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2D NUMERICAL MODELLING OF HORIZONTAL TWIN TUNNELS UNDER STATIC LOADS - CAIRO METRO TUNNEL (LINE 4)

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ملخص البحث

تعد شبكة مترو القاهرة من اكبر المشاريع القومية فى مصر. ويهدف هذا المشروع الى تنمية شبكة الموا صلات تحت الارضية التى تعمل على المشكلات المرورية الكبيرة فى منطقة القاهرة الكبرى التى تشمل ثلاث محافظات مزدحمه بالسكان وهى القاهره الجيزة واالقليوبيه. وقد تم مد شبكة المترو ليشمل مناطق عديدة خلال هذا القرن حيث ويعد المترو القاهرة الخط الرابع واحد منهم. ويتكون هذا الخط من نفقين افقيين وقطاع النفقين مستدير من الخرسانه بسمك 0.30 متر. يهدف هذا البحث الى دراسة النفقين الافقين من الخط الرابع فى مشروع مترو القاهرة باستخدام التحليل العددى تحت تاثير الاحمال الاستاتيكية مع الاخذ فى الاعتبار طريقة وتتابع الحفر. تم استخدام طريقة العناصر غير المحدده ببرنامج PLAXIS ثنائى الابعاد مع الاخذ فى الاعتبار رد فعل التربة. كما تم عمل دراسه بارمترية باستخدام عدة عوامل وهى عمق النفقين عن سطح الارض , المسافه الافقيه بين النفقين, منسوب المياة الجوفية فوق النفقين و اخيرا جساءة التربة حول النفقين. وقد اظهرت النائج ان طريقة الحفر للنفقين توثر على مقدار الازاحه وقوى الاجهادات داخل بطانة الخرسانة للنفقين. كما اظهرت ايضا النتائج ان المسافه الافقية بين النفقين لها تاثير كبير فى ازاحة التربة والاجهادات داخل بطانة الخرسانة للنفقين.

ABSTRACT

Cairo metro network is one of the major national projects in Egypt. It aimed at developing underground transportation system to solve the severe traffic problems in Greater Cairo which includes three crowded governorates; Cairo, Giza and Qalyubia. In recent century, the project is expanding and more lines are constructed. The tunnel constructed for Cairo Metro Line 4 are twin tunnels having a circular cross section that consists of a precast segmental lining thickness of 0.30 m. In the present study, the horizontal twin tunnels of Cairo Metro Line 4 were numerically modeled under static loads taking into account the sequence of excavation. The analysis of this study was done using the commercial finite element software PLAXIS 2D to study the soil structure interaction. Also a parametric study has been performed using different parameters, which included tunnels depth (d), distance between twin tunnels (S), ground water level (G.W.L.) and surrounding soil stiffness (E). Results showed that the construction procedure affects the soil displacement and internal forces. Also it shows that the clear distance between tunnels (S) has a major effect on soil movement and internal forces in tunnel lining.

1. INTRODUCTION

Twin tunnels are constructed because of their many advantages, including control of the soil movement and internal forces of lining. Procedures of construction of twin tunnels lead to decrease internal forces in one of them as a result of construction of one of them before the other. Greater Cairo metro line No. 4 passes under the River Nile in Egypt, whereas Phase No. 1 of the line will extend from El-Malek El-Saleh station on line No. 1 to Hadaek AlAshgar station. It will meet the route of line No. 2 in Giza station. The study area for Greater Cairo metro line No. 4 starts from station No. 1 (El-Malek El-Saleh) and extends up to station No. 6 (Madkor Station).

Abd-el.rahim et al. (2015) study the twin tunnel configuration for Greater Cairo metro line No. 4 includes vertical, horizontal and diagonal alignment. Based on the calculated result, the clear distance between tunnels has a major effect on soil movement and internal forces in tunnel lining.

Do et al. (2014) concluded that due to the interaction of twin tunnels, an increase in the surface settlement can be expected compared to that induced above a single tunnel. Chehade and Shahrour (2007) concluded that construction of tunnels causes movement of soil and straining action in the lining of the tunnel. Also the procedure of construction impacts on soil settlement and lining forces. Moller (2006) studied the internal forces in tunnel lining and displacement of soil and found that tunnel design needs an honest idea of surface settlements and lining internal forces. Garner and Coffman (2013) found that the design of the tunnel depends on the induced settlement in the tunnel. Therefore, they proposed method giving acceptable ground surface settlement profile to generate a tunnel system configuration. As well as the proposed characterization method can be used to help designers to eliminate potential configurations that would cause excessive surface settlements.

Chen et al. (2012) concluded that a good estimation of surface settlement is very important to the construction of tunnels in very crowded cities because failure of neighboring structures due to extra surface settlement above the tunnels. They examined the interaction of multi-tube tunnels on ground surface settlement and the methods of prediction of the transverse ground surface settlement profile.

Zhechao Wang et al. (2012) found that for shallow tunnels constructed in clay soil, a surface settlement above tunnels depends on the creep of soil. They concluded that behavior of clay creep is very important for long term settlement above tunnels. Mazek and Almannaei (2013) used finite element analysis to determine a model dimension of cross section for line No. 3 at Cairo metro and they found that minimum width equals to ten times of the diameter of the tunnel. Migliazza et al. (2009) computed vertical settlement of ground surface during excavation and using empirical method and finite element analysis where they found numerical data are similar to experimental data.

In the present study, the interaction between twin tunnels under static load conditions has been studied using numerical finite element method (FLM) using a commercial software PLAXIS 2D. The main purpose of this study was to provide a numerical model which would allow the behavior of the interaction of mechanized twin tunnels to be evaluated. This evaluation includes the structural forces induced in the lining of circular twin tunnels and ground displacement surrounding the two tunnels taking into account the soil structure interaction (SSI). Also the sequence of excavation in the static performance of the horizontal twin tunnels of Cairo Metro Line No. 4 has taking into consideration. A parametric study has been performed under different parameters, which include the tunnels depth (d), the distance between twin tunnels (S), the ground water level (GWL) and the surrounding soil stiffness (E).

2. Case Study: Greater Cairo Metro Line No. 4.

The Greater Cairo metro line No.4 passes under the River Nile in Egypt land. Phase No.1 of line No. 4 will extend from El-Malek El-Saleh station on line No. 1 to Remaya square station. It will meet the route of line No. 2 in Giza station. The study area for Greater Cairo Metro Line No. 4 starts from Station No. 1 (El-Malek El-Saleh) and extend up to Station No. 6 (Madkor Station) as shown in Figure 1 Abd-el.rahim et al. (2015) (a, b).

Recently National Authority of Tunnels (NAT) Abd-el.rahim et al. (2015) (a, b)suggested twin tunnel system for metro line No.4, as shown in Figure 2 (a). In this study, the analysis of this system with another system proposed by the authors which is a single tunnel system, as shown in Figure 2 (b, will be presented. The proposed cross section by the contractor for twin tunnels shows that the outside diameter is 6.40 m and lining segment thickness 0.30 m. Also, cross section of single tunnels show that the outside diameter of the tunnel is 9.10 m and lining segment thickness is 0.50 m. Therefore the studied problem consists of two proposed systems (single and twin tunnels) as shown in Figure 2 (a) and Figure 2 (b) Abd-el.rahim et al. (2015) (a, b).

Single tunnel system Fig. (b) : The proposed system single tunnel starts from station No.1 to station No.5. In this present study, the numerical analysis of single tunnel will be between station No.3 and station No.4 (Section No.1).

Twin tunnel system Fig. (a) : Horizontally aligned twin tunnels are a widely used for tunnel configuration in urban metro projects. But, vertical aligned twin tunnels are used between station No.3 and station No.4 because a narrow street between these two stations. For that, diagonally aligned twin tunnels are used to connect the vertical and horizontal alignment.

The numerical analysis of twin tunnels will only the horizontal alignment between station No.5 and station No.6 (Section No 4), as shown in figure 2 (b). Figure 3 shows the geological cross sections and different configuration of tunnels [1,10].

