surface

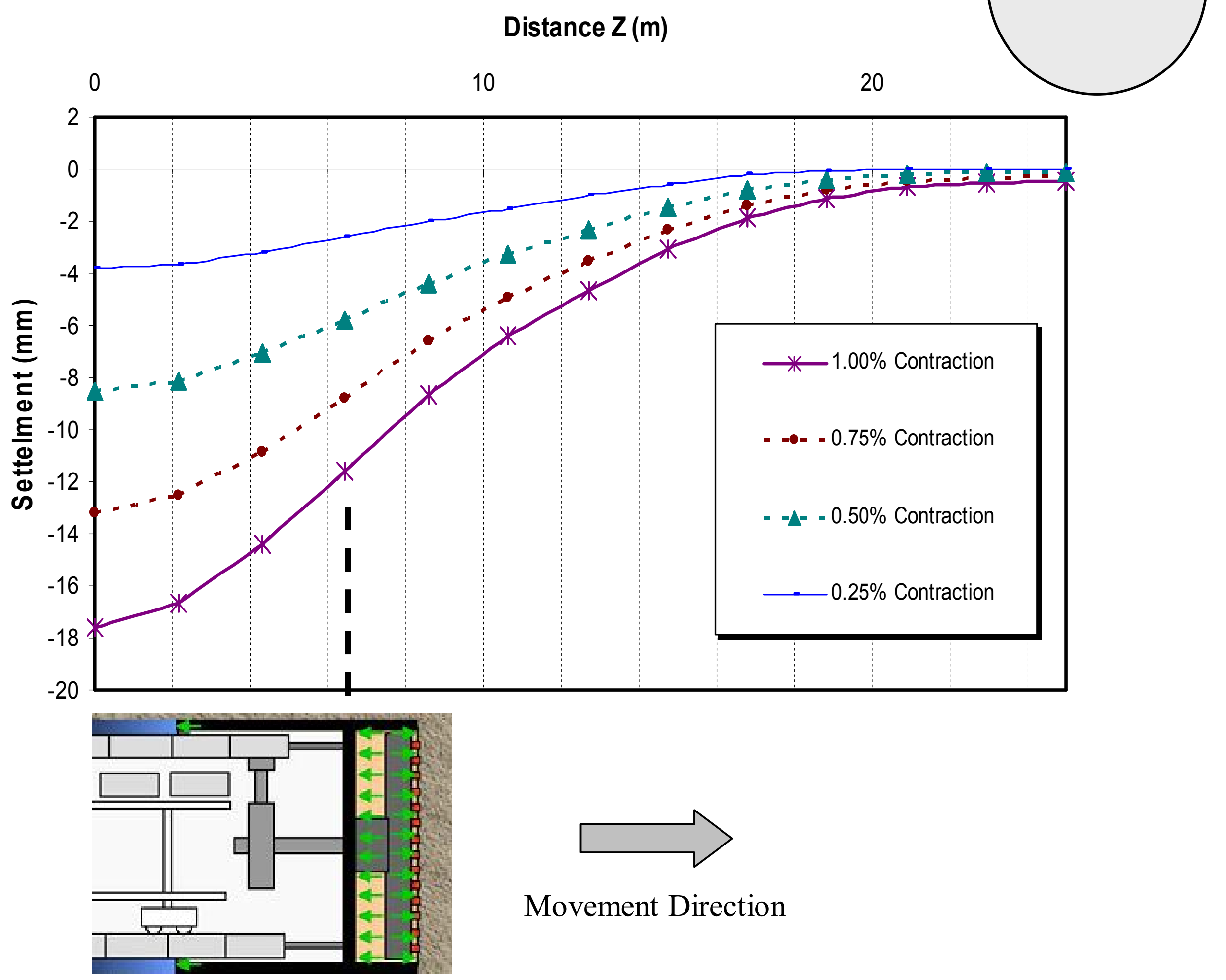


Figure 21: The Settlements through at the ground surface above and in front of TBM

