ISSN: 0067-2904
GIF: 0.851

# Stresses and Displacements Analyses around Tunnel Opening Under Water Body Using Finite Element Method (FEM) in Baghdad City/Middle of Iraq

**Hamed H. Abdullah[1]*, Ameer H. Al-Saffar[1], Raed S. Jasim[2]**
[1]Department of Geology, College of Science, Baghdad University, Baghdad, Iraq
[2]Department of Oil Engineering, College of Engineering, University of Missan, Iraq

**Abstract**

In this study, the stresses and displacement around a tunnel opening under water body in Baghdad city, middle of Iraq, during excavation and lining are discussed. For this purpose, the finite element method (FEM) was adopted as an effective approach to analyze the problem using (SIGMA/W) program. The research includes the study of the behavior of soil due to excavation of a tunnel by calculating the displacements and stresses in three positions of the tunnel (crown, wall, and invert) during the various stages of construction. The surface settlement is also studied. The finite element analyses were carried out Using (Elastic- plastic) and (linear elastic) models for the soil and the concrete liner respectively.

**Keywords:** Displacement, effective stress, deviatoric stress, Atterberg limits.

# تحليل الاجهادات والهبوط حول فتحة نفق تحت جسم مائي باستخدام طريقة العناصر المحددة (FEM) في مدينة بغداد/ وسط العراق

**حامد حسن عبد الله[1]*، أمير حيدر الصفار[1]، رائد ساعي جاسم[2]**
[1]قسم علم الارض، كلية العلوم، جامعة بغداد، بغداد، العراق
[2]قسم هندسة النفط، كلية الهندسة، جامعة ميسان، العراق

**الخلاصة:**

في هذه الدراسة تم تحليل الاجهادات والازاحة خلال مراحل الحفر والتبطين لنفق تحت جسم مائي في مدينة بغداد وسط العراق. تم اعتماد طريقة العناصر المحددة (FEM) كمنهج فعال لتحليل تصرف النفق باستخدام برنامج (Sigma/W). وتضمن البحث دراسة سلوك التربة نتيجة حفر النفق عن طريق حساب الازاحات والاجهادات في مواقع ثلاثة وهي (Invert, Wall, Crown) من النفق خلال الحفر والتبطين.

أجريت التحليلات باستخدام العناصر المحددة بأعتماد نموذجين وهما اللدن مرن والمرونة الخطية لتمثيل التربة ومادة بطانة النفق على التوالي.

## Introduction:

A tunnel is an underground structure that passes beneath the ground. Tunnel may be constructed for many purposes, such as carrying traffic as railway tunnels and highway tunnels. It may be constructed for conveying utilities such as water supply tunnels and sewer tunnels [1]. The necessity of these constructions in urban areas has brought about the need for an efficient and safe method for the deep excavations without severely affecting the adjacent structures. In general, excavation refers to the removal of a material within certain specified limits, for construction purposes [2]. The stresses and the displacements in surrounding soil and tunnel lining depend not only on the soil mass properties and the in-situ stresses field, but depend also on the type and stiffness of the lining [3].

*Email: ameer_alsaffar@yahoo.com

**Location of the study area:**

The study area is located in middle of Iraq, Baghdad Governorate between latitudes 33° 17- 33°14 and longitudes 44° 26 - 44° 21. The tunnel is located in Baghdad city that links Dora highway on the west bank of the river to Baghdad technical institute, Tariq bin Ziyad square in Al-Zafaranya city on the eastern bank of the river. This project is a proposed tunnel which is part of an integrated project to develop the transport system in Baghdad that passes under the Tigris River as shown in Figure-1.


**Figure 1-** The path of tunnel in the study area [4].

**Geology of the study area:**

Baghdad province lies within the Unstable Shelf of the Arabian Plate, mostly within Tigris Subzone of the Mesopotamian Zone [5]. Most of the present structures are subsurface and they have no surface expressions. Two of these structures are anticlinal structures; the first is the East Baghdad structure having NW-SE trend and the second is the west Baghdad structure with NNW – SSE trend [6]. The stratigraphic column consists of clayey silt, clayey sand, silty clay and silty sand, and the area sediments are shown in Figure-2.

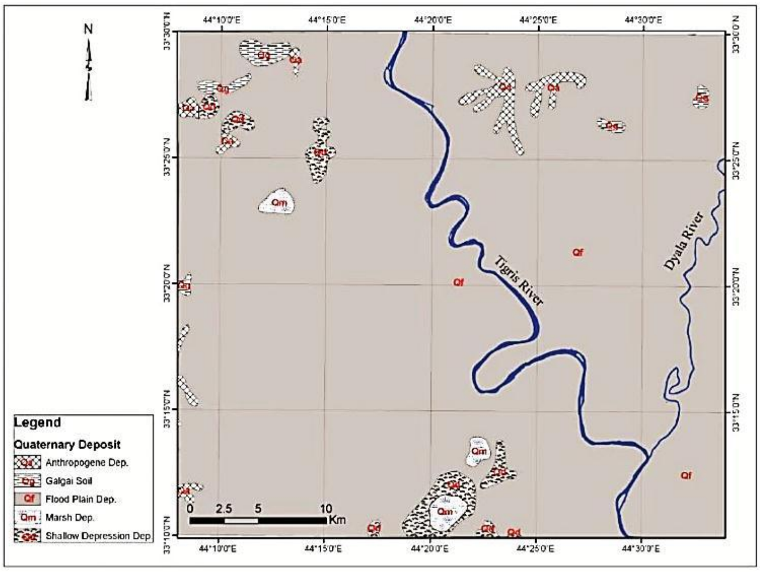



**Figure 2-** Geological map of Baghdad area after [7].

**Previous studies of tunnels:**

Mair and Taylor, (1993) [8], studied soil plasticity by comparing subsurface ground movements around tunnels in London clay with closed form solutions for contracting spherical and cylindrical cavities in a linear elastic perfectly plastic medium, respectively.

Karim, (1994) [9] evaluated the stresses and deformations associated with semicircular tunnel underlain by rigid base and surrounded by sandy soil with static loading conditions using finite element method. The study clarified that the soil stiffness increases with increasing angle of internal friction and causes a reduction in both stresses and deformations of the tunnel. An increase in the modulus of elasticity of the tunnel material was found to reduce the deformations of tunnel and increases in stresses.

Dasari et al., (1996) [10] used a finite element program to model the New Austrian Tunneling Method (NATM). The nonlinear behavior of London clay was modeled by a strain dependent and modified Cam-clay model and the tunnel lining was modeled by constant time-dependent elastic model. The construction process was modeled in two and three dimensions and by removing the elements in sequence.

Kasper and Meschke, (2004) [11] presented the simulation of a tunnel advance in soft cohesive soil below the ground water table using a three-dimensional finite element simulation model for shield-driven tunnel excavation. A Cam-Clay plasticity model is used to describe the material behavior of cohesive soils.

Salim and Gell, (2011) [12] studied the capabilities of a finite element method for analyzing the influence of a twin-tube highway –tunnel on the stability of a nearby water–transmission tunnel by using the computer program (SIGMA/W). To design tunnel meets existing underground structures in a smaller distance, they found that the maximum increase of stresses occur where the horizontal distance of the tunnel axis reach (14m). Great vertical distance (14m) between the underground openings.

