Numerical Stability Analysis of Tunnel by PLAXIS

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ABSTRACT

One of the most significant current discussions in Tunneling is settlement and stability. In recent decade, numerical modeling has been introduced to check the stability and settlement. When the tunnel has been made, stability is an important factor due to advancing cycle and cost especially in soil or weak rock. Study on behavior of surrounding soil and rock at this condition is a great challenging of engineers section, recent development in the field of Finite Element method have led to a renewed interest in the analyses of tunnel stability and prediction of ground movement. The merit is that we can have an appropriate estimation of behavior of soil or rock before drilling and to find out which part of tunnel is under a major settlement risk, especially when the tunnel is drilled into multi layer soils. PLAXIS is one of the most famous software in the field of Finite Element method that can be analysis the behavior of tunnel and the amount of ground movement. According to the calculated thickness of lining, 35 cm thickness observed as optimum thickness of coverage system, based on the analysis the most displacements is obtained in ceiling and floor that is equal to 9.65E-03 meters. The main stress computed in the model plus the lining is -478 kN/m^2. Stress is returned to normal status in 13 meters distance from the center of the tunnel.

KEYWORDS: Settlement, Tunnel Stability, Numerical Method, PLAXIS, Axial and Shear forces, Bending moments.

INTRODUCTION

Ground movement is an important problem that we are facing during the tunneling and after construction, since the amount of displacement is not clear, and it depends on soil and rock properties. On the other hand, most of tunnels are drilled in urban areas and they are under the risk of settlement. There are three main methods to monitor these settlements i.e. empirical, numerical and analytical methods. In recent decade, there is an increasing interest in the numerical methods to develop numerical solution for prediction of settlement due to tunneling. Numerical methods developed for calculating of soil deformation during the tunneling. The combination of these methods and the field results will allow having more investigation on the surface settlement, factors and the predicting of settlement (Strokova, 2010).

Numerical methods such as finite element analysis, is used to predict the ground movement during the tunneling. The numerical simulation method can bring up the nonlinear interplay between the tunnel and surrounding soils, the elasto plastic behavior and the complexity of the construction operations (Zhiguo et al., 2011).

The Finite Element method also prepares the framework for performing the individual effects of the parameters of settlements (Hashash and Whittle, 1996). Not only numerical methods have been often used to predict the soil movement, but also are used to predict the interaction between tunnels and the structures which are made in the ground or underground (Chen et al., 2011). These methods aim to computing and monitoring the ground movement at every point of tunnel and around ground. They calculate condition of construction and the ground such as; geometry, initial stresses, ground behavior, excavation stages, etc (Leca, 2007).

This method is to determine the optimal parameters of the model of the surface settlement induced by tunneling and to calculate the settlement assumed for tunnels under design (Strokova, 2010). The numerical simulation could be taken as the operation process calculation from different angle. On the other hand, because of the complex construction process, many geological problems were faced and only parts of them could be solved (Wei and Sun, 2008).

The Finite element method take account of heterogeneous ground layers with more complicated models, as well as initial and boundary conditions same as actual field conditions and time effects (Leca, 2007). Even though the Finite Element method is well tool for predicting the ground movement due the tunneling, its application to the problem of predicting ground dispalcement in soft soil limited (Rowe et al., 1982).

For all underground activities or drilling the empirical methods and engineering judgment have got a serious role but today with a development of computer, numerical analysis becomes a common method. Moreover numerical analysis is used for ground movement and it is a possibility for Finite Element method to analysis of tunnel heading stability (Vermeer et al, 2011).

Prediction of settlement induced by shallow tunnel also requires appropriate simulation of the sequential construction stages such as NATM method. Two-dimensional 2D Finite Element analyses have been performed to simulate drilling (Azevedo et al., 2002).

In this study PLAXIS is used to investigate the stability and settlement of line-4 Tehran, Iran subway and to simulate behavior the soil and rock surrounded the tunnel.

MATERIALS AND METHODS

This paper is presented as a numerical analysis using PLAXIS on stability and settlement of line-4 Tehran subway as the origin of the way. Tunnel drillings have been made at both upper and lower cross sections and by NATM method. The Line-4 of subway tunnel has an estimated length of 14km. This should be mentioned that, there are some cross sections of this way with the other lines. Figure 1 shows a plan view of line-4 Tehran, Iran subway.