4.2 Displacements and Structural Forces for Deep Section in 3D

The resulted final displacements and structural forces for deep section along tunnel axis at 25.00 m below the ground surface are to be calculated according to taking different values of contraction ranging between 0.0% to 1.0% stepped by +0.25%. It can be noticed that the value of a contraction (volume loss) of 0.75% is the approximately value which should be taken in the evaluation of structural forces and settlements, reason for this choice is to be illustrated later. The value of a contraction 2.0% is taken into consideration but it is not included because of long- range of its results to the sensible values. Figure 22 shows the maximum total displacement (-21.36 mm) at the tunnel crown, while the max vertical displacement at the ground surface (-7.07 mm) above the tunnel axis can be illustrated in Figure 23.

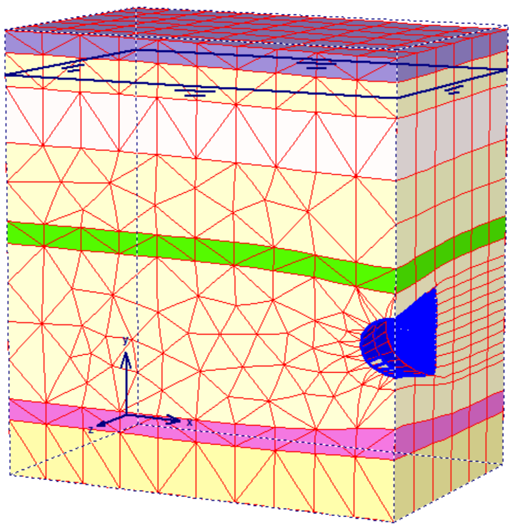


Figure 22: Deformed mesh (Extreme total displacement -21.36mm)