**Tigris river sediments:**

The sediments of Tigris river are different according to the seasons of the year. They are non-homogeneous sediments and vary horizontally and vertically. The water movement speed is an effective factor to deposit and accumulate sediments. When it is slow, the deposition rate increase [13].

**Assessment of soil study area:**

The assessment includes evaluation of some of the physical and index properties of the soil of the study area to understand the soil behavior to construct the tunnel in it. The data that used to assess the soil of the study area taken from report of Iraqi National Center for Construction Laboratories and Building Research.

**1- Grain size analysis:**

The clay and silt ratios are high in the first 10m that the clay reaches to 65%, and the sand and gravel ratios increase at the deeper depths. The sand ratio reaches to 89.4% at 15.5m depth.

**The Atterberg Limits:**

To describe the consistency of a soil four states can be recognized, namely, liquid, plastic, semi-solid (stiff) and solid (hard). Those consistency states are related to limiting water contents which are usually referred to as Atterberg limits. Three consistency limits are in general use, i.e. liquid limit, plastic limit and shrinkage limit [14].

**Liquid Limit (L.L):**

The liquid limit is defined as the moisture content, in percent, at which the soil changes from a liquid state to a plastic state [15].

The liquid limit values ranged in Al-Dora (36 – 51.6%) where the minimum amount 36% (intermediate liquid limit) at a depth of 14m and 51.6% at a depth of 7.5m (high liquid limit). In Al-Zafaranya the liquid limit ranged (35.1 - 54.7%) where the minimum amount 35.1% (intermediate liquid limit) at a depth of 6m and 54% (high liquid limit) at a depth of 8m. Table-1 shows the typical values of liquid limit with description.

**Table 1-** Description of the values of liquid limit [16].

| Discription | Liquid limit % |
|---|---|
| Very low liquid limit | <20 |
| Low liquid limit | 20-25 |
| Intermediate liquid limit | 25-50 |
| High liquid limit | 50-70 |
| Very high liquid limit | 70-90 |
| Extra high liquid limit | >90 |

**Plastic Limit (P.L):**

The plastic limit is defined as the moisture content at which a soil crumbles when rolled down into threads 3 mm in diameter. Being able to roll a moist piece of clay is an indication that it is now in its plastic state [15]. Plastic limit values are ranged in Al Dora (18.7 – 27.5%) where the minimum ratio is 18.7% at a depth of 6m, and the maximum ratio 27.5% at a depth of 16m, in the area of Al Zafaranya plastic limit ranged (18 - 23.9%) where the minimum value 18% at a depth of 1m and 23.9% at a depth of 4m.

**Plasticity index PI:**

It is the difference between the liquid limit and the plastic Limit. The range of water content is high when the soil deforms plastically. When the plastic limit is equal to or greater than the liquid limit the plastic index is recorded as zero. One can use this index to classify the soil as shown in Table-2.
Plasticity index values are ranged in Al Dora (12 - 29.4%) where the minimum value is 12% (cohesive) at a depth of 16m, and 29.4% at a depth of 9.5m (cohesive). In Al Zafaranya the plasticity index is ranged (15.9 – 34.4%), the minimum value is 15.9% at a depth of 6m (cohesive), and 34.4% at a depth of 8m.

**Table 2-** Classification of soil according to plasticity index [17]

| Plasticity index | Soil type | cohesiveness |
|---|---|---|
| 0 | Sand | Non – cohesive |
| < 7 | Silt | Partly cohesive |
| 7-17 | Silty clay (clayey silt) | Cohesive |
| > 17 | clay | Cohesive |

**Consistency index (Ic):**

It is the ratio between the (LL-Mc) and the plasticity index PI. The soil is in the plastic status if Ic = 0-1, solid or semisolid if Ic > 1, and it's in the liquid status if Ic = 0 or negative [18]. The Ic is ranged (0.49-1.07), where the minimum value 0.49 (plastic) at 6m depth and the maximum consistency index values are ranged in Al Dora (0.5-1.1) where the minimum value is 0.5 at 13.5m depth (plastic) and 1.1 at 1m depth (solid or semisolid). In Al Zafaranya the plasticity index value 1.07 (solid or semisolid) at 0.5m depth.

**Description of the problem:**

The stresses and displacements of the tunnel are studied for tunnel with 7.5 m diameter, 2.5 and 5.5m depth with load 20 kPa that came from the weight of water in the Tigris River during summer season, excavated in the fine silty sand layer. Figure-3 shows the soil profile and concrete lining of the tunnel and Table-3 illustrates the range of values for parameters used in the parametric study.

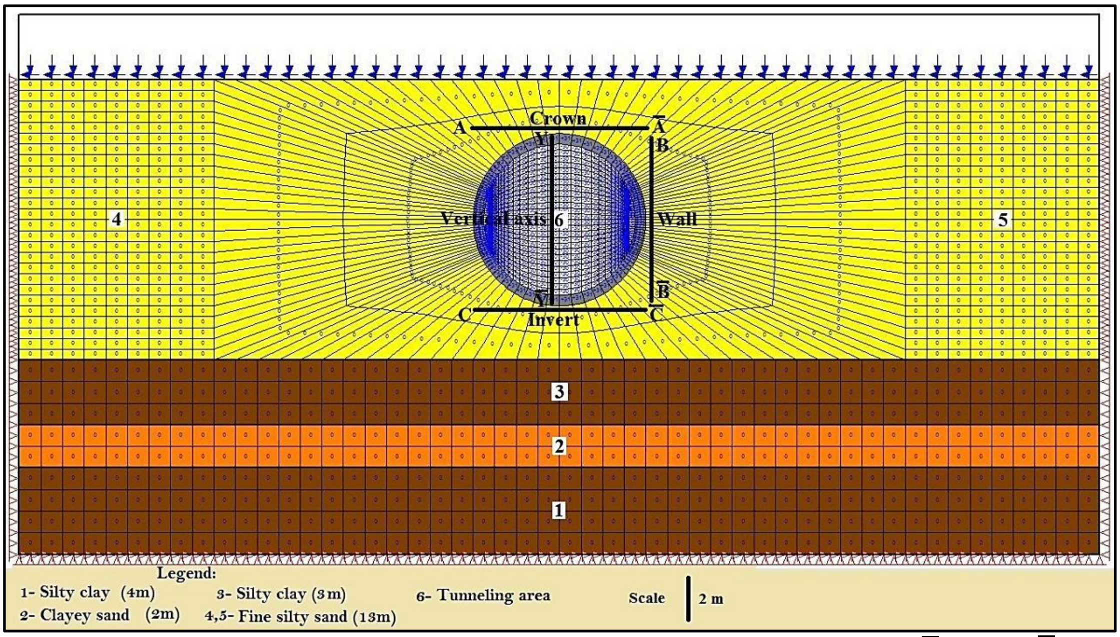



**Figure 3-** Soil profile and concrete lining of the tunnel with 2.5m depth. A-Ā: crown, B-B̄: wall, C-C̄: invert, Y-Ȳ: vertical axis.

