Jurnal
Teknologi

Full Paper

3D Numerical Modelling of Shallow Tunnel in Weathered Granite Incorporating Multi-stage Excavation and Pre-support

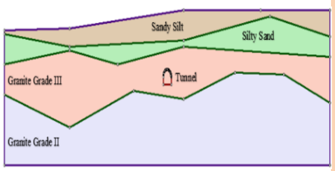
Article history
Received
18 January 2016
Received in revised form
8 March 2016
Accepted
18 March 2016

Sarder M. Yahya[a], Rini A. Abdullah[a*], Mohd Ashraf Mohamad Ismail[b], Hisham Mohamad[c], Muhammad Azril Hezmi[a], Siti Norafida Jusoh[a]

[a]Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[b]School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia
[c]Civil and Environmental Engineering Department, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia

*Corresponding author
asnida@utm.my

Graphical abstract



Abstract

Generally tunnelling in urban ground condition is not always favourable due to the tunnels' susceptibility to major displacement especially when excavated in the soft soil and/or weak weathered rock formation. Apart from conventional support systems, pre-support measure like forepoling umbrella arch is frequently used to reinforce the ground. Modern computational tools allows the inclusion of multi-stage excavations and pre-support which was not possible in two dimensional (2D) plane strain. This paper demonstrates the three dimensional (3D) finite element analysis of Pahang-Selangor raw water transfer tunnel, as a reference case, where multi-stage excavation and pre-support are incorporated as intrinsic part of the model. The New Austrian Tunnelling Method (NATM)-3 segments which encountered Grade III weathered granite, having shallow overburden cover, was selected for numerical analysis using RS^3 software. Comparison between simulated and observed data has shown good agreement during verification.

Keywords: Shallow tunnel; weathered granite; tunnel pre-support; finite element analysis

Abstrak

Secara umumnya pengorekan terowong di dalam bandar tidak digemari kerana terdapat kebarangkalian yang tinggi berlakunya pergerakan terutama apabila korekan melibatkan tanah yang lembut dan/atau pembentukan batu lemah terluluhawa. Selain daripada sistem sokongan konvensional, langkah pra-sokongan seperti payung gerbang *forepoling* sering digunapakai bagi mengukuhkan keadaan tanah. Pengunaan perisian komputer masakini membolehkan pengiraan pada korekan pelbagai peringkat dan pra-sokongan yang mana tidak dapat dilakukan di dalam terikan satah dua dimensi (2D). Kertas kerja ini menunjukkan analisis tiga dimensi (3D) unsur terhingga pada terowong pemindahan air mentah Pahang-Selangor sebagai kajian kes, di mana pelbagai peringkat korekan dan pra-sokongan diaplikasi sebagai aspek penting di dalam model. Kaedah korekan *New Austrian Tunnelling Method* (NATM) -3 segmen di dalam batuan granit terluluhawa Gred III, dengan beban atas cetek, telah dipilih untuk analisis berangka menggunakan perisian RS^3. Perbandingan antara data simulasi dan lapangan menunjukkan keputusan yang sekata.

Katakunci: Terowong cetek; granit terluluhawa; pra-sokongan terowong; kaedah analisis berangka

1.0 INTRODUCTION

In various cities around the world, the continuously growing development projects are utilizing the underground space due to having limited available surface space resulting from pre-existing structures. These tunnels are commonly situated in populated urban areas and are shallow in nature. The ground condition may not always be favourable, and therefore is susceptible to major displacement due to tunnelling process especially excavated in the soft soil and weak weathered rock formation [1-3]. Rock masses situated at shallow depths exhibit weak mechanical behaviour than similar rock masses at greater depth under confined stress. This is due to the fact that rock masses near the surface are prone to weathering and stress relief which disrupts the interlocking between rock particles, and therefore tend to exhibit more mobility [4].

For the above-mentioned issues, to prevent any undesirable scenario and to ensure excavation safety by reinforcing the ground different pre-supports are employed in compliance with design requirements such as ground freezing, inserting jet grouted columns, incorporating umbrella arch and so on. Among them the umbrella arch pre-support has widely been used to ensure stability during tunnel excavation by preventing tunnel face from collapsing especially in unfavourable subsurface conditions such as poor self-standing and/or weathered ground formation with a shallow overburden vulnerable to excessive displacement [3, 5].

The forepoling umbrella arch pre-support system installation procedure is less time intensive and more cost efficient compared to the above-mentioned pre-support system. For these reasons, the use of umbrella arch pre-support systems has been increased over the last few years. The inclusion of this support cannot be captured in 2D analysis since it is extruded in z-direction.

Generally numerical modelling illustrates a real life physical phenomenon in an idealized and simplified conceptual model. This method is proven to be an effective tool for anticipating possible scenarios arising in underground excavation. Also, numerical modelling provides a simulation environment of probable uncertainties that might occur during tunnel excavation. Contrary to the construction experience obtained during real life tunnel excavation, the same tunnel can be excavated repeatedly varying different parameters in numerical modelling. The previously most encountered challenge of numerical model in 2D was incorporating the sequential excavation stages. However, this problem is solved now with the evolution modern 3D computational tools.