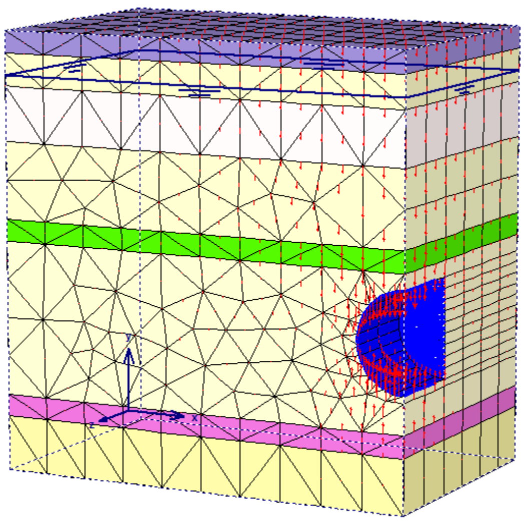
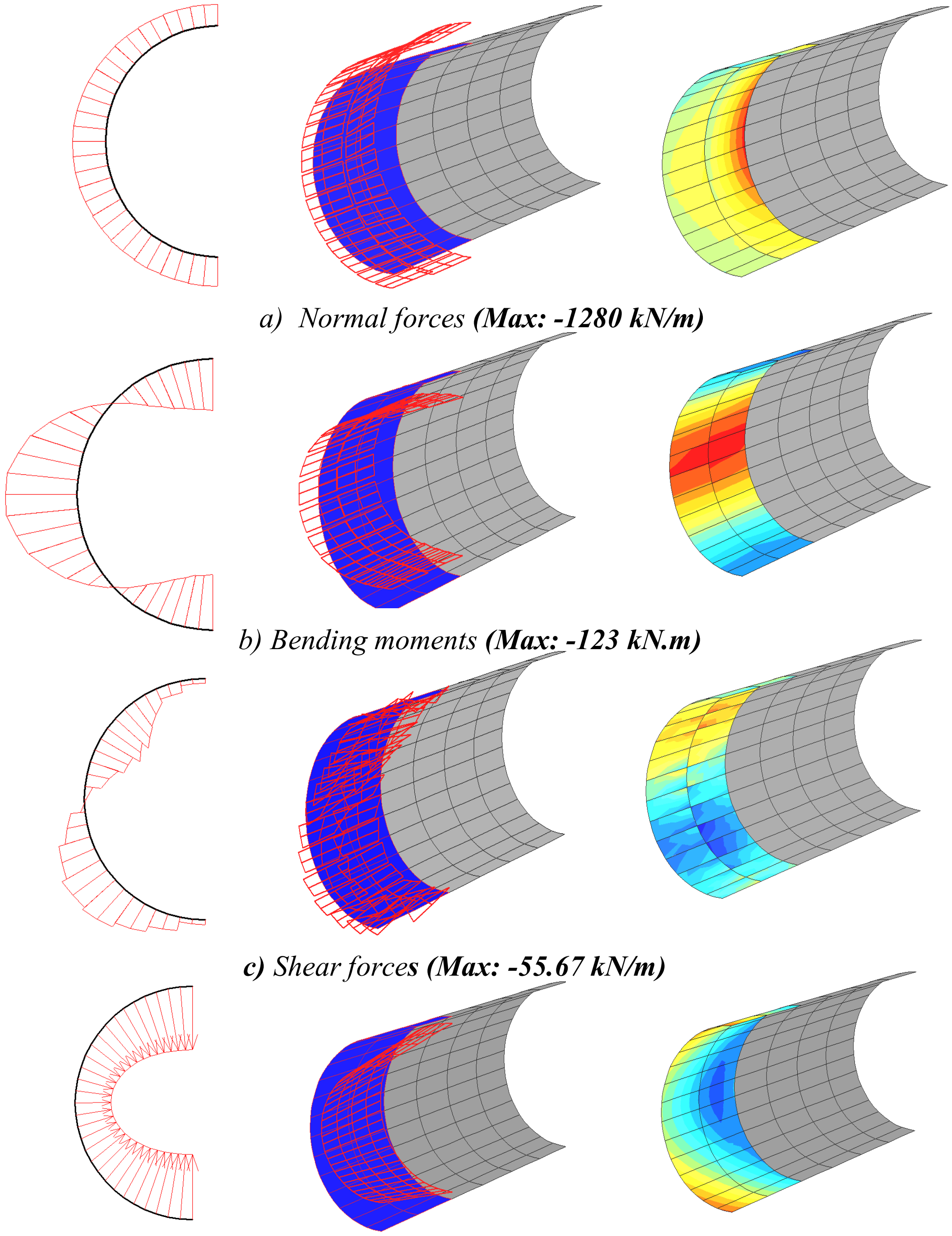


Figure23: Vertical displacement (At surface -7.07mm)

Figure 24 illustrates the critical values of normal forces, bending moments and shear forces in tunnel lining for the deep section. Figure 25 shows the relationship between the vertical deformation and depth with variation of contraction values ranged from 0.0% to 1.0% and the maximum surface settlement is (-7.07 mm) according to taking the volume loss value of 0.75% to simulate the iconicity of the TBM, and this value is considered allowable but less than measured value in the situ. The effectiveness of contraction on the surface settlement can be illustrated in Figure 26. Figure 27 shows that the 0.75%

contraction curve is semi-similar to the measured curve from site according to (JV) Report for deep section. Hence, it can be said that the cause of non full similarity of the 0.75% contraction curve to the measured curve belongs to differences in the geotechnical properties for deep section at the site. The surface settlements in the front of the face of TBM can be predicted in 3D analysis as shown in Figure 28.