**Table 3-** The range of values for parameters used in the parametric study [19]

| Parameter | Range of values | Units |
|---|---|---|
| Tunnel depth | 2.5 and 5.5 | m |
| Tunnel diameter | 7.5 | m |
| Modulus of elasticity of lining (concrete) | 95760.517 for silty clay, 23940.129 for clayey sand, 191521.035 for fine silty sand and 41000000 for concrete | kPa |
| Cohesion of soil (C) | 12 for silty clay, 11.0124 for clayey sand, 20.101 for fine silty sand and 27579 for concrete | kPa |
| Angle of internal friction(ϕ) | 32 for silt clay, 40 for clayey sand, 35 for fine silty sand and 55 for concrete | degrees |
| Load of Tigris river | 20 | kPa |
| Poisson's ratio | 0.45 for silty clay,0.35 for clayey sand, 0.35 for fine silty sand and 0.2 for concrete | - |
| Ko (lateral earth pressure) | 0.6 for silty clay, 0.45 for clayey sand, 0.45 for fine silty sand and 1 for concrete | - |
| Density (γ sat) | 1842 for silty clay, 2162.4 for clayey sand, 1762.03 for fine silty sand and 2400 for concrete | $Kg/m^3$ |

The tunnel excavation with TBM (Tunneling Boring Machine) method is supposed in this research, and the software that used to analyze the stresses and displacements is SIGMA/W (2007). The deformation meshes and vectors are shown in Figure-4 which indicate the deformations that effect on the tunnel opening during excavation and lining.

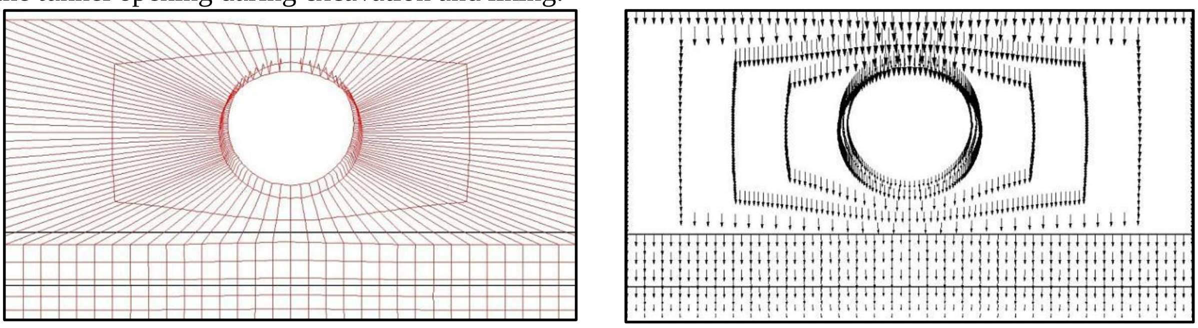


**Figure 4-** Deformation meshes and vectors during lining.

The deviatoric stress is a stress component in a system which consists of unequal principal-stresses. There are three deviatoric stresses, obtained by subtracting the mean (or hydrostatic) stress ($\sigma^-$) from each principal stress (i.e. $\sigma_1 - \sigma^-$, $\sigma_2 - \sigma^-$, and $\sigma_3 - \sigma^-$). Deviatoric stresses control the degree of body distortion [18]. They decrease after excavation and during lining around tunnel opening to less than 2 kPa and increase with depth as shown in Figure-5 and y displacement during lining decreases with depth around tunnel opening from 0.18m to 0.08m as shown in Figure-6. y-effective stress after excavation and during lining decreases near the tunnel opening to less than 5 kPa and increases with depth as illutrated in Figure-7, 1 kPa=1KN/m$^2$.

By drawing the relationships between y displacement with distance during lining, the value of y displacement in the crown is 0.184m at 5m distance, and decreases in the wall to 0.108, and decreases in the invert to 0.074m. The x displacement with y-coordinate (which represents the depth) decreases with depth in the vertical axis and reach 0 in the center as shown in Figure-8 The negative values in maps mean that the displacement or stress increases toward the tunnel opening, while the positive values mean that the displacement and stress decreases toward the tunnel opening.

