The 2014 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM14)
Busan, Korea, August 24-28, 2014

Study on cross section excavation in non-mechanized tunneling techniques

Aminaton Marto[1)], *Houman Sohaei[2)] and Mohsen Hajihassani[3)]

[1), 2), 3)]*Department of Geotechnics and Transportation, Universiti Teknologi Malaysia, 81300 UTM Johor Bahru, Johor, MALAYSIA*
[2)] *houmansohaei.engi@gmail.com*

ABSTRACT

Shallow tunneling may leads to ground movements which may cause damage to the urban structures and utilities. During the last decades, several excavation methods have been developed to minimize the effects of tunnel construction on the surface settlement. Among these methods, the new Austrian tunneling method (NATM) has been used widely to construct large diameter tunnels mainly due to its flexibility to adapt different ground conditions. This paper discusses the effects of excavation sequence on the surface and subsurface settlement, obtained through the finite element analysis. In this regard, several excavation sequences were simulated using the ABAQUS software. In order to validate the numerical simulation, the collected data from Karaj Metro tunnel in Iran was utilized. The results revealed that the Side Galleries excavation model produced the lowest surface and subsurface settlements among other methods.

1. INTRODUCTION

The undeniable usefulness of undergroundconstructionsin urban areas has become a significant factor to decline the congestion at the ground surface due to swift growth in major cities.Demanding for railway or road tunnel as an underground construction system has been significantly increasedduring last decades. Nowadays, tunnels are excessively used in a large proportion of the urban areas due to the growth of cities and population.
As long as the construction of tunnels has far-reaching utilize more than a century, the design has gradually improved on the basis of analytical and numerical solutions. Numerical modelling has been applied to simulate the tunnel construction in different cases. Excavation of a tunnel has some effects on distribution of in-situ stresses in the surrounding areas of the tunnel which cause to form new stress distribution around the tunnel. The construction of a tunnel through urban areas can lead to ground deformations and therefore, damage is occurred to the overlaying structures and services (Sohaei et al., 2011).

[1)] Professor
[2)]PhD Student
[3)]Post-doctoral fellow

The New Austrian Tunnelling Method (NATM) was developed by Rabcewicz (1965) and later by Muller (1978) in Austria. NATM usage was undertaken in shallow and large tunnels into the rock mass; nowadays, the demand of NATM is in the soil mass with different resistance. The method has been established based on the use of surrounding mass strength to stabilize the tunnel with a noncircular and enlargement of tunnel opening. The use of NATM tunnelling method has been known to be cost-saving and it has control over the settlement. This method utilizes a thin and flexible shell of shotcrete as a temporary support system in the excavated exposed areas through the soft soil.Several researches have been conducted to investigate the effects of heading distance on NATM tunnelling operation (*e.g.* Ng et al. 2004; Karakus and Fowell 2004; Yoo 2009; Farias et al. 2004). However, limited researches have been conducted to analyze the effects of different partial face excavation, in particular the effects of excavation sequence on the surface and subsurface settlement.
To reduce the yield zones around the tunnel, NATM tunnelling offered the cross-section which is divided into several parts. The cross-section is excavated in each stage of the excavation sequence. One of the important features in NATM tunnelling is excavation sequences design, which depends on the soil condition, tunnel geometry and tunnelling requirements which may reduce the yield zone, and consequently ground displacement.
This study investigates the effect of excavation sequence on ground movements due to sequential tunnelling. In this regard, Line No.2 of Karaj metro tunnel (KMT) was utilized as the case study. In order to determine the optimum excavation sequence in KMT tunnel, two different cross sections were analyzed. Finally, the optimum excavation sequence in terms of ground movements, plastic zones and moment in the tunnel lining were determined.