a) Normal forces ***(Max: -1280 kN/m)***

b) Bending moments ***(Max: -123 kN.m)***

c) *Shear forces* ***(Max: -55.67 kN/m)***

d) *Total displacements* ***(Max: 22.44 mm)***

Figure 24: Structure forces and settlements for deep tunnel in 3D

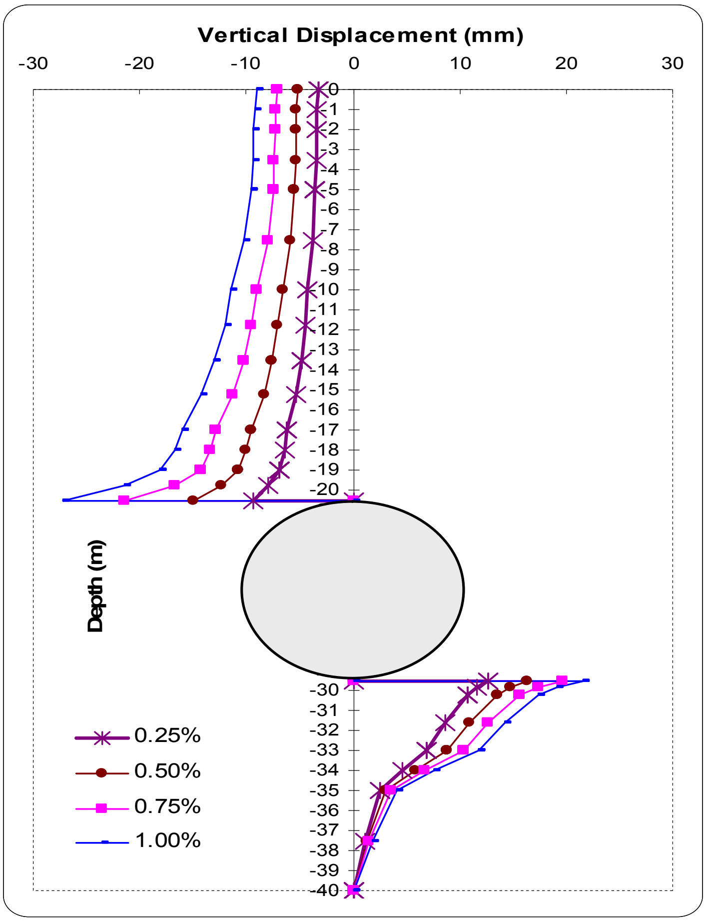


Figure 25: Vertical Displacements and Depth changing with contraction

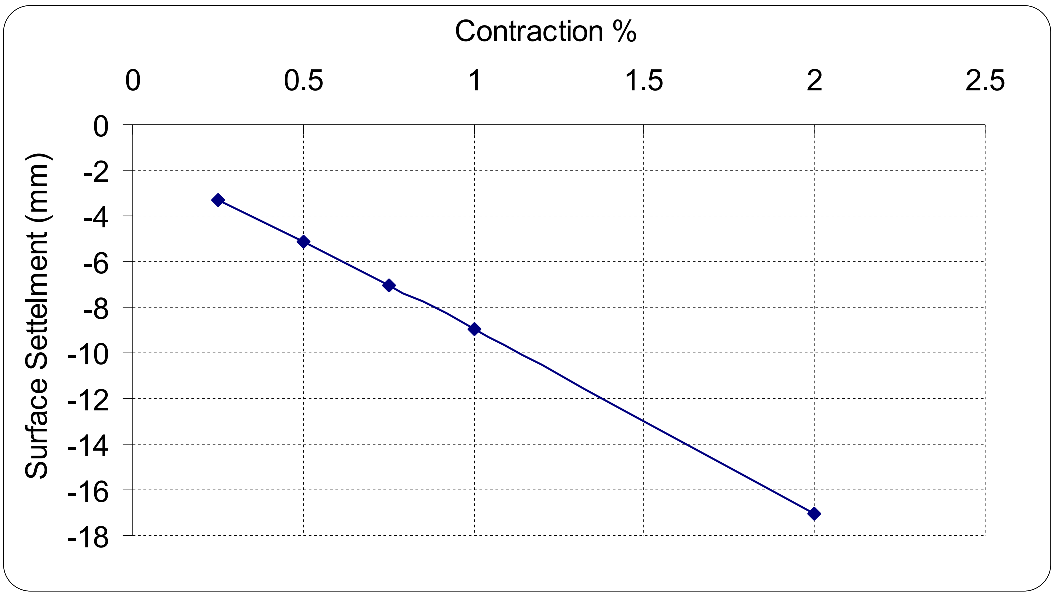
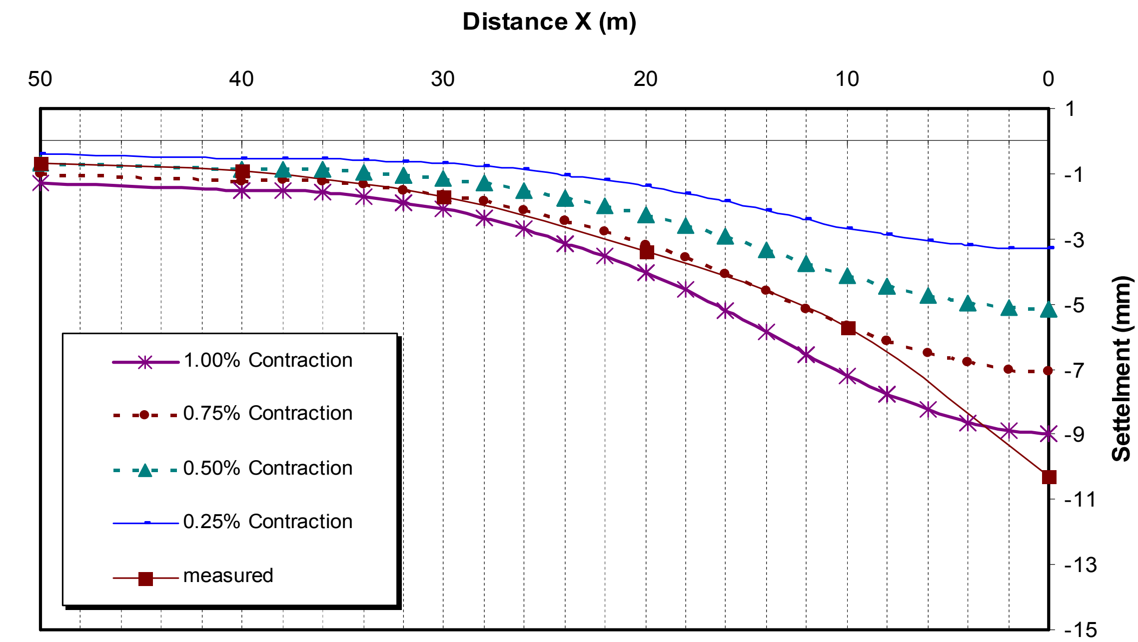