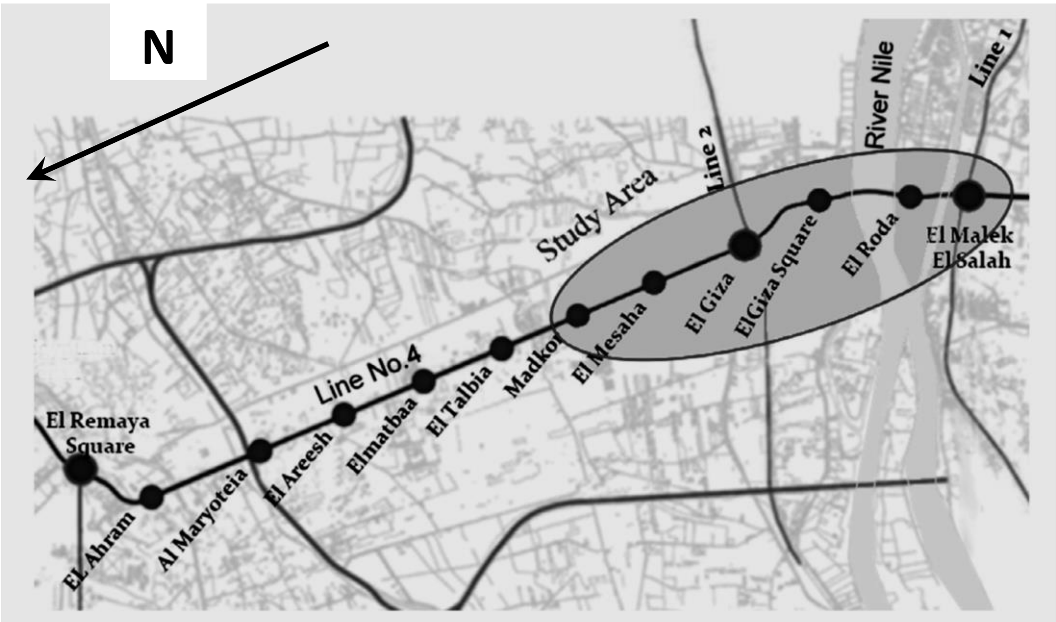
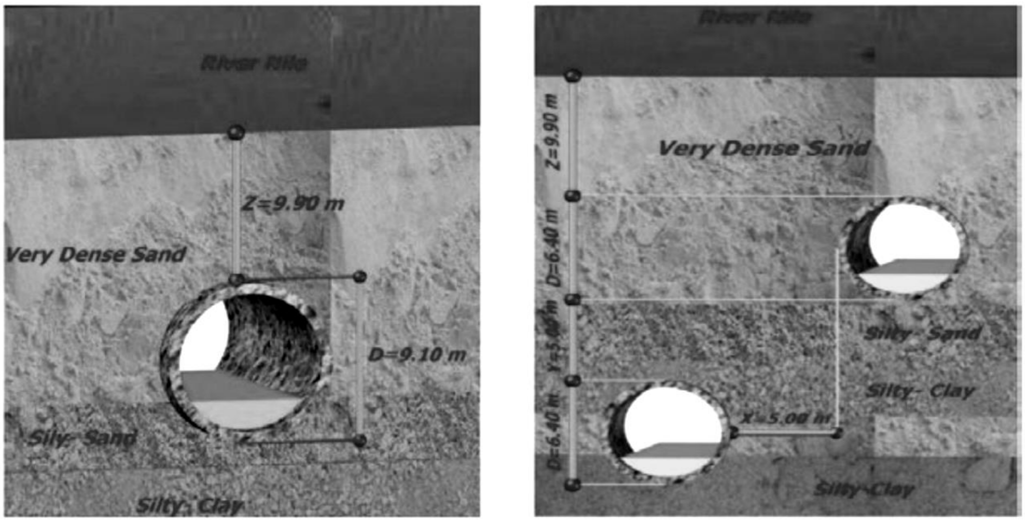


Figure 1: General layout of Greater Cairo metro line No. 4 (Phase No. 1) [10].



(a) Single system *(b) Twin system*

Figure 2 (a): Proposed single system and twin tunnel system [10].

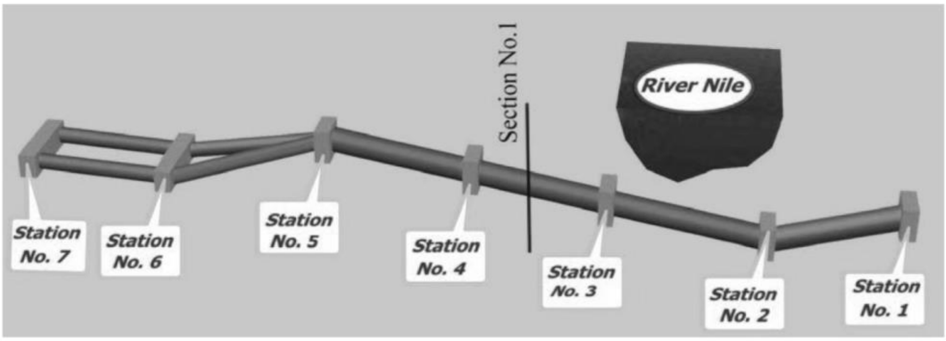


Figure 2 (b): Proposed single tunnel system [10].

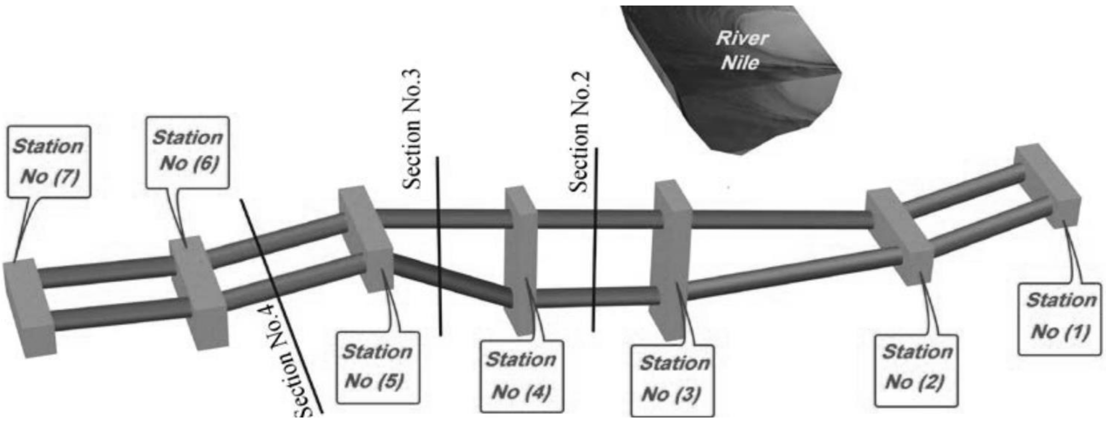


Figure 3: Geological cross sections and different configuration of tunnels [10].

3. Numerical Modeling

In this study, Finite Element Analysis was conducted using PLAXIS Brinkgreve (2002) Finite Element program. In PLAXIS program, a 2-D plane strain model were used for soil modeling and 2-D beam elements for tunnel lining modeling. To simulate the soil behaviour, 15-node triangular element was used.. The Mohr-Coulomb constitutive model was used for the soil. The vertical boundaries were taken relatively far away from the tunnel. It is constituted by a rectangular domain 120m wide and 55 m high, in order to place far enough the lateral boundaries as shown in Figure 4.