2. CASE STUDY DESCRIPTION

Karaj is a large city located about 40 km to the west of Tehran, the capital of Iran. To address thelong-standing traffic congestion problem in this city, the new subway system was constructed.Line No.2 of KMT, spanning 27 km, was constructed between Kamal-Shahr, in north-western of Karaj and Malard, placed in the south of the city. This line composed of a single tunnel that was excavated using NATM technique (Marto et al. 2012).
The city is located on the alluvial sedimentary soils which has been the results of rivers activities and seasonal floods. Based on the observations during excavations, the subsurface soils contained inorganic clay with sandy clay at the top, followed by sandy clay and sometimes silty sand with over-layer clayey and silty gravel (Hajihassani et al. 2011).According to the visual observation and in-situ and laboratory tests, the soil of the investigated areas could be categorized into three groups which were the disturbed soil, coarse soil layer and fine-grained soil layer. To obtain geotechnical properties of the soil in addition to the laboratory tests, in-situ plate loading test, in-situ direct shear test, Lefranc test, and Standard Penetration Test were performed by the contractors. Table 1 shows the soil properties in the study area.

Table 1 Geotechnical properties of soil layers in the study area (Tunnel Rod, 2011)

Properties	Unit	Top Soil	CL-SC	SM-SC	GC-GM
Density	(kg/m^3)	1700	1810	2010	2040
Frictional angle (Φ)	(°)	15	20	30	33
Cohesion (c)	(kPa)	50	40	35	25
Elasticity modulus (E)	(MPa)	35	40	45	70

Poisson ratio (υ)	-	0.4	0.4	0.35	0.3
Permeability (k)	(m/s)	10^{-7}	10^{-7}	10^{-5}	10^{-7}

Based on the geotechnical analysis, NATM technique was selected for tunnel construction in KMT project. In order to contribute in ground self-stability until completion of the lining construction, the tunnel excavation was designed into two sections; top heading and bench. The top heading was being excavated in one step and the bench in two steps. After excavating the top heading for a distance of about 1.2 m, the exposed area was supported using steel lattice girder and a layer of shotcrete. Finally, subsequent to the installation of waterproof membrane, completed excavation areas were supported using concrete tunnel liner.Fig. 1 shows the excavation dimensions of the tunnel. The tunnel has a horseshoe-shape with 7.80 m height and 8.40 m width.

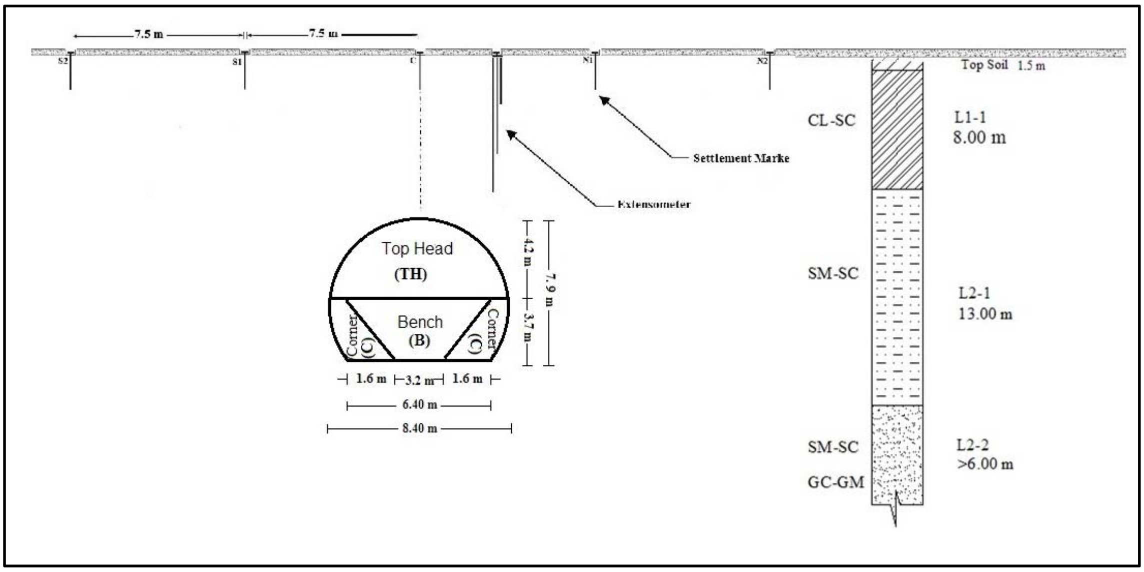

Fig. 1 The excavation sequence and ground profile in Karaj metro tunnel (KMT)

Surface settlement observation was carried out on the study area. For the purpose of monitoring the settlement, a large number of settlement markers were installed and the surface settlements were measured frequently. Settlement markers were placed approximately at 25-100 m intervals along the tunnel alignment. This amount was reduced in critical areas such as the portal of stations in order to provide a more accurate inspection. There were five monitoring points in each transverse section that were established on the centre, left and right sides of the tunnel axis with the distance of 7.5 m. The monitoring points consisted of settlement markers in the form of steel rods. They were grouted about 100 cm into the ground to isolate the rods from asphalt movement.