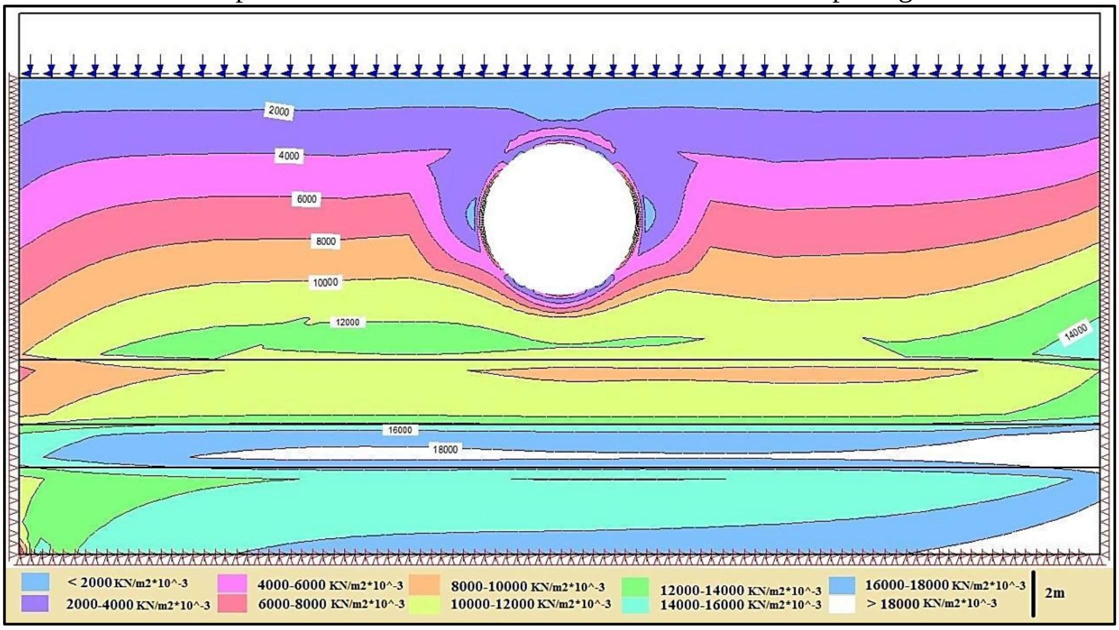



**Figure 5-** Contour map of the deviatoric stress during lining.

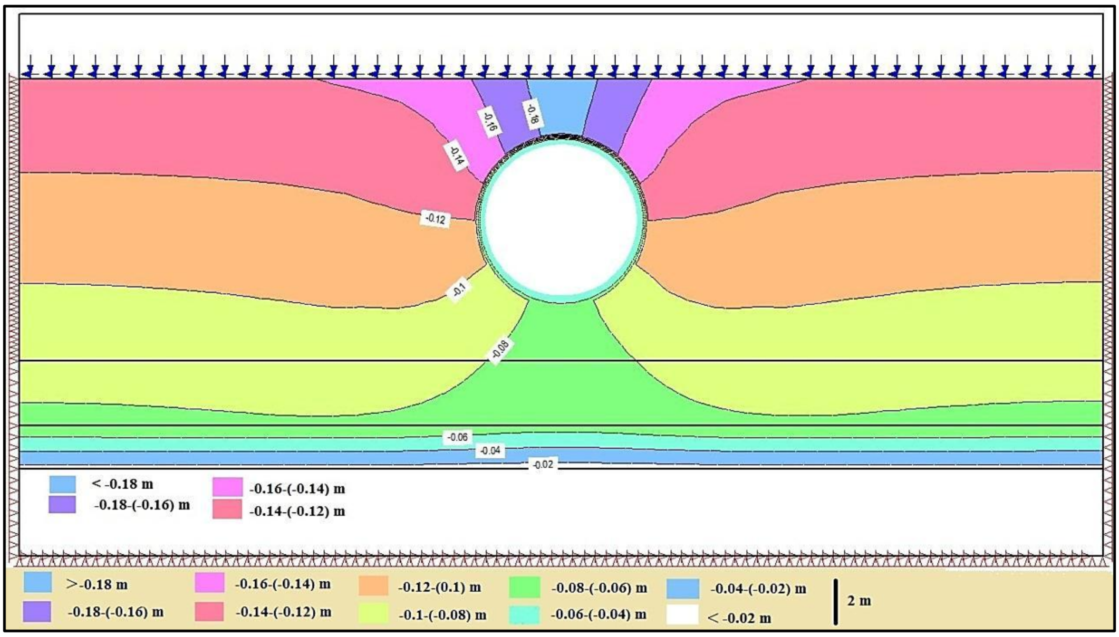



**Figure 6-** Contour map of y-displacement during lining.

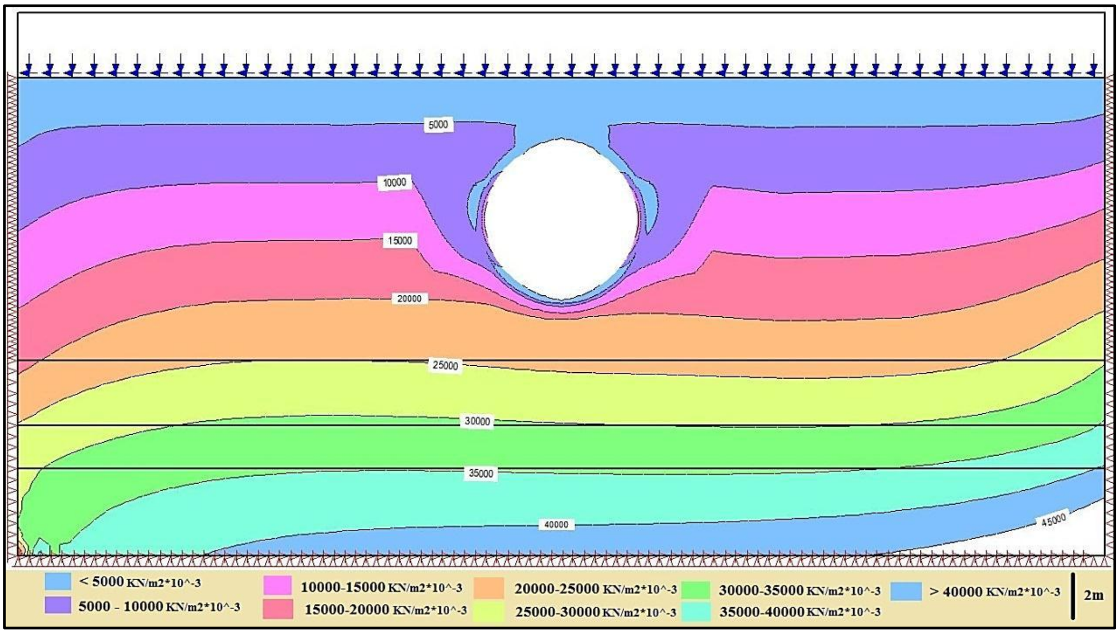
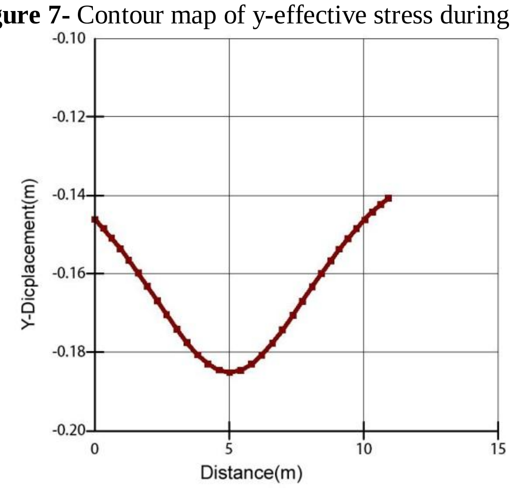
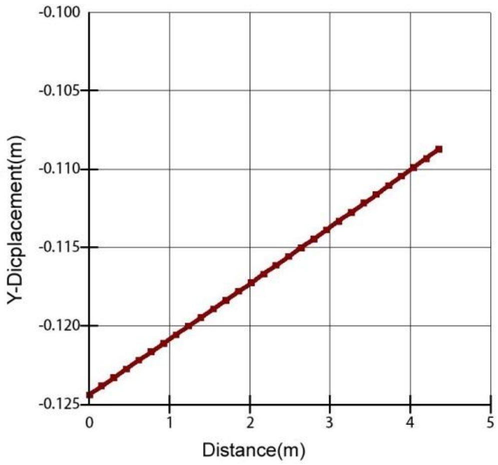