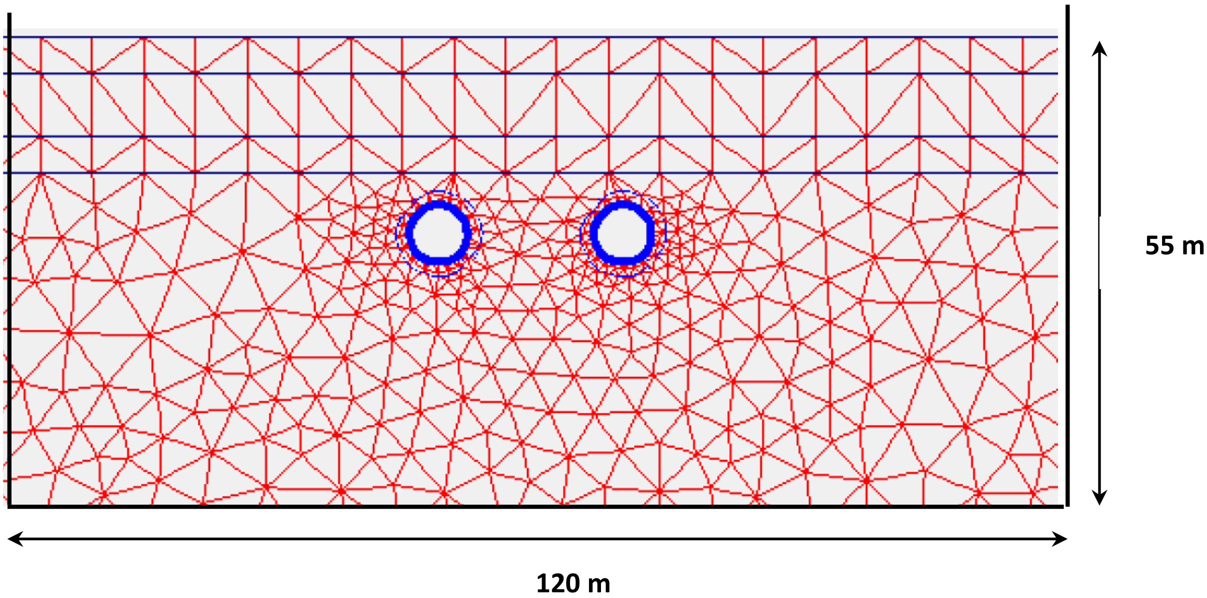


Figure 4: A typical PLAXIS model with boundary conditions for Greater Cairo Metro Line 4 - Section No. (4).

3.1 Material Parameters

The geological formations along the bored tunnel are typical Nile alluvial deposits as shown in Figure 2 (a) section No. (4) and five main formations are recognized as follows:

Top Soil ; Top Clay; Dense Sand; Very Dense Sand and Bottom Clay.

Geotechnical parameters are based on the geotechnical investigation study . The soil parameters are given in Table 1. The water table was at the ground surface. The tunnel lining is from concrete and the properties of concrete segment are shown in Table 2.

Table 1: Geotechnical soil parameters.

	Unit Weight □ (kN/m3)	Young Modulus E (MPa)	Poisson Ratio n	Fiction Angle f°	Cohesion C (kPa)
Top Soil	18	10	0.35	27	0
Dense Sand	20	75	0.29	36	0
Very Dense Sand	20	100	0.28	38	0
Top Clay	19	8.5	0.40	20	8.5
Bottom Clay	19	30	0.40	20	20

Table 2: Properties of concrete segment.

Property	Value
Design Standard Strength F_{cu} (MPa)	50
Modulus of Elasticity , Ec(MPa)	31500
Poisson Ratio (n)	0.20
Unit Weight of Concrete (kN/m^3)	25

3.2 Analysis of Output Results

Parameters to be analyzed: - the straining actions of the twin tunnel lining under static load, also the max displacement of the twin tunnels under static load.
The results of the analysis of the models show a significant increase of the internal forces that act on the lining. Furthermore, the deformations in the segmental lining increase with the effect of the static load. Table 3 shows a parametric study taking into account the sequence of excavation. The results indicate and comparatively the effect of the sequences of excavation on the stability and safety of the TBM tunneling for the increase of the internal forces in lining and its deformations.

Table 3: Lining Stresses and Total Displacement for the left and right tunnel of Cairo Metro Line No. 4 Twin Tunnels.

Exacation Process	Left Tunnel				Right Tunnel			
	Total disp (m)	Axial Force (KN/m)	Shear Force (KN/m)	Bending (KN.m/m)	Total disp (m)	Axial Force (KN/m)	Shear Force (KN/m)	Bending (KN.m/m)
Left Tunnel	0.00300	-1210	30.55	-48.69	0	0	0	0
Right Tunnel	0.00473	-1210	29.39	-46.53	0.00471	-1210	-29.95	-47.55

3.3 Framework of Study

This parametric study is devoted to investigate four design parameters. These parameters include the following:
The Clear Distance between Twin Tunnel (S): At 1D horizontal distance, 2D, 3D and 4 D where D is the diameter of single tunnel.
Twin Tunnel Crown Depth (d): At 2D, 3D, 4D and 5D where D is the diameter of single tunnel.
The Ground Water Level Depth (GWL): Where it is correlated with single tunnel Diameter (D) and studied at level 1 D, 2D, 3D, 4D and 5D.
The Surrounding Soil Stiffness (E): Where it is represented for two different types of surrounding soil with different stiffness the Clay increasing gradually from top clay to bottom clay (E1, E2 and E3) and the Sand increasing gradually from dense sand to very dense sand (E1, E2 and E3).

3.3.1 The Distance between Twin Tunnel (S)
From Fgure 5 (a,b,c,d) The clear distance between tunnels (S) shows that it has a major effect on soil movement and internal forces in tunnel lining more than other studied

parameters and should be more than about 3 D to decrease the effect of interaction between tunnels and to reduce the additional straining actions due to static load.
Also from this Figure, it can be deduced that increasing the spacing S between tunnels decreased the value of displacements by 8% from S=1D to 3D then stay almost constant till 4D. Shear forces and bending moments values decreased by around 5% from 1D to 4D. Axial forces remains almost unchanged.