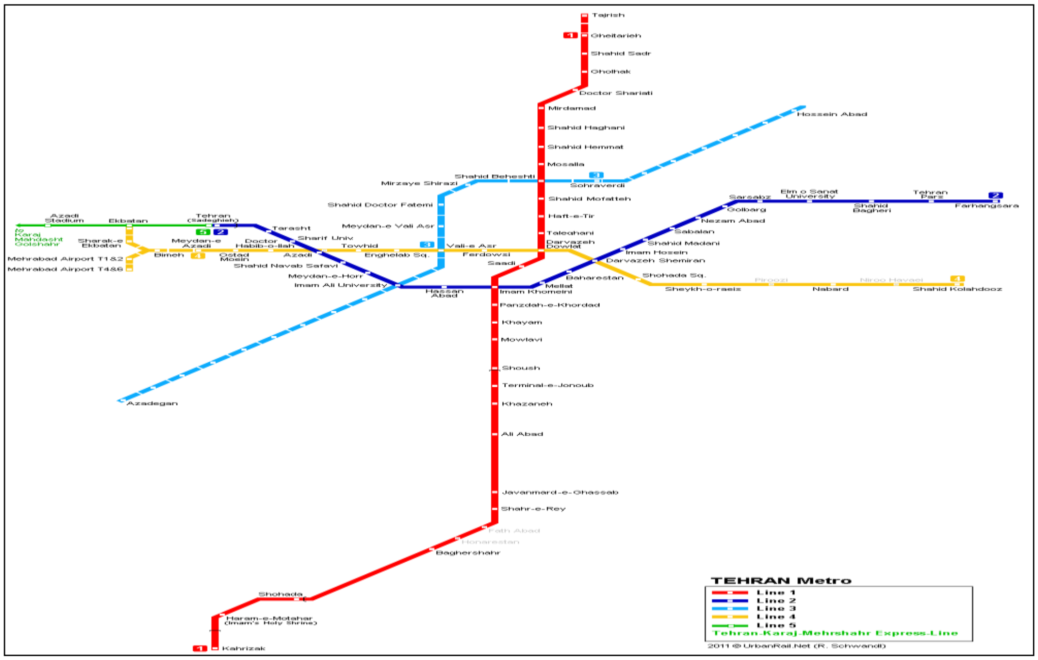

Figure 1: Plan view of line-4 of Tehran Subway and other lines

The yellow line in the Figure shows line-4 of Tehran subway and its junction with other lines. This paper is also analyzed stability of tunnel at Ekbatan Town between Station A_4-3 to A_4-2.

This tunnel has been drilled in a sand formation. This formation includes two GW layers (well graded gravel, fine to coarse gravel) and the other GM layer (Silty gravel). Figure 2 shows the two different layers and also the relevant thicknesses.

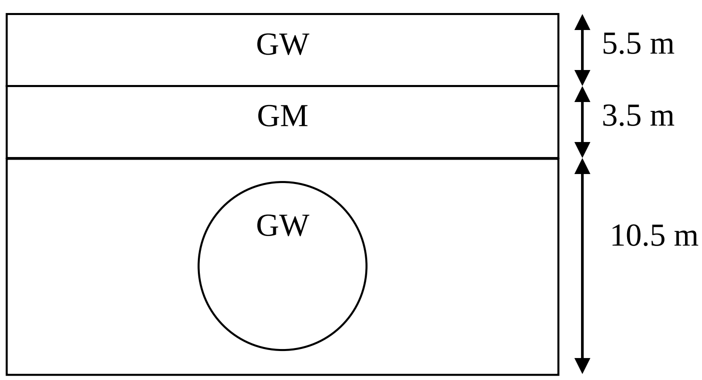

Figure 2: Geometry of difference soil layers

As it is shown in Figure 2, there is a repetition of layer GW at two sections. Tunnel has been drilled at GW as shown with light blue lines in Figure 3.