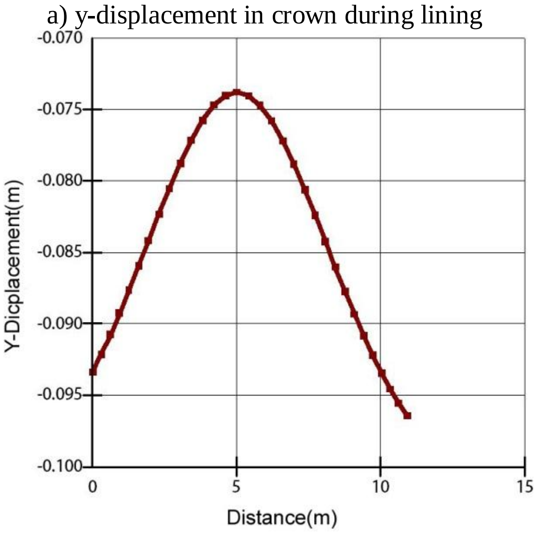

**Figure 7-** Contour map of y-effective stress during lining



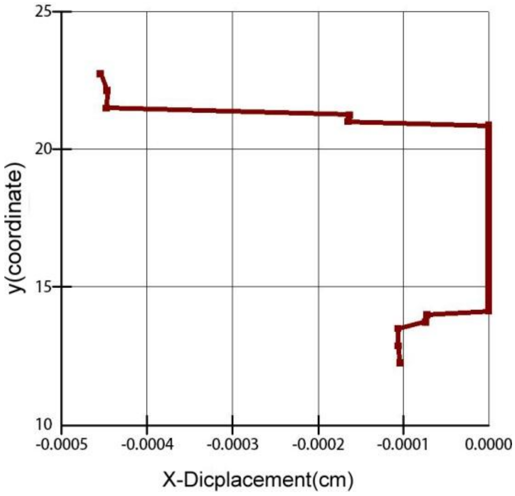

a) y-displacement in crown during lining




b) y-displacement in wall during lining



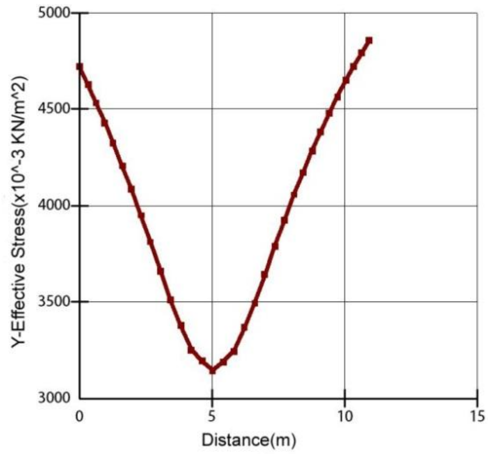

c) y-displacement in invert during lining



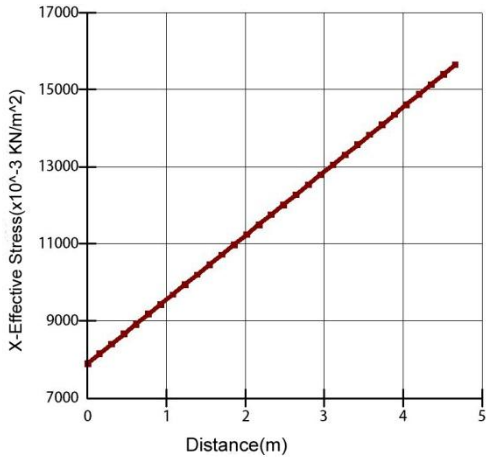

d) x-displacement in vertical axis during lining

**Figure 8-** Y and x-displacement in the crown, invert and wall during lining.

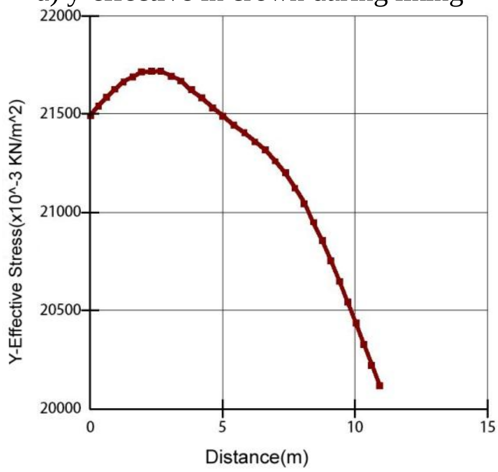
By drawing the relationship between y-effective stress with the horizontal distance, the value of y effective stress reaches in the crown to 3.15 kPa, and increases to 15.7 kPa in the wall, and reach in the invert to 21.7 kPa and. The y effective stress increases toward the tunnel opening in the vertical axis and reach more than 22 kPa as shown in Figure-9.



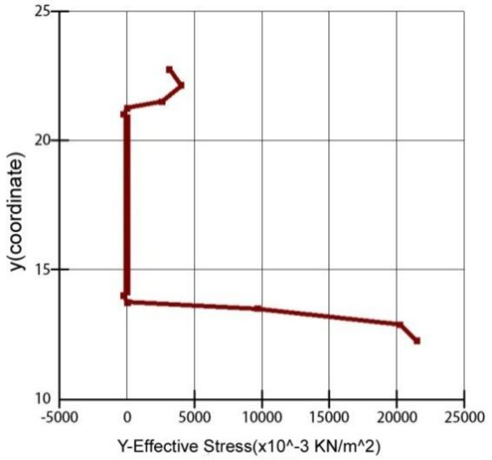

a) y-effective in crown during lining




b) y-effective in wall during lining




c) y-effective in invert during lining




d) y-effective in vertical axis during lining

**Figure 9-** Y-effective stress in the crown, invert and wall during lining.

The y-displacement along surface in this case reach to 0.186m as shown in Figure-10.

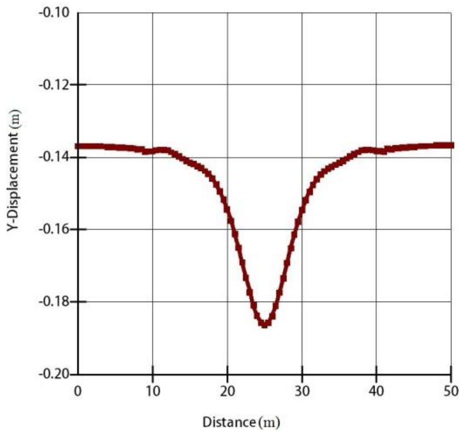



**Figure 10-** Y-displacement along the surface during lining.

The other case shows the stresses and displacements of the tunnel that are studied for tunnel with 7.5 m diameter, 5.5 m depth and load 20 kPa that came from the river water weight, excavated in the fine silty sand and silty clay layer. Figure-11 shows the soil profile and concrete lining of the tunnel with depth 5.5m. The deformation meshes and vectors are shown in Figure-12 which indicates the deformations that effect on the tunnel opening during lining. The deviatoric stresses after excavation and during lining reach around tunnel opening to less than 5 kPa and increases with depth as shown in Figure-13 and y displacement during lining decreases with depth around tunnel opening to 0.4m as shown in Figure-14. And the y effective stress, after excavation and during lining, decreases near the tunnel opening to less than 5 kPa and increases with depth as illutrated in Figure-15.