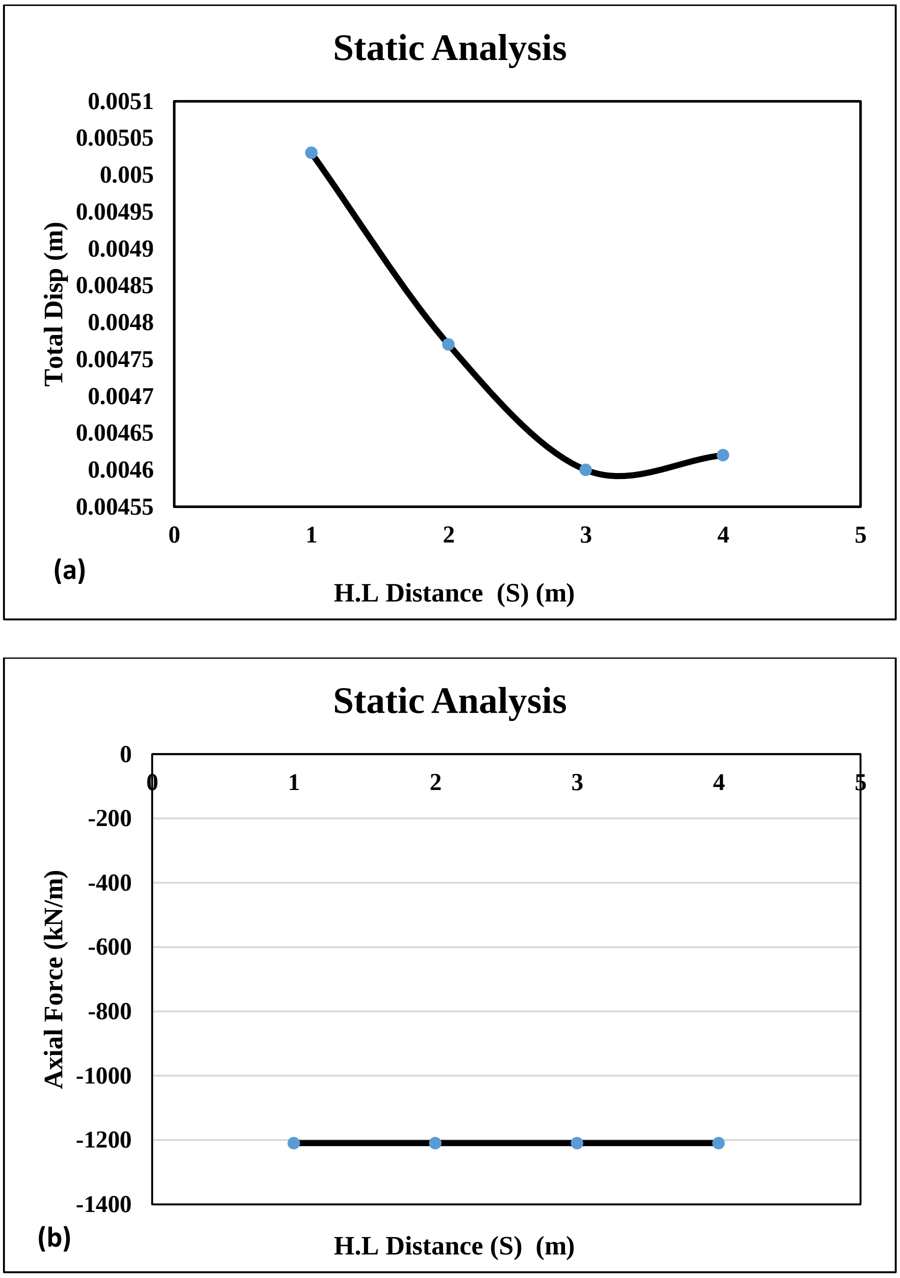
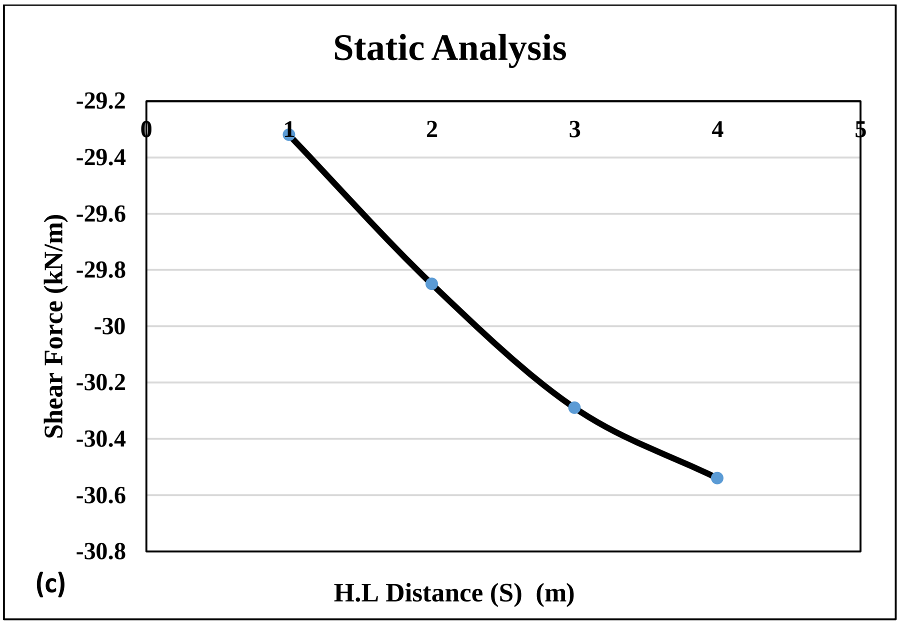


Figure 5: Effect of spacing (S) on the displacement and straining actions of twin tunnels.



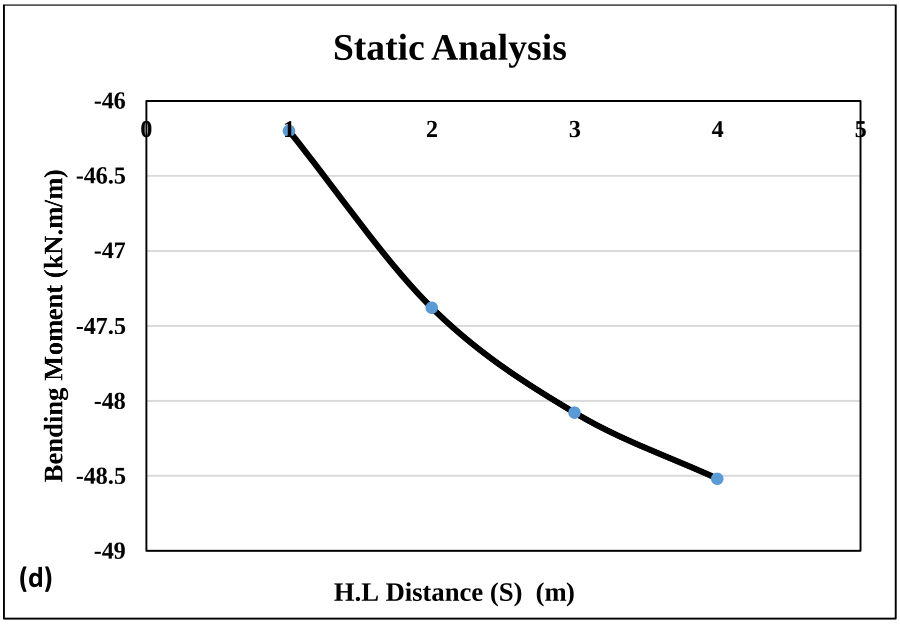


Figure 5: Effect of spacing (S) on the displacement and straining actions of twin tunnels (Contd).

3.3.2 Twin Tunnel Depth (d)

In this section the static effect of the depth of the crown of tunnels on the straining actions of tunnels lining was studied by changing the depth (d) from 2D to 5D where D is the tunnel diameter in meters. Figure 6 (a,b,c,d) shows that: Max deflection of tunnels increased slightly by 5% with the depth increase.

Axial forces increased linearly with the depth to double the values from 2D depth till 5D depth for static loads. Shear forces decreased with depth for static load.

Finally, for bending moments, values for static load oscillated with depth to increase to the double the value from 2D depth to 5D depth.