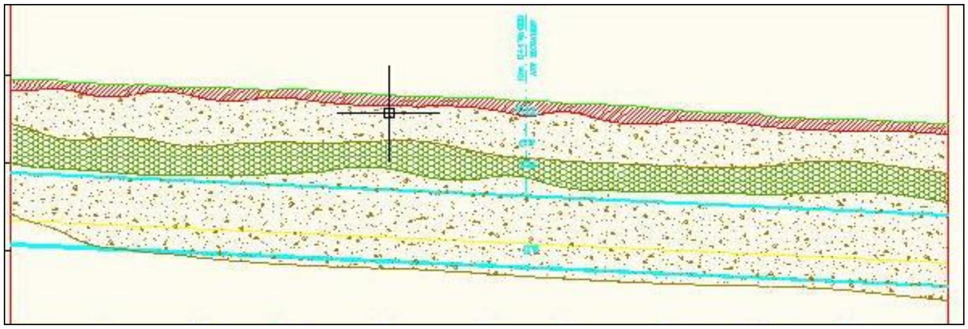

Figure 3: Geological Profile of the Area

The aerial geological parameters have been obtained by field and laboratory experiments. This should be highlighted that experimental method is based on SPT number with relevant formulations based on laboratory analysis. Table 1 shows the physical parameters of soil layer.

Table 1: Physical Parameters of GW layer (Geno)

Gravel content (%)	Sand content (%)	Passing No. 200 (%)	γ_d (gr/cm^3)	Water content(%)	d_{10}	d_{30}	d_{60}	C_U	C_C	Plasticity	Void Ratio
63.1	33.8	3.1	2.02	6.7	0.5	3.4	15.5	32	1.7	N.P	$e_{n=0.312}$ $e_{min=0.2}$ $e_{max=0.5}$

In order to find the friction angle based on experimental formulas density estimated by following equation:

$$D_r = \frac{e_{max} - e_n}{e_{max} - e_{min}}$$

where,
e_{max}=Maximum soil porosity
e_{min}=Minimum soil porosity
e_n=Natural porosity of soil
Meyerhof is one of the most famous formulas to obtain ϕ and estimated density:
$\phi=30+25D_r$ If passing particles from mesh 200 are lower than %5
$\phi=25+25D_r$ If passing particles from mesh 200 are greater than %5 and lower than %12
$\phi=20+25D_r$ If passing particles from mesh 200 are more than %5
According to Table 1:

$$e_n = \frac{GS}{\gamma d} - 1 = 0.312$$

D_r is obtained 62.6 % and ϕ is equal to 45°

The experimental formulation for measuring the cohesion rate based upon estimated density is as follows:

$C = -1+0.02D_r$ (kg/cm^2) if Dr>50
$C = 0.0$(kg/cm^2) if $D_r<50$

Regarding the scope of changes of D_r the viscidity of this layer is equal to 0.5 (kg/cm^2). There are many different methods for finding the elasticity module based upon experiment, however, followings are the most well known methods (Geno):

$E=12(N+6)$ (kg/cm^2) N<15
$E=40+12(N-6)$ (kg/cm^2) N>15
$E=2/22N^{0.888}$ (MPa)

According to the above-mentioned formulas, N is SPT number. Module E is obtained through the formula of 1000 kg/cm^2 and it is possible to consider poison ratio for this soil equal to 0.3 (Geno).

Table 2 shows the physical properties of GM layer.

Table 2: Physical Parameters of GM layer (Geno)

Gravel content (%)	Sand content (%)	Passing No. 200 (%)	γ_d (gr/cm^3)	W (%)	d_{10}	d_{30}	d_{60}	C_U	C_C	Void Ratio
60	32.2	8.5	1.99	7.3	0.25	2.4	11.6	49	2.06	0.332

The same as the calculation for the parameters of GW layer, those properties for GM layer have been obtained and the summary of these parameters indicated in Table 3.Although, in some cases, geotechnical properties of soil are showing weakness soil, by applying stabilizer and injection method, it is possible to increase soil properties further analysis (Daneshmand et al., 2011; Okonta and Manciya, 2010; Mtallib and Bankole, 2011)