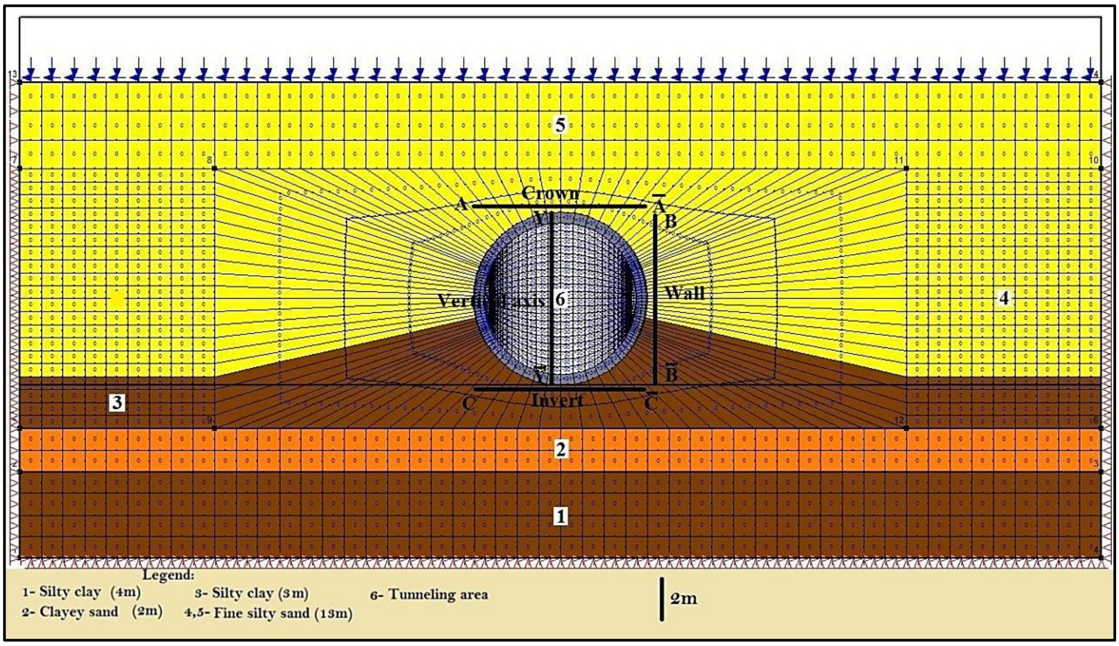



**Figure 11-** Soil profile and concrete lining of the tunnel with 5.5m depth.

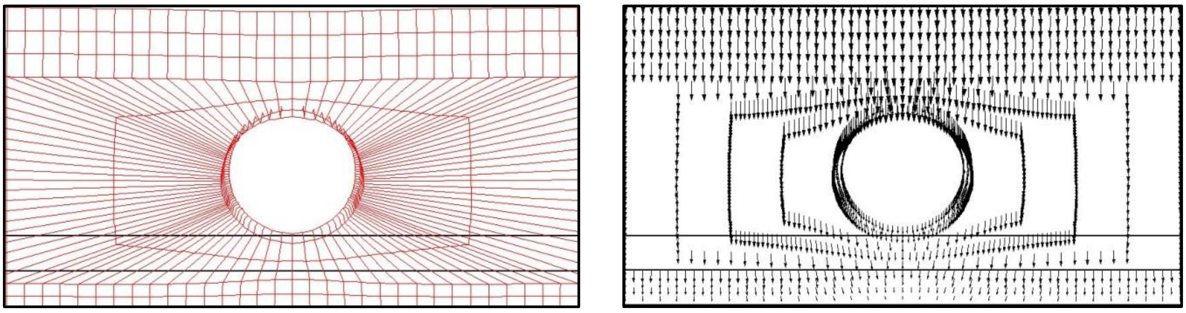


**Figure 12-** Deformation meshes and vectors during lining.

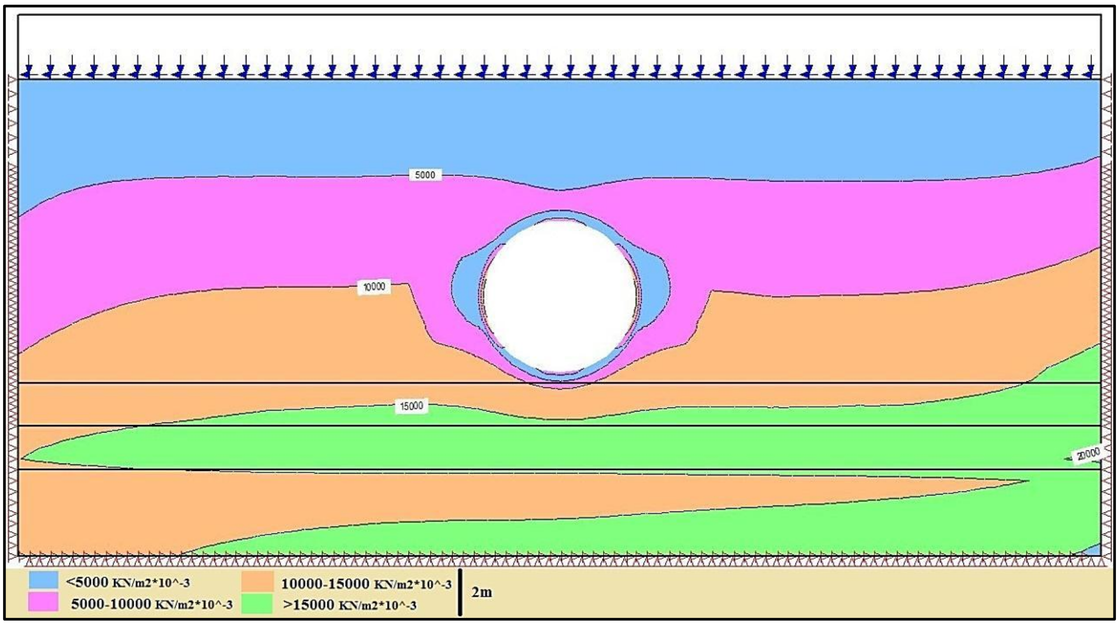



**Figure 13-** Contour map of the deviatoric stress during lining.

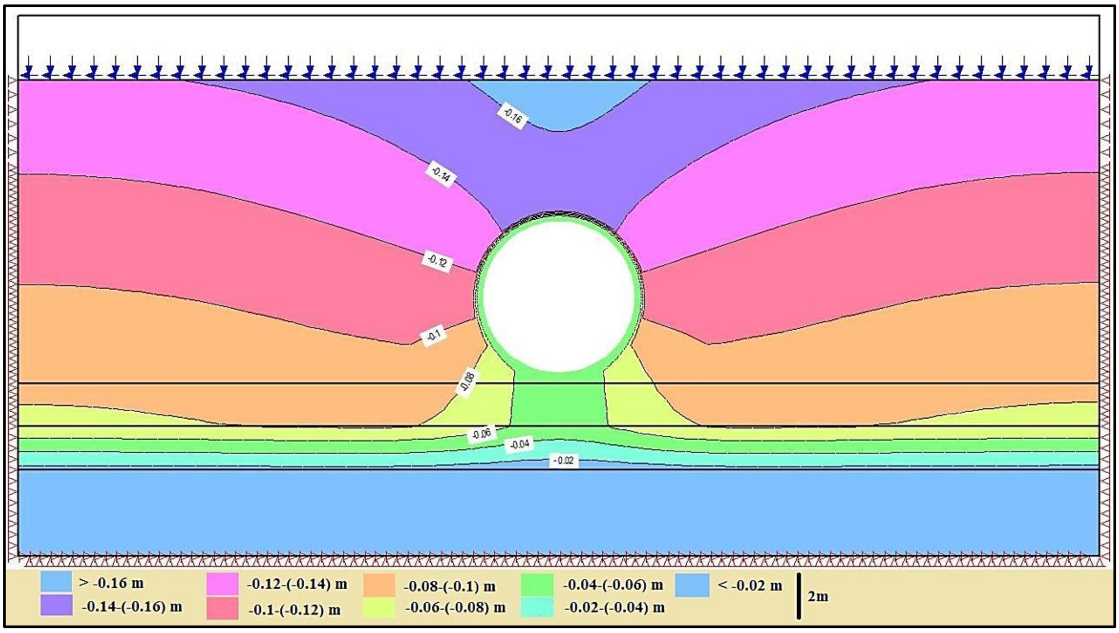



**Figure 14-** Contour map of y-displacement during lining.

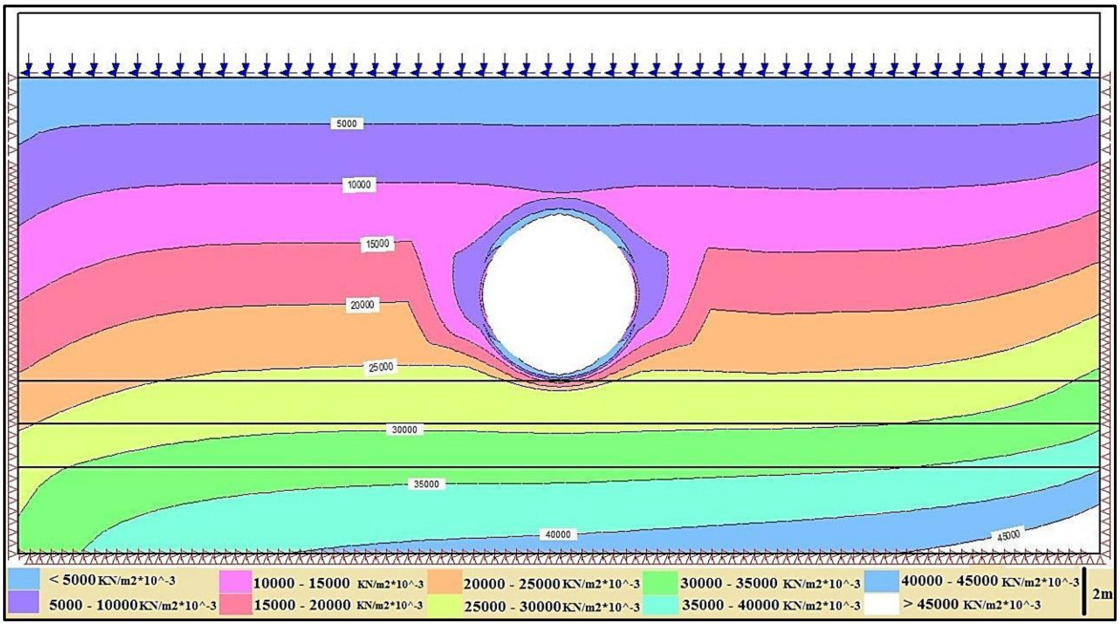
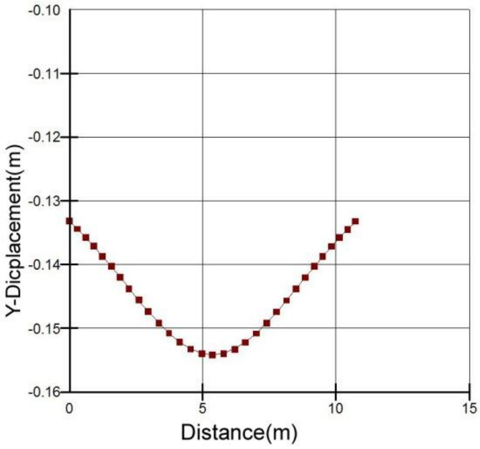
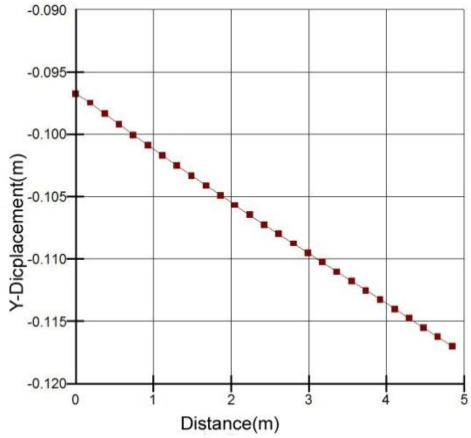



**Figure 15-** Contour map of y-effective stress during lining.

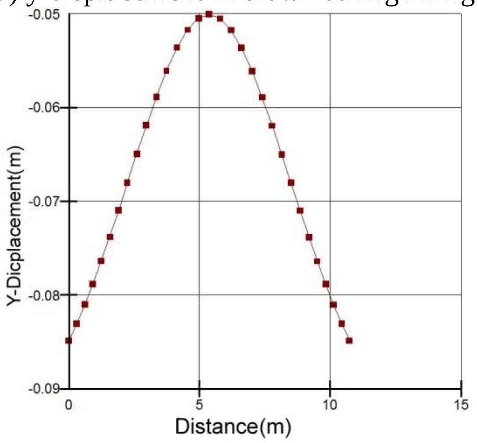
By drawing the relationships between y-displacement with distance during lining, the y-displacement in the crown reaches to 0.154m, and increases in the wall to 0.117m, and reaches in the invert to 0.05m. The x displacement with y-coordinate (which represents the depth) decreases with depth in the vertical axis and reaches to 0 m in the center as shown in Figure-16.