3. NUMERICAL SIMULATION

3.1 Abaqus 2D Finite Element (FE) Simulation

The general analysis of Abaqus was divided into three stages:

Stage I.The geostatic step:As an initial stage, consists of the horizontal and vertical geostatic stresses. The horizontal stress refers to the coefficient of lateral earth pressure and the vertical stress refers to the active pressure in initial soil condition. Once the setting of the whole initial condition is done, the next step involves the checking of the results in model interims of displacement where have to be near to zero. This stage which is used for equilibrium between boundary conditions and gravity load in every elements of the soil.

Stage II.The tunnelling processes: Tunnelling accomplishment of the numerical model with Abaqus is divided into two main parts; the general part and the tunnel construction part which also involves the installation of the shotcrete shell.

The general part deals with the drawing of the geometry condition and application of the material properties, material behavior, boundary conditions, and meshing. The tunnel construction part is dealing with the progress of excavation and installation of the shotcrete shell.

3.2 Model Geometry

To draw a geotechnical model, the boundaries have been chosen to be far enough from the tunnel axial, Helwany (2007), so that the effects of boundaries interactions are minimized. Fig. 2 shows geometry of the model in 2D FE analysis.

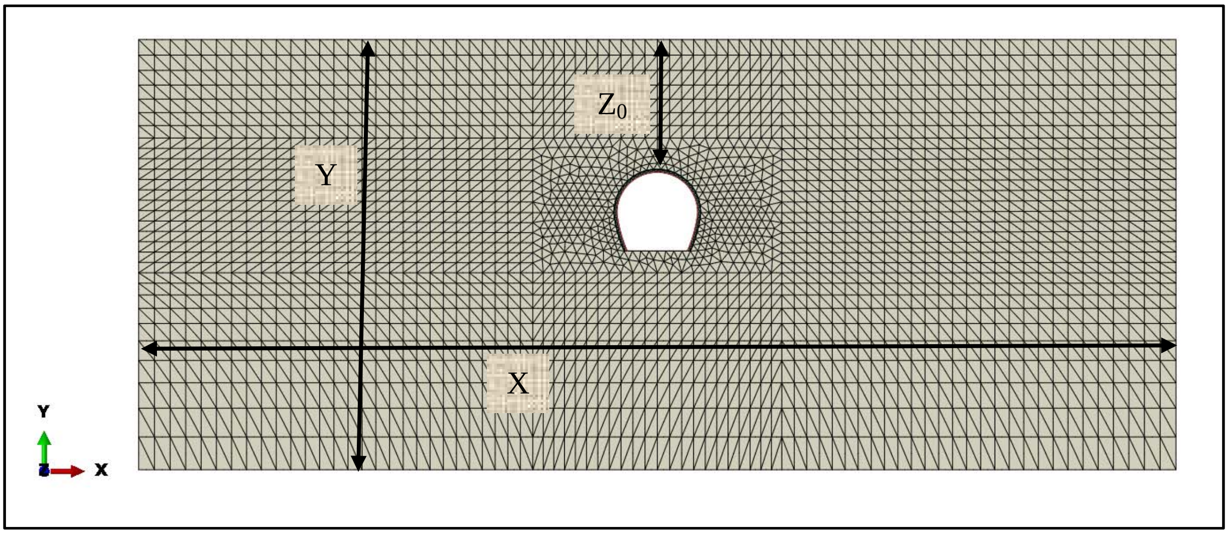

Fig. 2 Geometry of the FE model

It is recommended that the model dimensions extent to be at least 4 times of tunnel diameter from the excavation area, in which the effects of boundary can be negligible (Tan et. al, 2005). Therefore, the model dimensions selected to be Y= 41.5 m height andX = 100 m as revealed in Fig. 2.