Figure 26: Surface Settlements and Contractions



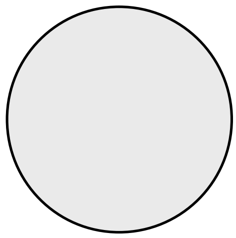


Figure 27: The Settlements through at the ground surface

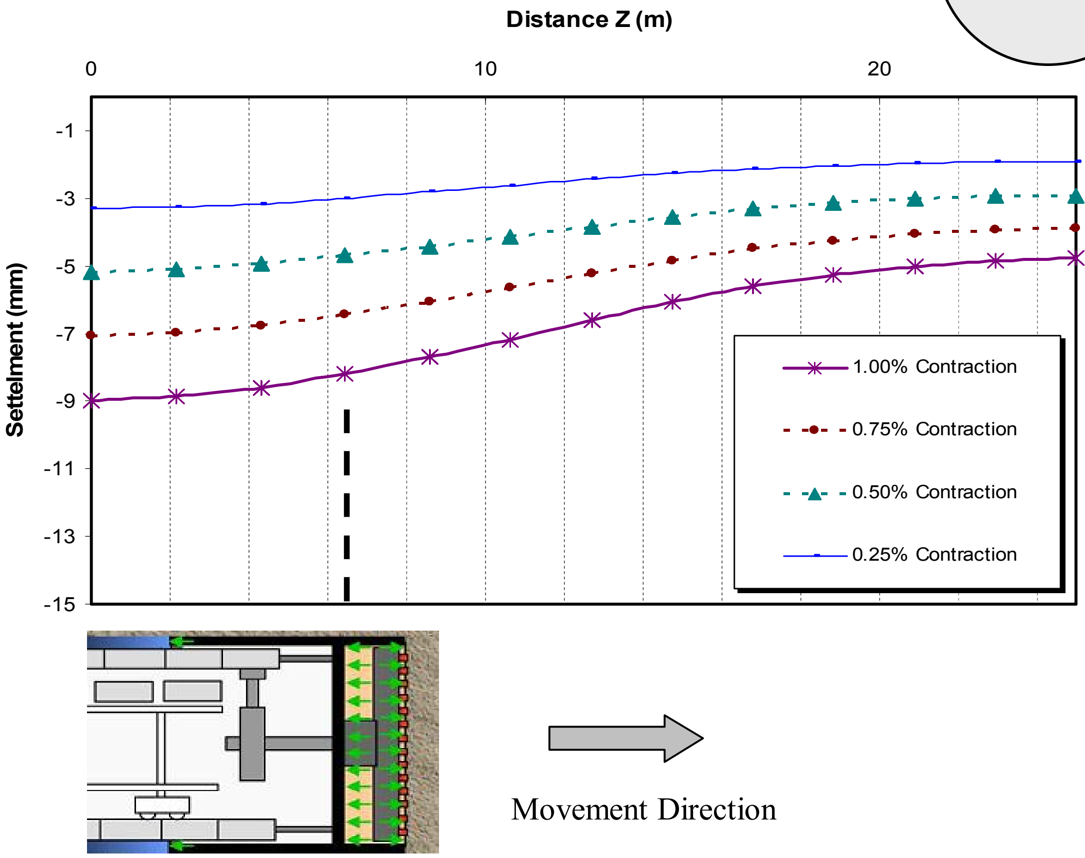


Figure 28: The Settlements through at the ground surface above and in front of TBM

4.3. Discussion of 3D Analysis Results

The deformations occurring during tunnel construction around a tunnel boring machine can be predicted with good accuracy using a phased excavation scheme in a 3D finite element calculation. This phased excavation scheme includes the effects of the support pressure at the tunnel face, the iconicity of the shield as well as the grouting pressure at the shield tail. The tunnel boring process is simulated by advancing the tunnel boring machine stepwise through the model.

It can be noticed that the surface settlements which have been calculated according to taking different values of contraction ranging from 0.0% to 1.0% stepped by +0.25% is approximately similar to the measured curve from site at value of contraction of 0.75% for shallow and deep sections. It can be noticed that the maximum surface settlement for the shallow section is (-13.18 mm) for the deep section is (-7.07 mm). These values approximate to the measured values from site (-13.1 mm) for shallow and (-10.30 mm) for deep section, thus it can be said that these values are in a good correlation with the monitoring system results performed before for Cairo Metro line III. Hence, it can be concluded that the value of a contraction (volume loss) of 0.75% is the appropriate value which should be taken into consideration. Therefore, in general the contraction (volume loss) was varied over the practical range 0.75% ± 0.20 should be taken in the 3D TBM analyses to simulate the iconicity of the TBM. The reason for this range refers to the type of soil. Also, settlements at the surface along the axis of the tunnel in the front of TBM face can be estimated in the 3D analysis opposite in the 2D analysis where this could be difficult, these settlements can be illustrated in Figure 21 for shallow section and Figure 28 for deep section. The resulted final settlement along tunnel axis for the shallow and deep sections is illustrated in Figure 20 and Figure 27.