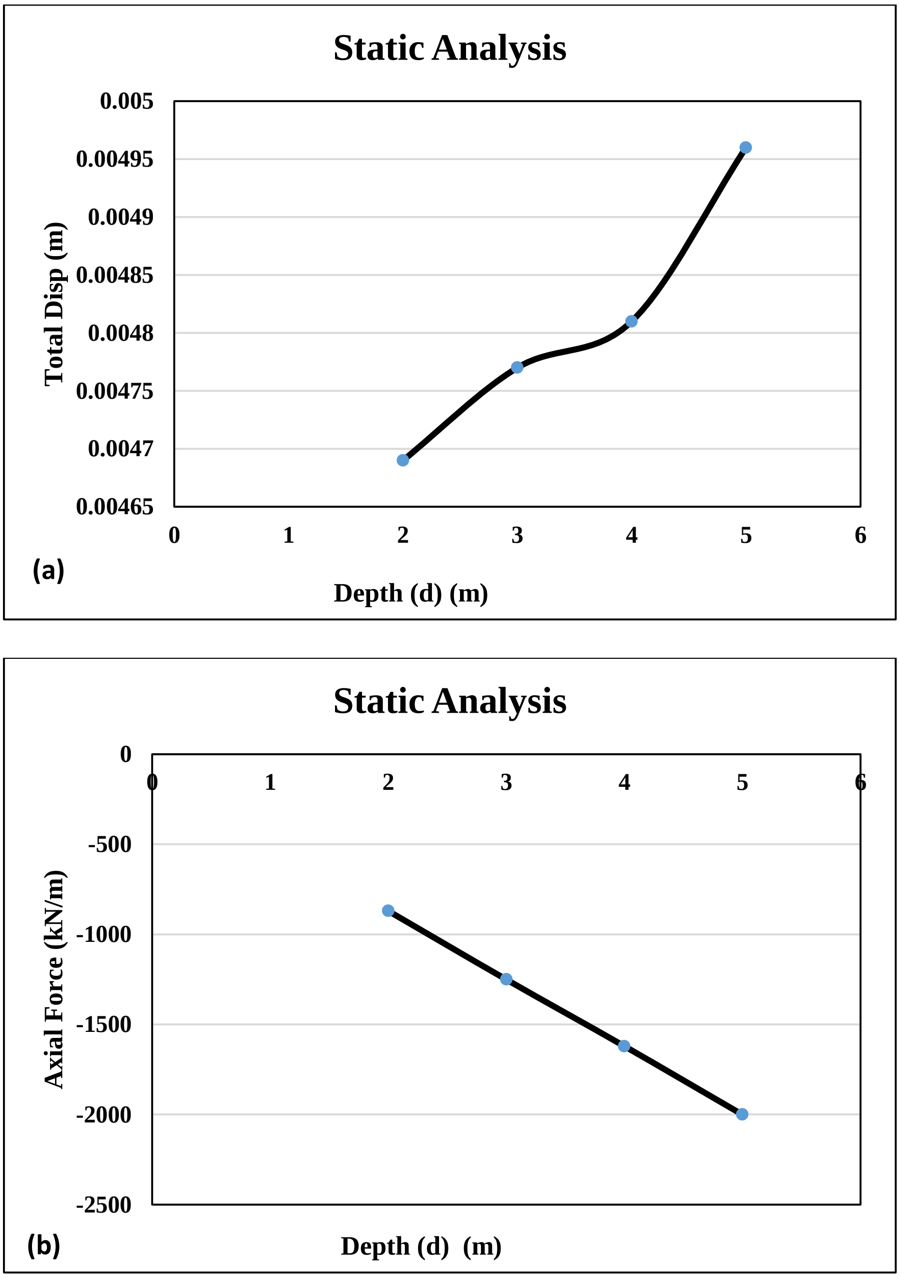
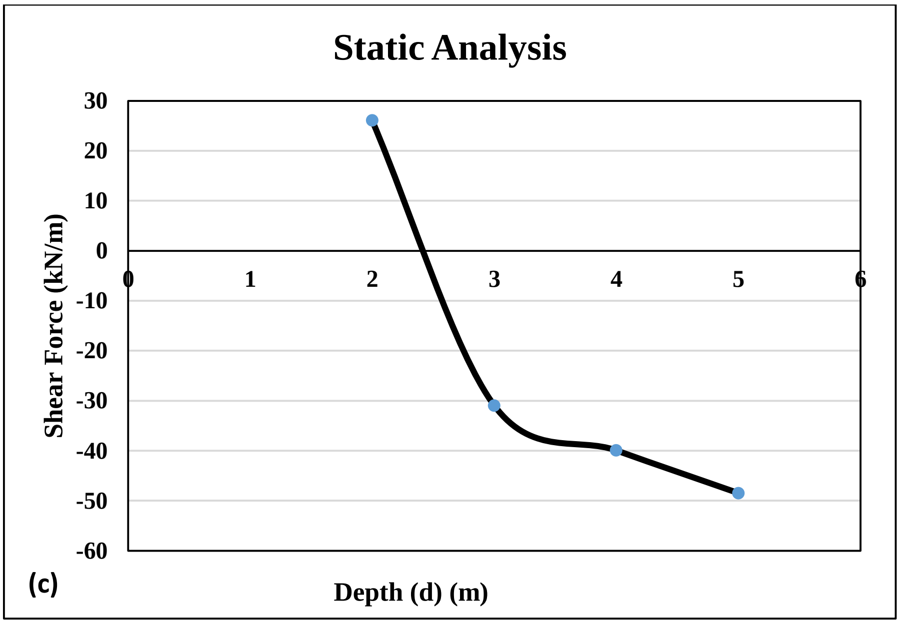


Figure 6: Effect of Twin Tunnel Crown Depth (d) on the displacement and straining actions of twin tunnels.



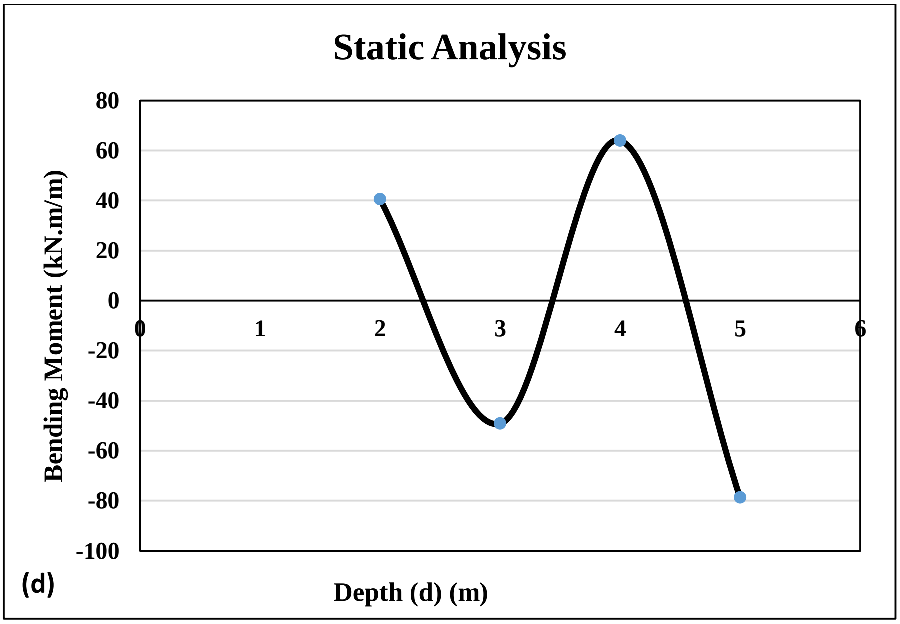


Figure 6: Effect of Twin Tunnel Crown Depth (d) on the displacement and straining actions of twin tunnels (Contd.).

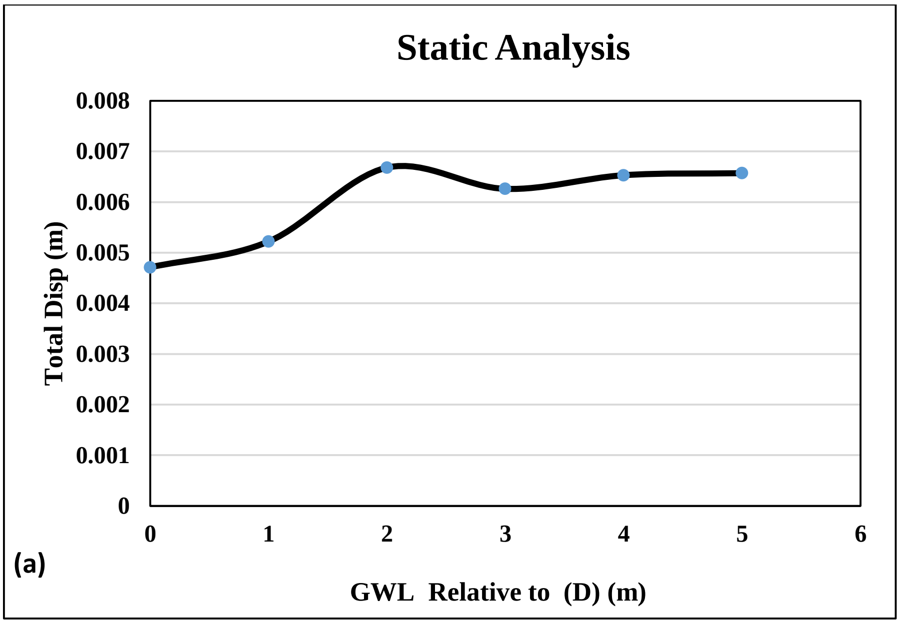
3.3.3 The Ground Water Level (G.W.L.)

In this section, the ground water level (G.W.L.) was studied at levels 0,1D,2D,3D,4D,5D.