Table 3: Geotechnical Properties of Soil Layers (Geno)

Layer	**ϕ(°)**	**γ (kg/cm^3)**	**v**	**E(kg/cm^2)**	**C(kg/cm^2)**
GM	40	1.99	0.3	700	0.13
GW	45	2.02	0.3	1000	0.5

Tunnel has been drilled completely below GW layer and the water table is located below the tunnel therefore there is no influence of pore water pressure at the time of drilling except for surface raining. The primary cross section of tunnel after the drilling is 57.82m^2 which is reduced up to 56m^2 after installations of first and second supports and the length of drilling way is equal to 2.5km.

Based on the soil properties, geometry of layers and location of tunnel which is in a civil environment, the best suitable method of drilling is recognized to follow by NATM Austrian

Method. Tunnel has two northern and southern faces, due to the falling situation of northern advancing; the progress of southern advancing is more than northern one. Tunnel face was drilled at both upper and lower sections by loader and in those places with lack of fixed job frontier it was drilled manually by workers. At first, upper parts was drilled and after different cycles of progress and installation of primary supporting system, lower part. Figure 4 shows all these procedures and manner of drilling both sides of upper and lower parts.

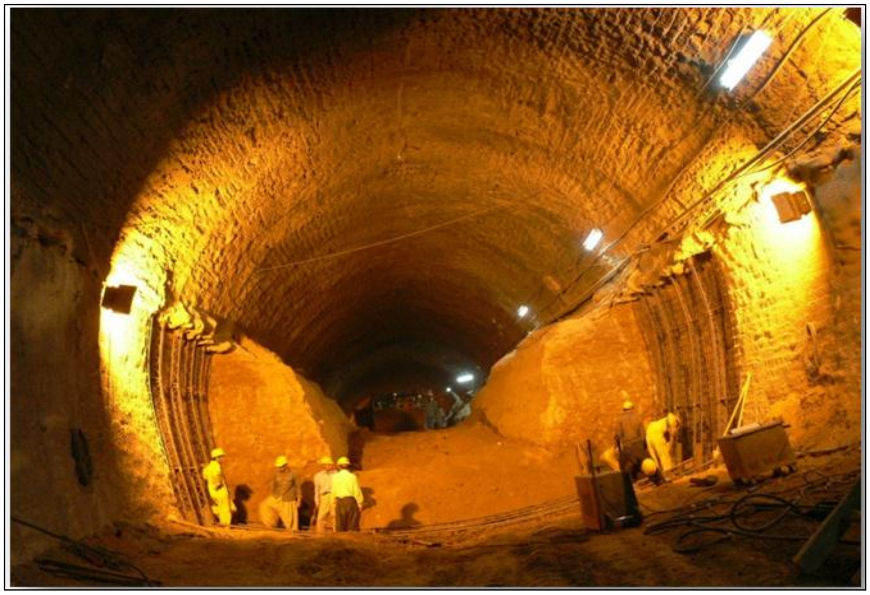

Figure 4: Tunnel Drilling At Both Cross Sections

Tunnel supporting is at both primary and secondary parts which would be installed after 0.5m progress of face. For this purpose armature is used in 25 parts of tunnel crown with steel mesh at a distance of each armature, and then shotcrete was performed. The support of lower part was similar to tunnel crown but with a difference that tunnel floor was concreted completely and prevented from any swelling for enriching the tunnel foundation. Topography group controlled all procedures of installing primary support system and exact place of their installation. After complete installation of primary support system, PVC insulation coverage was covered and then installation of the final support system in the form of pre-fabricated concrete frames in order to reach to final cross section of tunnel. The final cross section of tunnel is $56m^2$.

The finite element method is widely accepted numerical method for analysis and design in almost all branches of engineering. PLAXIS is a finite element code for soil and rock analyses, originally developed for analyzing deformation and stability in geotechnical engineering projects (Ghoreishi et al., 2010). Table 4 shows the relevant specifications of lining.