In the model, boundary was supported from right side and left-hand-side with roller which closed the displacement/rotation in x directions and the bottom with close the endcastre in x and y directions.The thickness of the top soil, layers 1, 2, and 3 were 1.5 m, 8 m, 13 m, and 19 m, respectively. The tunnel was constructed through layer 2 which was approximately 12.5 m from the crown below the ground surface.

3.3 Simulation of KMT Tunnel Construction

In order to model the tunnelling process in Abaqus, the excavations were conducted with removing and deactivating one set of elements, and the software calculated the tension of re-distribution from the removing part. Adding a cover on the tunnel wall was done by re-activating the coverage elements. Since in Abaqus the model-change was used in simulating model as a tunnelling work, the size of the mesh chosen was suitable for excavation and lining parts.
The current KMT was excavated using NATM technique and the tunnel was supported with shotcrete. The tunnel width in the horseshoe-shape was 8.4 m wide and 6.4 m bench wide. The shotcrete thickness of 30 cm was considered as a supporting system. The soil was modeled using the Mohr-Coulomb model due to its simplicity. In addition, the limited available soil parameters also prompted the use of this model in the FE analysis. The soil was modeled as isotropic, linear elastic perfectly plastic material.

4. ANALYSIS AND RESULTS

This section presents the obtained results from the FE modelling for selection of the optimum excavation sequence for the KMT tunnel. In this regard, the ground settlementswere obtained using the FE analysis and subsequently were compared with the measured surface settlement in the study area. The results showed that the obtained surface settlements by FE analysis are in good concordance with the measured one. Furthermore, the tunnel was simulated using the Side Galleries (SG) construction method. The surface settlement, plastic zones and moment of the tunnel lining for KMT FE and SG models were analyzed. The analyses of the results are presented in the following sections.
Referring to the Fig. 3, opening area in this method is divided to three excavation parts; side drifts, top heading and bench. The first excavation procedure is side drifts excavation with the application of lining at the exposed areas followed by the top heading excavation. Subsequently, the middle linings are removed during the bench excavation.

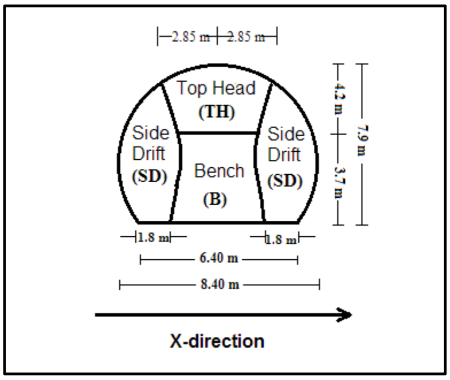

Fig. 3 Side Galleries (SG) construction method

4.1 Surface Settlement

The results of the KMT FE and SG models as well as the measured surface settlement are shown in Fig. 3. The comparison between the surface settlement the obtained by KMT FE model and measured values reveals that the parameters and simulation works are valid. The maximum settlement obtained from field data andFE simulation are 3.43 and 3.64cm respectively, which are close together. Although, the error in maximum settlement is about 2 mm for the FE and measured data, the troughs are fairly fit together. The results for SG model shows in Fig. 4 reveal a minimum surface settlement as the lining in the middle and small excavation area on the tunnel crown has major effects against the relocation of soil around the tunnel.