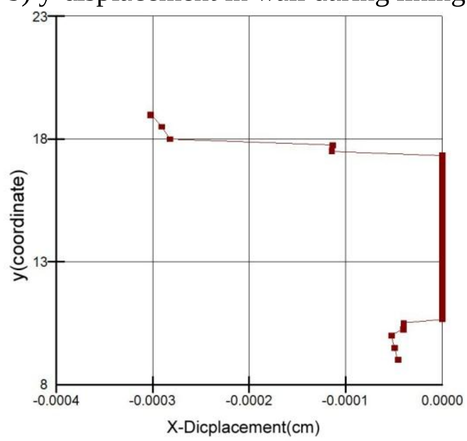

a) y-displacement in crown during lining




b) y-displacement in wall during lining



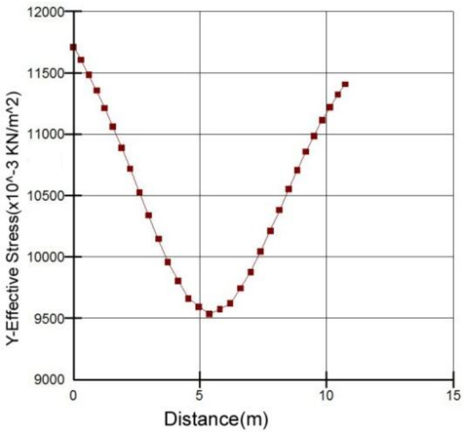

c) y-displacement in invert during lining



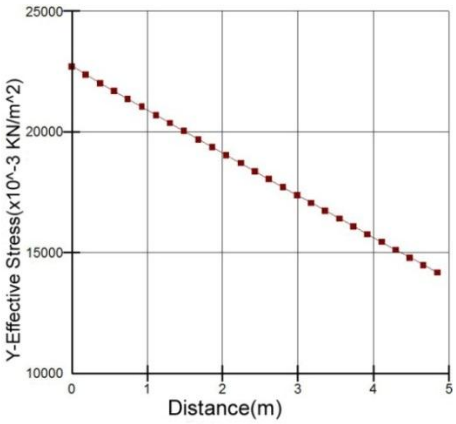

d) x-displacement in vertical axis during lining

**Figure 16-** Y and X-displacement in different sites during lining.

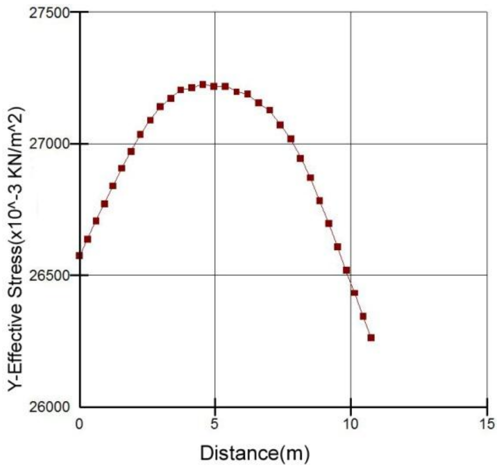
By drawing the relationship between y-effective stress with the horizontal distance, the y-effective stress reaches in the crown to 11.7 kPa, where as decreases to less than 14 kPa in the wall, and reaches in the invert to 27.25 kPa. The y effective stress increases with depth toward the tunnel opening in the vertical axis and reach to 27.3 kPa as shown in Figure-17.