5. DISCUSSION OF TBM ANALYSES RESULTS

Sets of sensitivity analyses were carried out; varying volume loss values that might be expected to influence the outcome of the analysis. The settlements and structure forces of the 2D and 3D analyses at different values of contraction (volume loss) of 0.50% and 0.75% can be collected and summarized in Table 3 for shallow section and Table 4 for deep section.

Table 3: Settlements and structure forces values for 2D and 3D analyses at V.L. 0.5% & 0.75% for shallow section

Case	Shallow Section				Unit
	V.L.= 0.50%		V.L.= 0.75%		
	2D	3D	2D	3D	
Max. Surface settlement	-12.33	-8.53	-22.04	-13.18	mm
Max. Tunnel deformation	-15.50	-15.56	-25.61	-21.11	mm
Max. Bending moment	79.25	89.82	78.81	88.88	kN.m/m
Max. Normal force	-584.64	-544.12	-535.56	-507.48	kN/m
Max. Shear force	39.56	40.99	39.23	39.45	kN/m

Table 4: Settlements and structure forces values for 2D and 3D analyses at V.L. 0.5% & 0.75% for deep section

Case	Deep Section				Unit
	V.L.= 0.50%		V.L.= 0.75%		
	2D	3D	2D	3D	
Max. Surface settlement	-11.09	-5.16	-17.64	-7.07	mm
Max. Tunnel deformation	-17.11	-17.83	-24.67	-21.37	mm
Max. Bending moment	128.64	126.74	120.45	123.54	kN.m/m
Max. Normal force	-1390	-1330	-1300	-1280	kN/m
Max. Shear force	60.80	60.82	56.44	55.56	kN/m

5.1 Evaluation of Settlements

Such 2D analysis can respond to a 3D analysis when the settlement values are taken the same. It has been shown that the settlement value, which responds to a 3D analysis, can be obtained from a 2D analysis, which requires a little computational effort but it depends on some factors. The determination of those factors can be researched of further research in the future.

The resulted final settlements for 2D and 3D analyses along tunnel axis for the shallow and deep sections are illustrated in previous analyses in Figures 6, 12, 18 and 25. It can be noticed that the maximum surface settlement for the shallow section is (-13.18 mm) and the maximum surface settlement for the deep section is (-11.09 mm). These values approximate to the measured values from site (-13.1 mm) for shallow and (-10.30) for deep section, thus it can be said that these values are in a good correlation with the monitoring system results performed of Cairo Metro line III. Hence, the expected surface settlement for other sections along the tunnel route will be on the average of -12 mm. All the surface settlements are less than the allowable values of the National Authority for Tunnels (30.00 mm). This indicates that the tunnelling process will be of no risk for the surface structures especially if the tunnel route follows main streets and avoid passing under the existing structures.

Table 3 and Table 4 show that settlements at ground surface in 3D analysis are always relatively smaller than its similarity in 2D analysis although of the convergence in the other values at the same contraction values. In my opinion, the reason of this refers to the 3D effect in the longitudinal section comparing with the 2D.

5.2 Evaluation of Structural Forces

On comparing 2D and 3D analyses one observes that a 2D analysis matches the values from a 3D analysis well, where it has been shown that the values of bending moments, normal forces and shear forces of a 2D analysis are found semi equal to its similarity in a 3D calculation as illustrated in Tables 3 and 4. Moreover it has been shown, that a relatively fine 3D mesh is required, because values of bending moments and normal forces are found to be much higher than from the solution of a relative coarse mesh. Due to this requirement computer run time gets excessive. Such full 3D analyses are not feasible in engineering practice. The resulted critical normal forces and bending moments for 2D and 3D analyses in tunnel segments for the considered sections are illustrated in previous analyses in Figures 5, 11, 17 and 24. A concrete cross section of 40 cm can safely support the moderate values of internal forces due to tunneling.