Table 4: Lining Specifications (Geno)

No.	Specifications of coverage	EA [kN/m] Axial stiffness	EI [kNm^2/m] Flexural rigidity	W [kN/m/m] Weight	v [-] Poison ratio
1	Lining	8E+06	80000.00	8.40	0.15

In order to explain any elastic behavior, it is necessary to provide all properties of materials including EA and EI resistance. Axial stiffness is a force applied latitudinal and bending stiffness is applied on the basis of power longitudinal basis.

RESULTS AND DISCUSSION

In this step and after designing of tunnel and its mesh, all calculations were performed in two phases. This is necessary to mention that types of calculations are based upon plastic and stage construction. At first phase, the soil in active situation was considered and tunnel support on inactive form without any further replacement and deformation. In next phase, an active support system and inactive soil inside the tunnel were considered. Figure 5 shows the relevant mesh of which is very fine especially at internal parts of tunnel with more precious calculations.

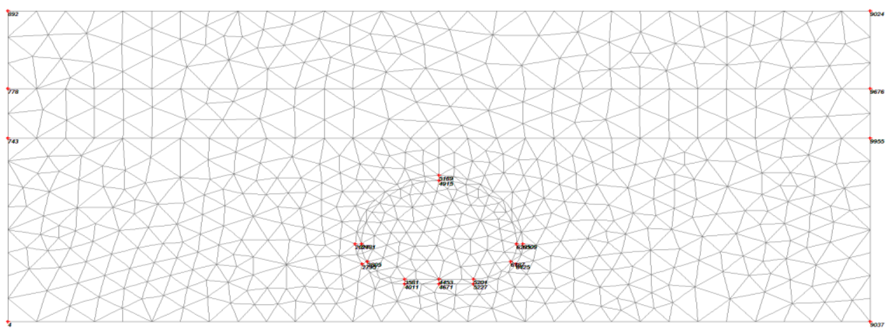

Figure 5: Mesh model in PLAXIS

After performing all calculations and applying loads Figure 6 is showing the relevant changes out of mesh.

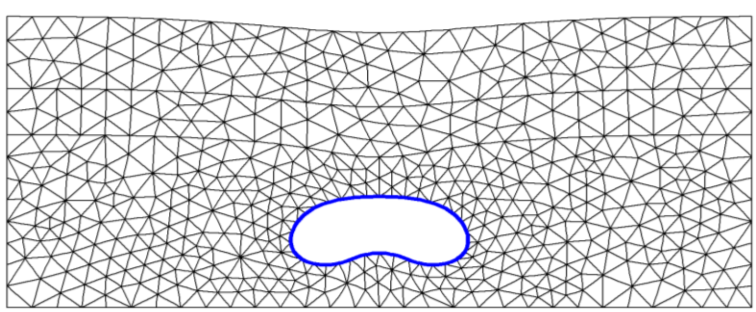

Figure 6: Deformation in mesh modeling

Regarding Figure 6 and relevant changes of model mesh, it is possible to observe ground level settlement which is equal to 9.65 E-3m with regard to total replacement of this model as mentioned in Figure 7.

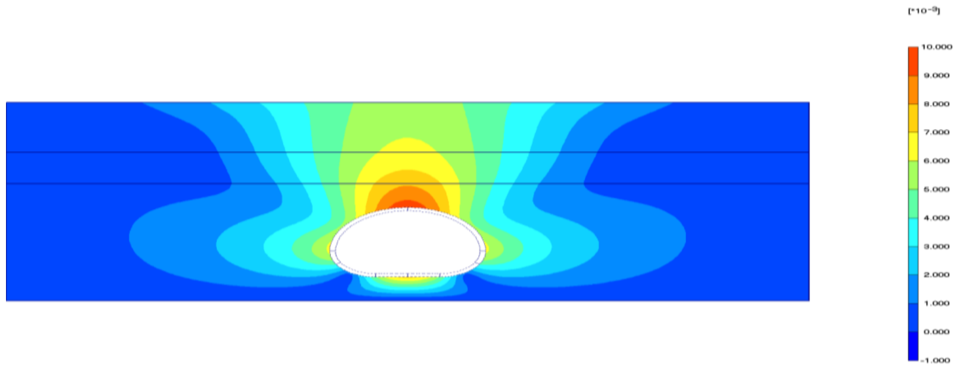

Figure 7: Total Replacement Plot

From Figure 7, it is obvious to conclude that most replacements are applied in ceiling of tunnel. More closeness to ground surface may cause a reduction in its amount. Now it is the turn of analysis all created stresses after drilling this tunnel as mentioned in figures 8 and 9.