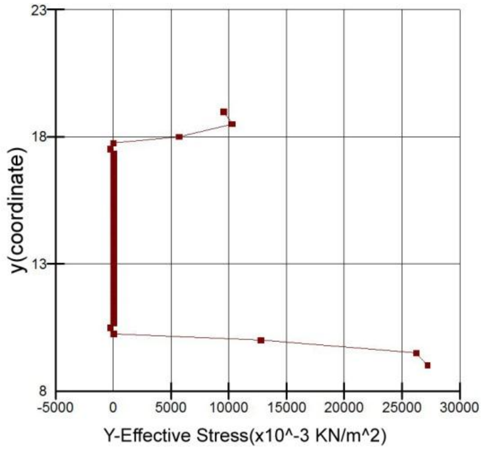

a) y-effective in crown during lining




b) y-effective in wall during lining




c) y-effective in invert during lining




d) y-effective in vertical axis during lining

**Figure 17-** Y-effective stress in the crown, invert and wall during lining.

The y-displacement along surface in this case reaches to 0.168 m as shown in Figure-18.

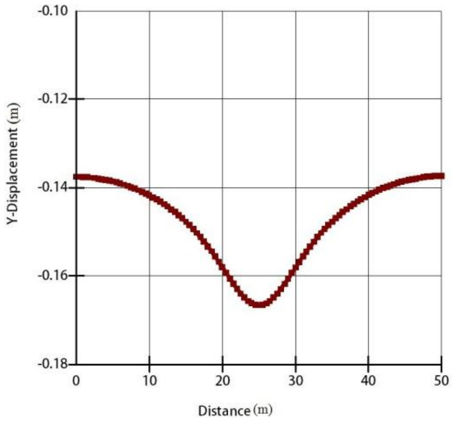



**Figure 18-** Y-displacement along the surface during lining.

**Results and Conclusions:**

From this study the following conclusions can be made:

1. By increasing the excavation, the y displacement above the crown increases as well as the vertical stress, while the vertical displacement at the invert increases toward the center of the tunnel and the vertical stress decreases.
2. It can be concluded that the use of an infinite element has no effect on the boundary conditions, and its presence just to extend the range of the calculated displacements.
3. It can be seen that the soil tends to move toward the excavation, and the maximum displacement occurs within the zone of excavation. The displacements decrease gradually away from the excavation zone.
4. In general, tunneling process causes moving of all the points surrounding the tunnel towards the center of the tunnel. This will lead to change the stresses below and above the tunnel. This may be referred to the reduction in vertical stresses caused by tunneling.
5. It is concluded that the best case to construct the tunnel in this study is at depth 2.5 m rather than 5.5 m because the stresses and displacements are less.

**References:**

1. Hummadi, R. A. **2001**. The Performance of Tunnels under Static and Dynamic Loading, Ph.D. Thesis, College of Engineering, University of Baghdad, Iraq. p:123.
2. Obaid, A. K.**2001**. Assessing the Behavior of Excavations by Finite Element Method, M.Sc. Thesis, University of Technology, Iraq. pp:8-9.
3. Brown, E. T., Bray, J. W., Ladanyi, B., and Hoek, E. **1983**. Ground Response Curves for Rock Tunnels, *Journal of Geotechnical Engineering Division*, ASCE,109(1), pp:15-39.
4. Google Earth Web Site. **6/1/2016**. https://www.google.iq/maps/@ 33.306378,44.3969321, 13z?hl=ar.

**5.** Buday, T. and Jassim, S. Z. **1987**. *The Regional Geology of Iraq*, 2, Tectonism, Magmatism and Metamorphism, p:352.

**6.** Hamza, N. M. and Yacoub, S. Y. **1982**. The geology of Baghdad- Falluja area, GEOSURV, Int. report, No. 1382, SOM library, Baghdad, Iraq. p:14.

**7.** Ali S. M. **2012**. Hydrogeological Environmental Assessment of Baghdad Area. Department of Geology, College of Science, University of Baghdad, Baghdad, Iraq. p:6.

**8.** Mair, R.J. and Taylor, R.N. **1993**. *Prediction of Clay Behavior Around Tunnels Using Elasticity Solutions*. Proceeding Predictive Soil Mechanics Worth Memorial Symp., Oxford, p:449-463.

**9.** Karim, F. C. **1994**. Estimation of Stresses Acting on Tunnel by Finite Element Method, M.Sc. Thesis, University of Technology, Iraq. p:234.

**10.** Dasari, G. R., Rawlings, C. G., and Bolton, M. D. **1996**. *Numerical Modeling of a NATM Tunnel Construction in London Clay*, Proceeding of the International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, Balkerene, Rotterdam, pp:491-496.

**11.** Kasper, T., and Meschke, G. **2004**. *3D Finite Element Simulation Model for TBM Tunneling in Soft Ground*, International Ground for Numerical and Analytical Methods in Geomechanics. p:14.

**12.** Salim, N. M., and Gell, K. **2011**. The influence of a designed twin-tube highway-tunnel on the stability of a nearby water-transmission tunnel, Sonderdruck Schriftenreihe der Georg-Simon-Ohm-Hochschule Nurnberg No.48.

**13.** Hattab, Najeeb, N., keja Je. **1986**. Studying the Soil Engineering Properties of Baghdad City. National Center of The Construction Labs, p:84. (In Arabic).

**14.** Winda J. Djoenaidi. **1985**. A Compendium of Soil Properties and Correlation. A Ph.D. Thesis in University of Sidney, pp:31-97.

**15.** Kalinsky, M. E. **2011**. *Soil Michanics Lab. Manual*. University of Kentucky, Second Edition, p:205.

**16.** Robert D. K., Richard D. W. **1971**. *Highway Materials*. McGraw-Hill Inc., US. p:429.

**17.** Al-Qasabi, Abdul Fattah. **1993**. *Soil Mechanic*. Scientific Books Printer in Egypt, p:334. (In Arabic).

**18.** Bowles, J .E.**1984**. *Physical and Geotechnical Properties of Soils*, Second Edition. McGraw-Hill International Book Company. p:365.

**19.** Geotechdata Web Site, **6/1/2016** http://www.geotechdata.info.html.