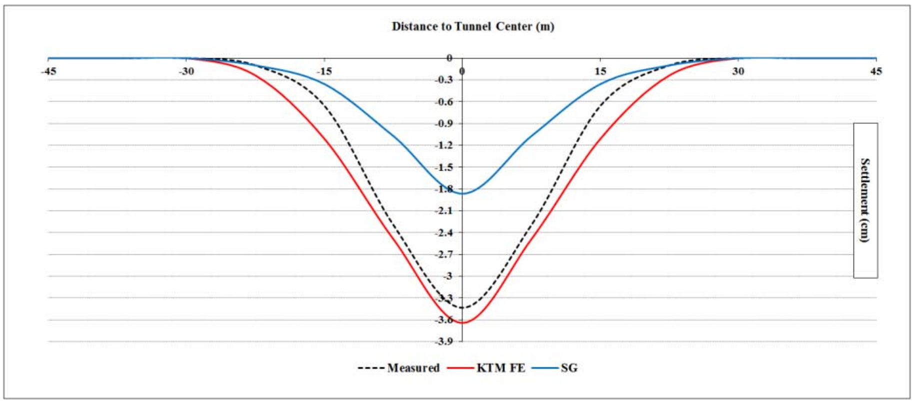

Fig.4 Surface settlementfor KTM and SG models

4.2 Plastic Zone

The plastic distribution zones of the KMT and Side Galleries model are shown in Fig 4. The maximum wide spread plastic distribution zone, in the KMT liner, is occurring on the tunnel wall.Whereas, in Side Galleries (SG)construction method, the plastic distribution zone is in the bench of the tunnel,slightly on the tunnel wall near to the bottom and negligible on the tunnel crown. With the comparisons of these two model of excavation, the high pressures induct on the wall and bench for KMT and SG, respectively. Therefore, the high plastic region should be fast install of lining.

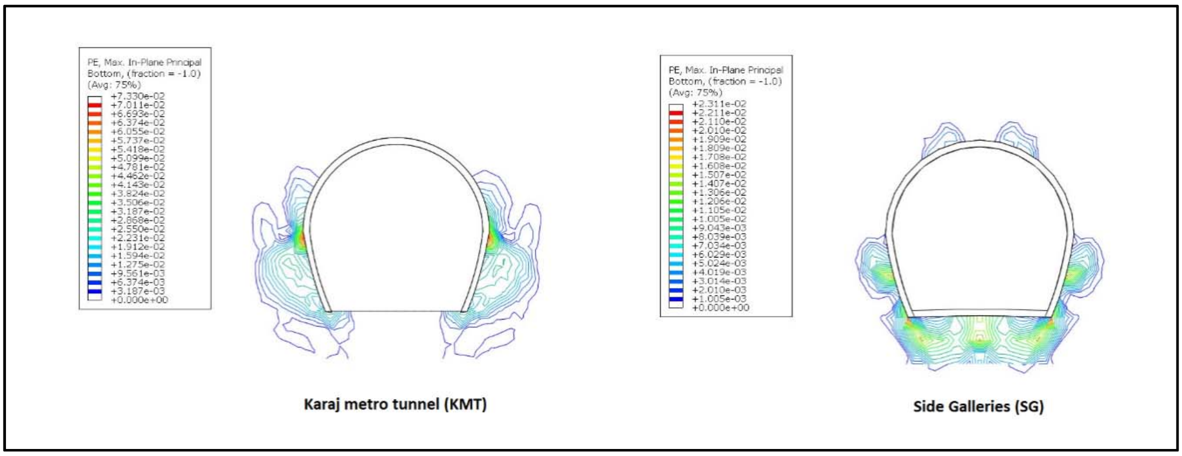

Fig.5Plastic zone for KMT and SGconstruction methods

4.3 Tunnel Lining

Fig 6. Shows the bending moment on tunnel liningof KMT and SG model. The maximum compression bending moment exposed more on the top of the primary support system in KMT lining, and it has more effected with the compare to the SG. The maximum tensilebending moment in KMT lining revealed on the wall of lining near to the bottom.