Figure 7 (a,b,c,d) shows that the displacement it increased by 40% with the increase depth of ground water level from 0 to 5D.

The presence of ground water in different levels increased the values of shear forces and bending moments from 50% to 100% compared to the section before without ground water but it had very slight effect on axial loads for static load.

It can be concluded that the ground water had major effect on shear and bending until the 3D depth (the depth of our case study), after that level ground water has minor effect.



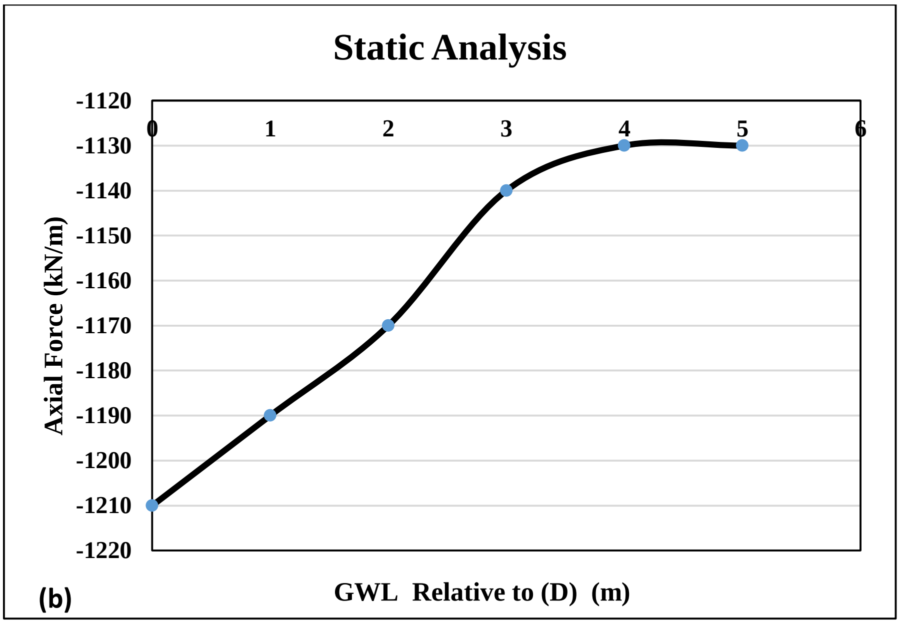
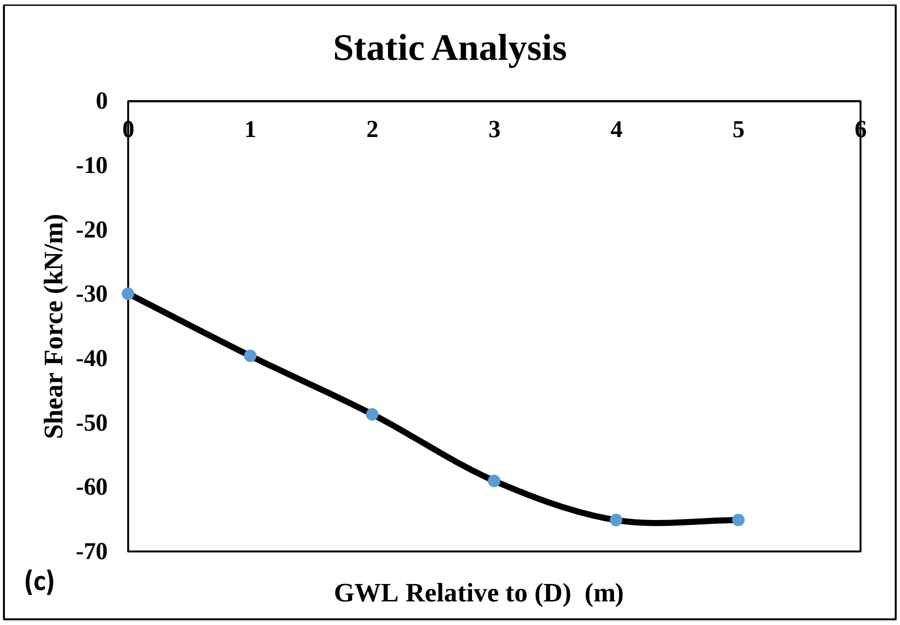


Figure 7 : Effect of The Ground Water Level Depth (GWL) relative to (D) on the displacement and straining actions of twin tunnels.



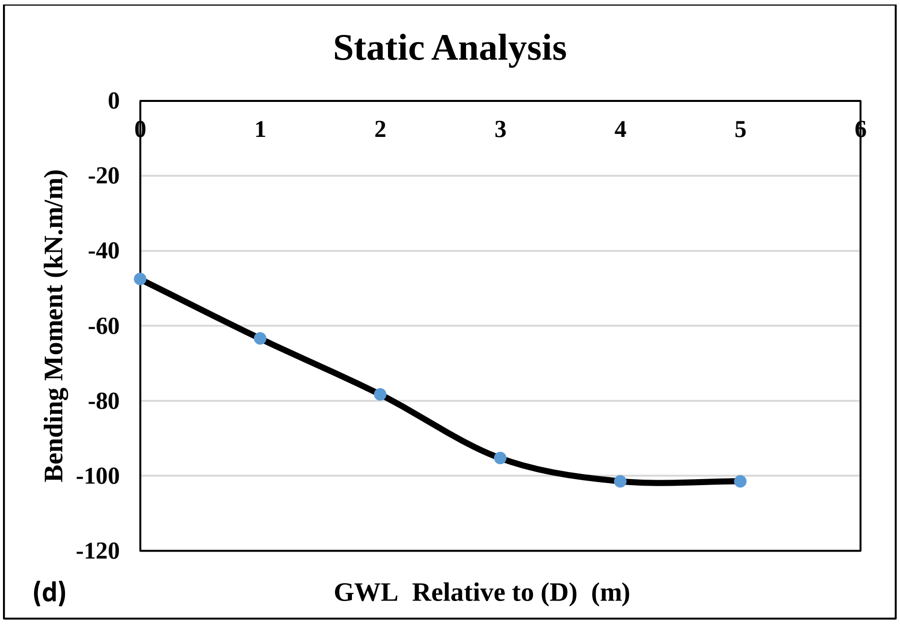


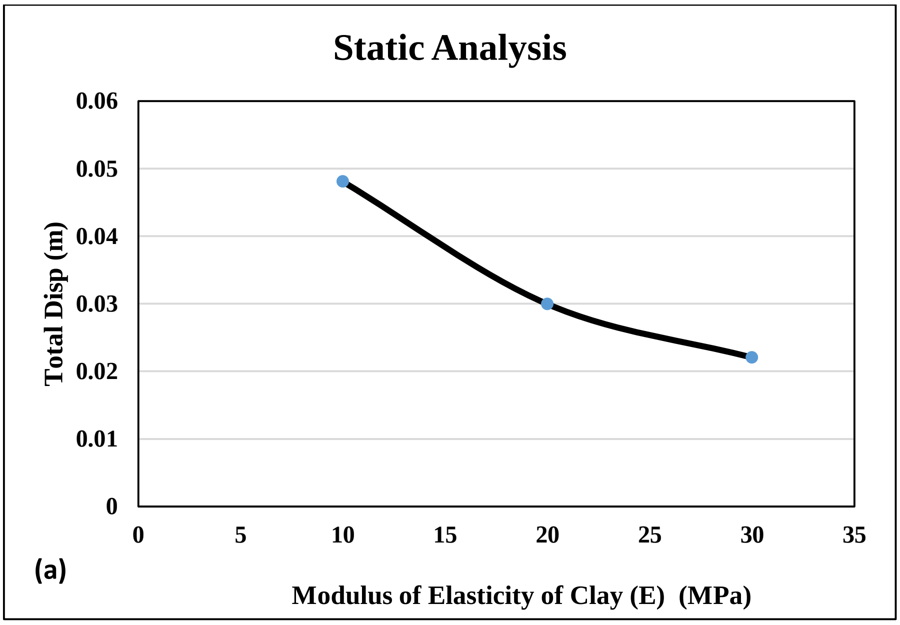
Figure 7 : Effect of The Ground Water Level Depth (GWL) relative to (D) on the displacement and straining actions of twin tunnels (Contd.).