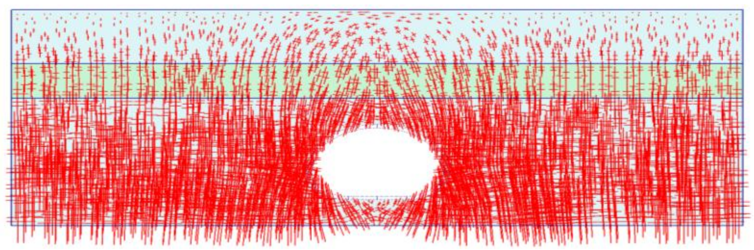

Figure 8: Stress vectors after drilling tunnel

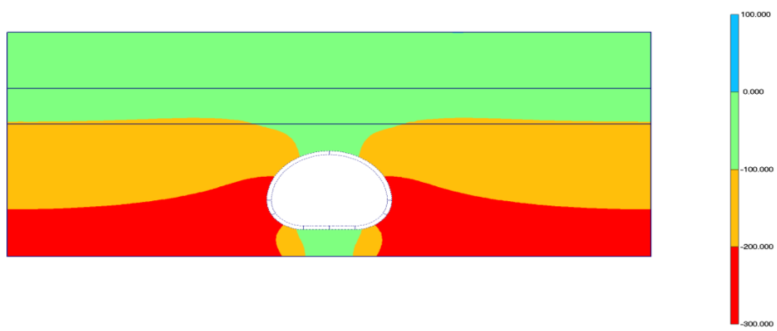

Figure 9: Plot of Effective Stresses

The major calculated stress rate is about 478 kN/m^2. Regarding figure 8, about three times of tunnel diameter have returned back to their normal condition while their distance is about 13m from tunnel center. Here the negative sign shows the pressure stresses. Figure 10 shows all plastic points. Plastic points mean stress points in plastic condition. Black squares are the signs of tensile rupture (tensile rupture point). Followings are different figures for showing this condition at different tangent stress points with maximum rates.

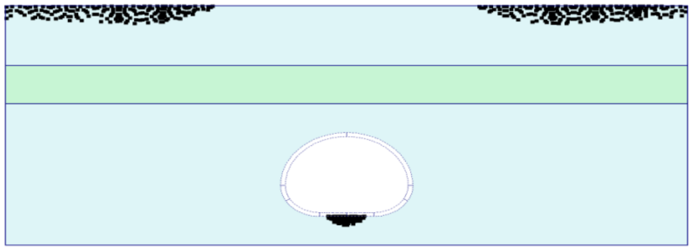

Figure 10: Plastic zones

Figures 11 through 13 show shear, axial forces and bending moments.

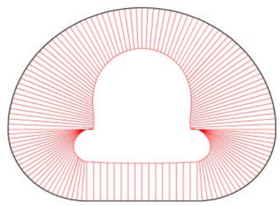

Figure 11: Axial forces maximum rate -1/08 E2 kN/m

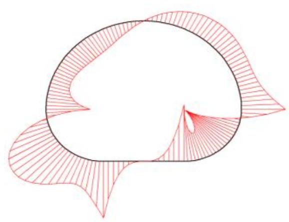

Figure 12: Shear forces maximum rate 71.58 kN.m

Negative sign shows the compressive stresses.

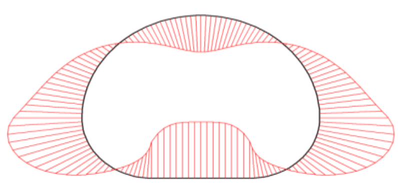

Figure 13: Bending moments with maximum rate of 118/90 kNm/m

In this part there is an analysis of different thicknesses of tunnel for measuring the replacement rate and finding out a suitable thickness for lining. Different thicknesses of 25, 30 and 35cm have been considered for further calculation. Figure 14 shows the relevant replacements. According to this diagram, it is possible to conclude that a thickness of 35cm as considered in designing of subway company are suitable especially at the primary standing time which is after 90 days from the start of replacement and reaching to replacement of other coverage. It is suitable with regard to the mentioned coverage and a suitable opportunity for the contractor to complete other job cycles in tunnel. This is necessary to mention that all measured points have been considered for replacement of different coverage at tunnel ceiling.