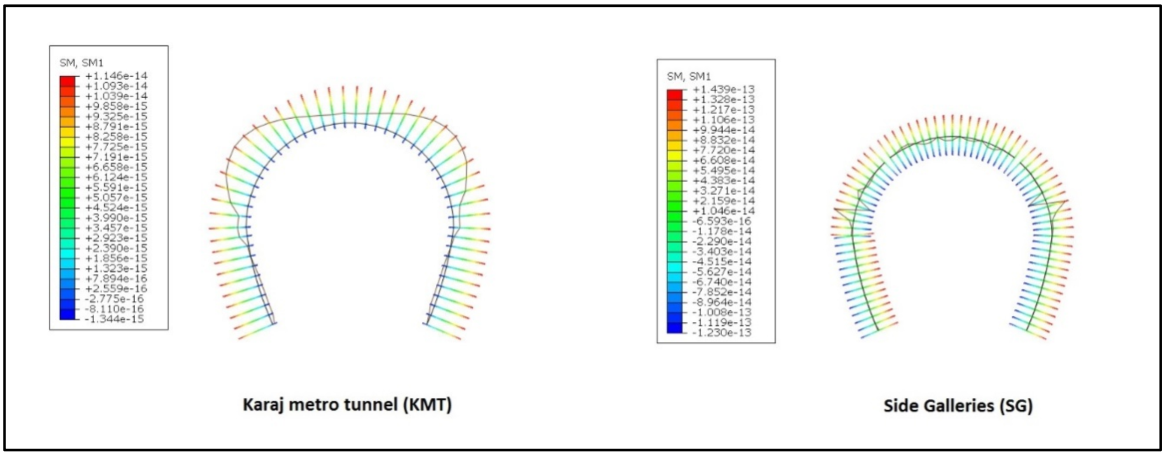

Fig.6Bending moments for KMT and SG models

5. CONCLUSION

The results of the FE modelling have shown good matching with the measured KMTsettlements data. To determine an optimum excavation sequence, a famous method namely SG construction method was examined for the same geological condition. Based on the FE results, the SG method was proposed for this tunnel as a new choice. This excavation method has produced smaller surface settlements, plastic zones and moment in the tunnel lining compared to the current KMT excavation method. The SG excavation method is therefore recommended to be applied in this project and other large section excavation projects with similar conditions.

ACKNOWLEDGMENT

This research has being carried out using the UniversitiTeknologi Malaysia (UTM) Research University GrantScheme, No. (Q.J130000.2522.06H60). The authorswould like to thanks UTM for the research grant andfacilities available in the Department of Geotechnics andTransportation, Faculty of Civil Engineering to undertakethis research work. The authors are also indebted to theTunnel Rod Construction Consulting Engineers Inc.,Iran, for providing the necessary data.

REFERENCES

Abaqus (2010). User’s manual. Hibbitt, Karlson and Sorenson, Inc.

Marto, A., Hajihassani, M. Kalatehjari, R. Namazi, E. Sohaei, H. (2012). Simulation of Longitudinal Surface Settlement Due to Tunnelling Using Artificial Neural Network. International Review on Modelling and Simulations 5 (2). pp. 1024-1031.

Farias, M.M., Junior, A.H.M., and Assis, A.P. (2004). Displacement Control in Tunnels Excavated by the NATM: 3-D Numerical Simulations, Tunnelling and Underground Space Technology. Vol **19**, pp. 283–293.

Helwany, S., and Wiley (2007). Applied Soil Mechanics with ABAQUS Application. United State of America: Wilet, J.

Sohaei, H. Hajihassani, M. Marto, A. Karimi Shahrbabaki, M. (2011). Influence of Construction Stages on Surface Settlement in NATM Tunnelling. Euro Asia Civil Engineering Forum (EACEF) Conference, Indonesia.

Karakus, M., Fowell, R.J. (2004). An insight into the New Austrian Tunneling Method (NATM), ROCKMEC'2004-VIIth Regional Rock MechanicsSymposium, Sivas, Turkey.

Moller, S.C. Vermeer, P.A. (2008). On numerical simulation of tunnel installation.Tunnelling and Underground Space Technology. **23**, 461-475.

Muller, L. (1978). The reasons for unsuccessful applications of the New Austrian Tunnelling Method, Tunnelling Under Difficult Conditions,InternationalTunnel Symposium, Tokyo, Pergamum. pp. 67-72.

Ng, C.W.W., Lee, K.M., and Tang, D.K.W. (2004). Three-Dimensional Numerical Investigations of New Austrian Tunnelling Method (NATM) Twin Tunnel Interactions. Canadian Geotechnical Journal. Vol. **41**, 523–539.

Rabcewicz, L. (1965). Die Neue Österreichische Tunnelbauweise, Entstehung, Ausführungen und Erfah-rungen, Der Bauingenieur, **40**. Jg., Heft 8.

Tunnel Rod (2011). Tunnel Rod Construction Consulting Engineers Inc. Instrumentation Report of Line 2 of Karaj Metro Tunnel, Technical Report.

Tan, T. S., Setiaji,R. R., and Hight, D. W. (2005). Numerical analyses using commercial software– A black box. Proceedings of Underground Singapore. pp. 250-258.

Yoo, C. (2009). Performance of Multi-Faced Tunnelling-A 3D Numerical Investigation. Tunneling and Underground Space Technology, **24**, 562-573.