3.3.4 The Surrounding Soil Stiffness (E)

Figure 10 (a, b,c,d) and Figure 8 (a,b,c,d) investigate the effect of surrounding soil stiffness of clayey and sandy soils on the displacement and straining actions of twin tunnel under static load.

3.3.4.1 The Surrounding Soil Stiffness (E), Soil Type is Clay

From Figure 9 (a,b,c,d), the following conclusions can be drawn that increasing the stiffness of surrounding clay from (E) from 10 , 20 and 30 MPa decreased the straining actions and displacement of the twin tunnel under static load.



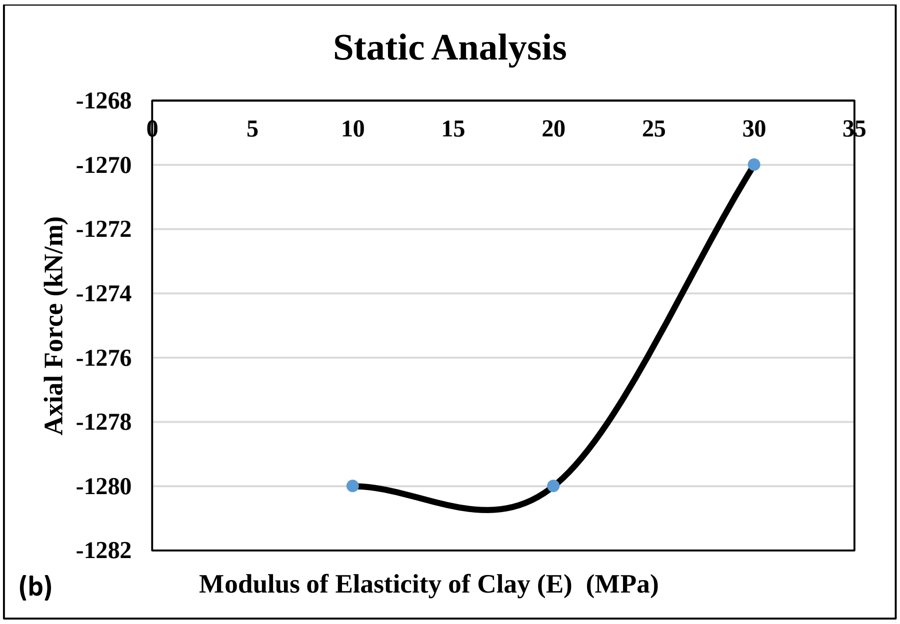
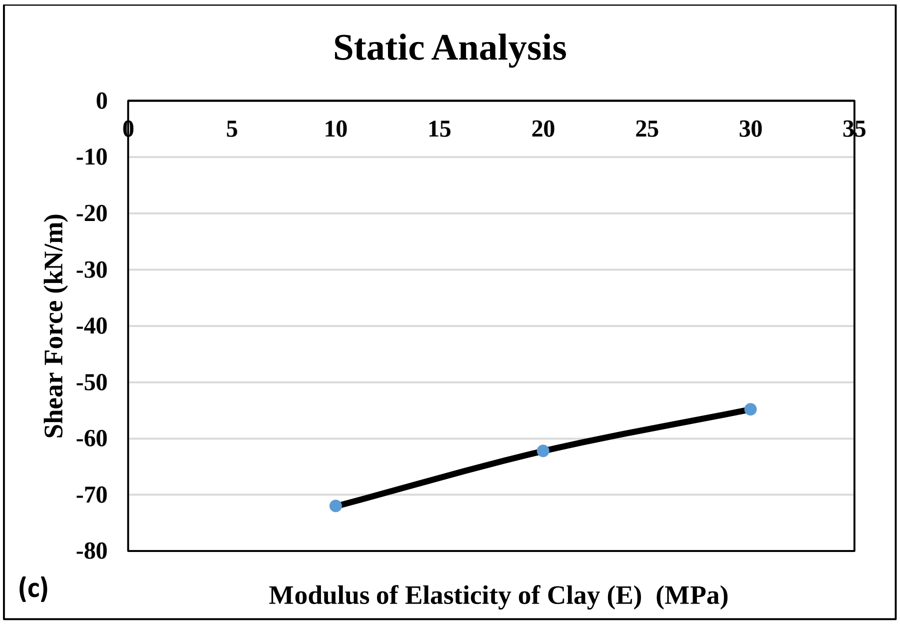


Figure 8: Effect of The Surrounding Soil Stiffness (E) (MPa) Type of Soil Clay on the displacement and the straining actions of twin tunnels.



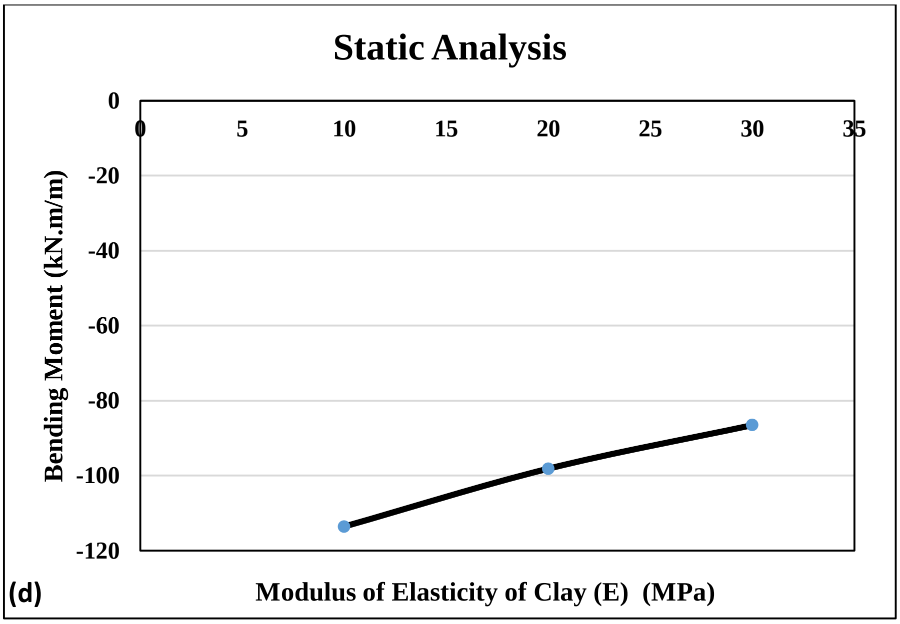
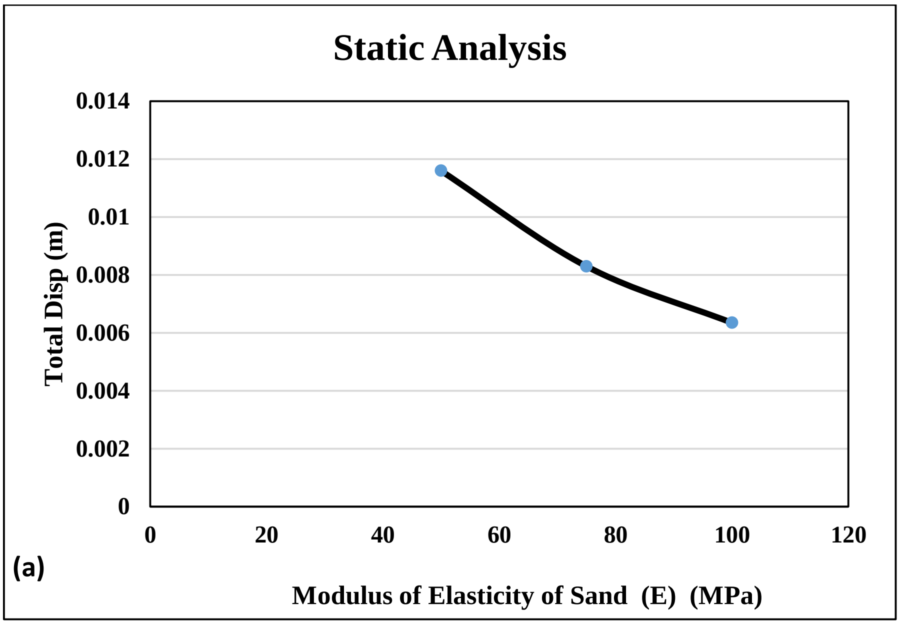


Figure 8: Effect of The Surrounding Soil Stiffness (E) (MPa) Type of Soil Clay on the displacement and the straining actions of twin tunnels (Contd.).