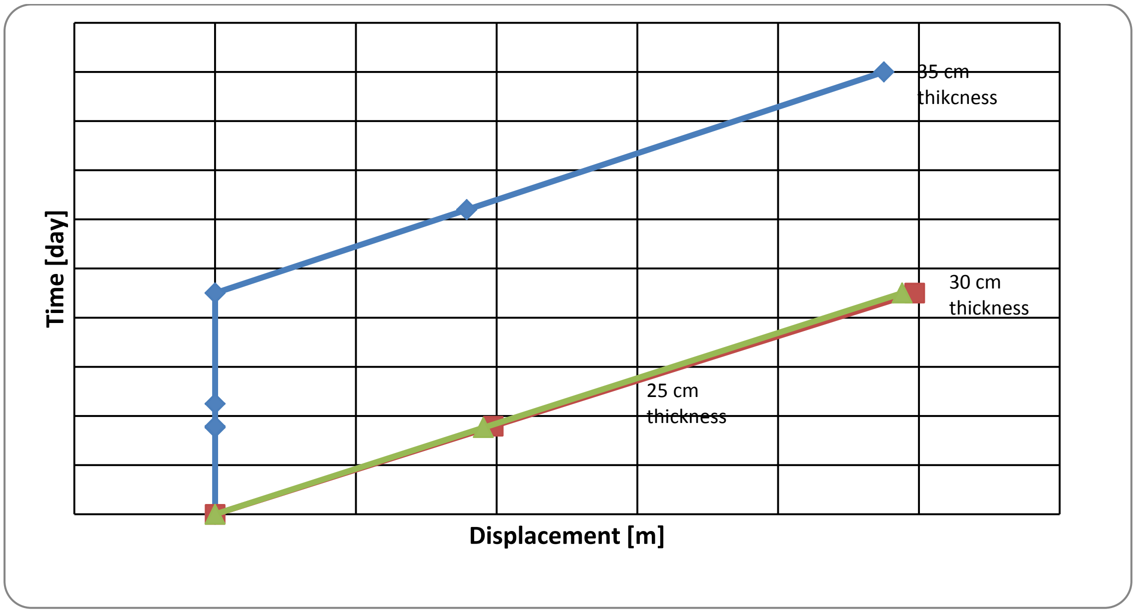

Figure 14: Different coverage replacement diagram in time basis

The green line is related to tunnel lining with a thickness of 25cm and length of 9E-03. The red line is standing for tunnel lining with a thickness of 30cm and length of 9.11 E-03 and finally blue line which is related to tunnel lining with a thickness of 35cm and length of 8.9E-03.

CONCLUSION

In present study, an analysis of tunnel resistance at Tehran Line 4 subway has been provided. PLAXIS 8.2 software could provide further resistance and model making analysis of this project. It has observed that the most replacement rate appeared at ceiling and bottom of tunnel and total replacements are 9.65E-02. The major calculated tension in model is accompanied with lining of-478 kN/m^2. Tension center may return to its normal situation in a distance about 13m from tunnel center. It is also concluded that type of concrete is suitable for the considered coverage and is resistant against probable pressures after construction with regard to all axial, shear forces and bending moments obtained by simulation and its analysis with concrete resistance in tunnel coverage. The optimized coverage thickness of tunnel among different thicknesses i.e. 25, 30 and 35cm was obtained as 35cm. The replacement produced at tunnel ceiling is also calculated as 10E-03. There were some obvious replacements in tunnel walls with such a thickness. By assuming the thickness of tunnel coverage for 30cm, the total replacement is 9.8E-03. General replacement is equal to 9.65E-03. It is possible to conclude that this coverage is suitable for tunnel.

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