5.3 Effectiveness of Variation of Volume Loss

Prediction of the total amount of volume loss would be useful for tunnel designers, but is difficult because volume loss apparently depends on a number of factors that are not known at the design stage. These include the tunnelling machine type, the construction sequence and the effectiveness of the grouting behind the lining, the latter being a 'workmanship' factor. The designer ideally knows the soil properties and in situ stress state. It can be noticed that volume loss does not necessarily increase with stress (or depth).It can be found that the relationship between the surface settlement and the contraction (volume loss) values can be extracted as be shown in Figures 7, 13, 19 and 26, where the volume loss was varied over the practical range from 0.0% to 2.0%. The increase in settlements with volume loss would have been expected to be linear, but is actually slightly nonlinear, with larger than expected maximum settlement at high volume loss.

It can be noticed that the surface settlements which had been calculated according to taking different values of contraction ranging between 0.0% to 1.0% stepped by 0.25% is approximately similar to the measured curve from site at value of contraction of 0.50% for 2D analysis and at value of contraction of 0.75% for 3D analysis. Therefore, in general it can be concluded that the volume loss value should be taken to simulate the iconicity of the TBM in the practical range 0.50% ± 0.20 for the 2D analysis and in the practical range 0.75% ± 0.20 for the 3D analysis. The reason for this range refers to the type of soil properties. The difference in contraction values for the two types of analyses can be referred to the effective of the third dimension in analysis. It must be referred to the situ of tunneling process to get the actual contraction value which used in different cases.

6. Conclusions

Numerical analysis is a powerful tool for the evaluation and for quantitative interpretation of field data for assessing the original design or construction. Although modeling all the boundary conditions and controlling the interaction between the ground and tunnels seems to be impossible, the proposed numerical modelling 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 TBM. 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. The comparison between the results of this model and the field measurements compiled during construction of the Cairo-Metro Line III tunnel indicated the ability of the model to simulate such complicated soil-structure interaction problem.

Till now most of the research work concentrate on carrying out numerical analysis of the tunnels using the 2D-finite element programs instead of using 3D-finite element programs because they are faster, cheaper, therefore saving time and cost. This is despite the fact that they are less accurate than 3D-finite element programs. Although tunnelling operations can be efficiently analyzed by 2D Finite element method, however, in this thesis, 3D Finite element method has been added to gain more efficient and accurate simulation results. Most of the available studies have used the 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 for the shallow and deep TBM sections in this study and comparing its values to the field measurements compiled during construction of the Cairo-Metro Line III, and perceiving that all the surface settlements are less than the allowable values of the National Authority for Tunnels (30.0 mm). This indicates that the tunneling process will be no risk for the surface structures especially if the tunnel route follows main streets and avoid passing under the existing structures and also shows the ability to simulate such complicated soil-structure interaction problem.

2- As the tunnel depth increases the values of settlement decreases in the TBM because the model becomes stiffer, where the deep section of the tunnel produced a ground surface settlement less than the other shallow section.

3- The ideal contraction value which should be taken to simulate the iconicity of the TBM in the practical range 0.50% ± 0.20 for the 2D analysis and in the practical range 0.75% ± 0.20 for the 3D analysis. Whereas these values verify the convergence between the calculated settlement values and the measured.

4- Although of settlement increasing for TBM with volume loss was expected to be linear, it was found slightly nonlinear, with larger than expected maximum settlement at high volume loss which does not necessarily increase with depth.

5- The use of 3D models is useful to analyze the real sequence of soil excavation, face reinforcing and tunnel lining comparing with 2D models. Where the numerical results show the efficiency of 3D analysis to predict surface settlements in the longitudinal direction along the axis of the tunnel in the front of TBM face opposite to 2D analysis where this could be difficult.

6- It can be noticed, that the vertical displacement at the crown of the TBM is usually greater than the value of the vertical displacement at the ground surface for both sections shallow and deep.

7- The numerical investigation developed in this study has shown the possibility of simulating the tunneling excavation and lining phases using standard FEM commercial software. Thus, it can be said that the use of powerful simulation techniques will encourage updating modern construction techniques, minimizing construction cost and help the decision maker to choose the optimum solution for future tunnels projects.

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