3.3.4.2 The Surrounding Soil Stiffness (E), Soil Type is Sand

From figure 11 (a,b,c,d) , the following conclusions can be drawn that increasing the stiffness of surrounding sand (E) from 50 , 75 and 100 MPa decreased the straining actions and displacement of the twin tunnel under static load.



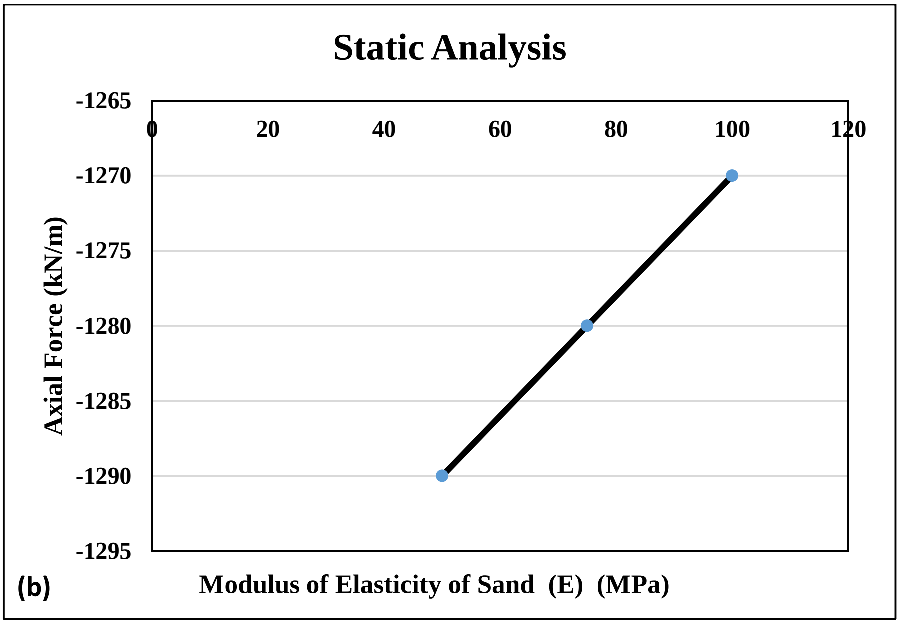
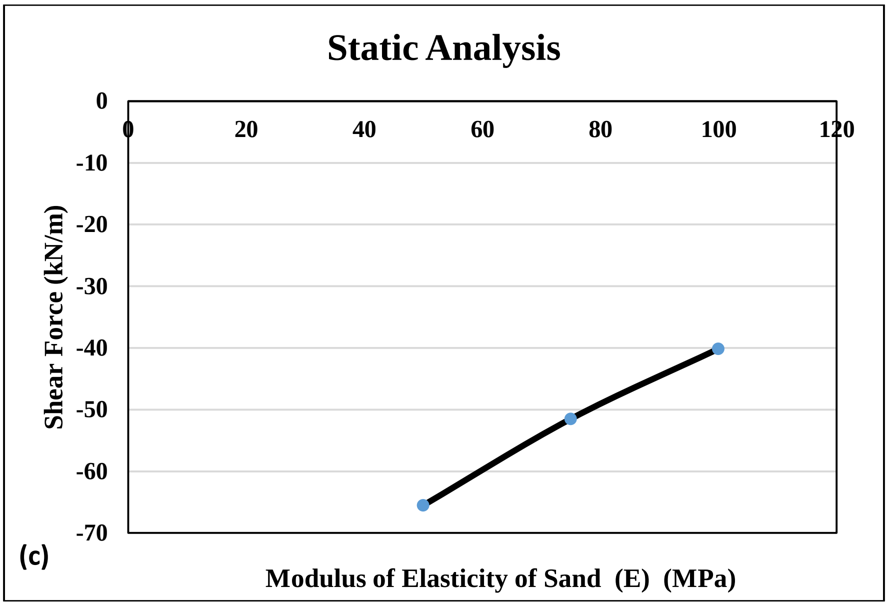


Figure 9: Effect of The Surrounding Soil Stiffness (E) (MPa) Type of Soil Sand on the displacement and the straining actions of twin tunnels.



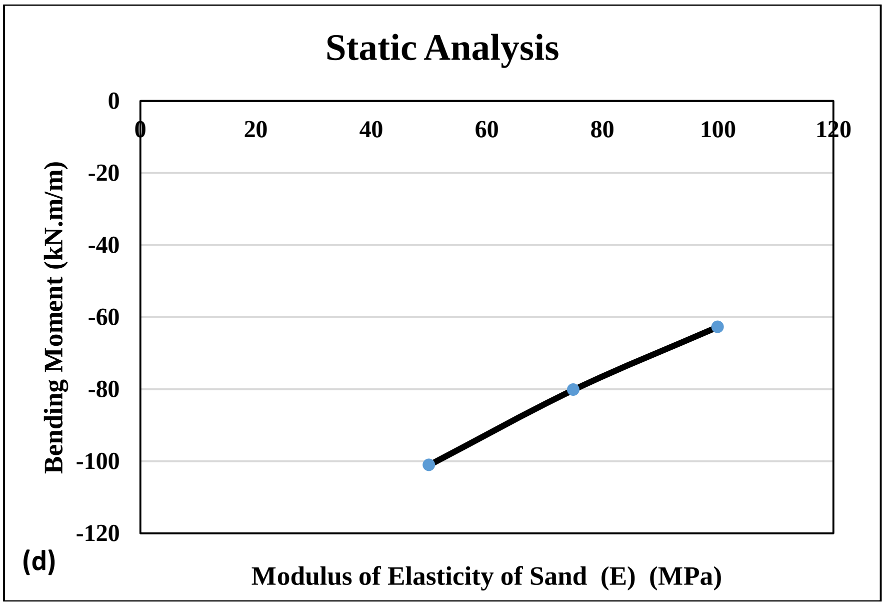


Figure 9: Effect of The Surrounding Soil Stiffness (E) (MPa) Type of Soil Sand on the displacement and the straining actions of twin tunnels (Contd.).

4. Summary and Conclusions

Extensive studies have been carried out to investigate accurately the full interaction between horizontal twin tunnel lining and the surrounding soils under static load. Numerical models have been prepared to establish the effect of the excavation sequence, the horizontal distance between tunnel (S), tunnel depth (d), ground water level (GWL) and soil stiffness (E). This numerical analysis is done by modal analysis based on the finite element method using PLAXIS 2D software. The following conclusions can be drawn:

1. The results of the analysis of the excavation sequence show a significant increase of the internal forces (shear forces and bending moments) that act on the lining. Furthermore, the deformations in the segmental lining increase with the effect of the static load.

2. The clear distance between tunnels (S) shows that it has a major effect on soil movement and internal forces in tunnel lining more than other studied parameters and should be more than about 3D to decrease the effect of interaction between tunnels and to reduce the additional straining actions due to load.
3. The values of tunnels displacements and internal forces increased considerably with the increase of tunnels depth (d) for static load.
4. The ground water level (GWL) had major effect on shear and bending until the 3D depth after that level ground water has minor effect.
5. Increasing soil stiffness (E) has good effect in reducing internal forces and displacement for twin tunnels subjected to static loading.

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