In this paper, the development of a finite element model incorporating multi-stage excavation and pre-support installation is demonstrated taking Pahang-Selangor Raw Water Transfer Tunnel as case study. Detailed step-by-step procedures are elucidated for constructing this numerical model succeeds by pre-requisite subsurface modelling. The model is verified by comparing simulated data with observed field data. The verified model can be used for further numerical parametric analysis of pre-support design parameters which will be published in forthcoming papers by the authors of this study.

2.0 CASE STUDY PROJECT DESCRIPTION

With the case study selected for this study is completed Pahang-Selangor Raw Water Transfer (PSRWT) tunnel project which is situated across two states of West Malaysia. This tunnel project was aimed to transport 1,890 MLD (Million Litres per Day) raw water via a transfer tunnel from the Semantan River of Pahang to the Langat District in Selangor. This project was intended to meet the anticipated water demand for domestic and industrial usage in Klang Valley, Kuala Lumpur and Putrajaya up to 2025.

This gravity driven tunnel was built by Malaysian Ministry of Energy, Green Technology, and Water (KeTTHA–Kementerian Tenaga, Teknologi Hijau dan Air). The contract was awarded to joint venture company SNUI JV which consists of two Japanese companies and two Malaysian companies namely, "*Shimizu Corporation, Nishimatsu Construction, UEM Builders Bhd. and IJM Construction*".

The main components of the water transfer tunnel are: A 44.6 km long main tunnel of length having diameter of 5.2 m; the inlet and outlet linking the basin, and inlet and outlet conduit. This tunnel has seven segments and four adits are situated across the length of tunnel. Both TBM (Tunnel Boring Machine) and NATM (New Austrian Tunnelling Method) were utilised in this project. The outline and different segments of the tunnel is shown in Figure 1.

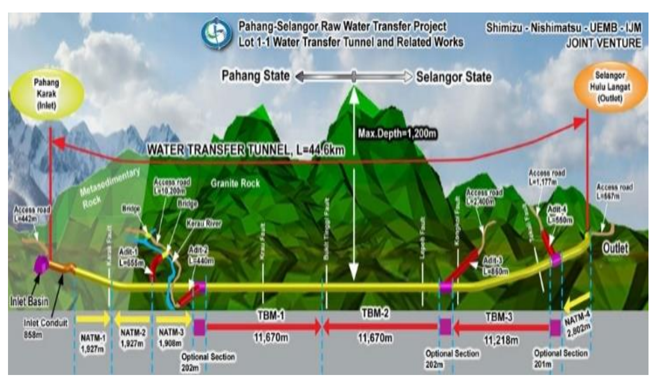


Figure 1 Outline of PSRWT tunnel [6]

3.0 SUBSURFACE MODELLING

Subsurface modelling is significant for determining the ground condition of the site in which the tunnel is built. Information of different strata type, thickness of soil and rock are significant for constructing the numerical model and its boundary condition.

A tunnel section of 20 m before Kerau river crossing was chosen for this study which is situated within Chainage 5910 to 5930. The reason is that, in this region the tunnel has comparatively low overburden of approximately 20 m which makes it suitable for studying shallow tunnel. The five boreholes surrounding this study section are BH15, BH34, BH35, TDH7D, and TDH7L. The borehole locations with respect to Chainage are shown in Table 1. The white rectangular area and straight line in Figure 2 show the location of selected boreholes and tunnel alignment respectively in Google™ Earth program.

The location of these boreholes in terms of UTM (Universal Transverse Mercator) coordinate system and their respective depth, elevation and direction (inclination with respect to 90˚ azimuth) are shown in Table 2.

A stratigraphy model was generated in EnviroInsite 2014 (HydroAnalysis, Inc.) based on borehole to borehole cross-section and integrated spatial interpolation feature as shown in Figure 3. The model is simplified by considering the most recurring lithological sequence in the five boreholes and hence 4 layers were chosen. The reason is to reduce the finite element model complexity.

Table 1 Location of boreholes and tunnel alignment with respect to chainage

Chainage	Borehole	Offset	Distance (m)
5912	BH34	Left	9.5
5915	BH35	Right	9
5917.4	TDH7D	Upon	1.2
5927.5	BH15	Left	7.1
5934.3	TDH7L	Upon	0.6

Table 2 Depth, UTM coordinates, elevation and inclination of boreholes

Borehole	Depth (m)	Eastings (m)	Northings (m)	Elevation (m)	Inclination (°)
BH34	31.3	444933.334	373400.251	103.79	0
BH35	32.5	444918.089	373411.365	104.38	0
BH15	35	444919.400	373390.700	98.13	0
TDH7D	49.1	444922.4	373401.9	104.3	33
TDH7L	25	444909.9	373390.4	96.88	33

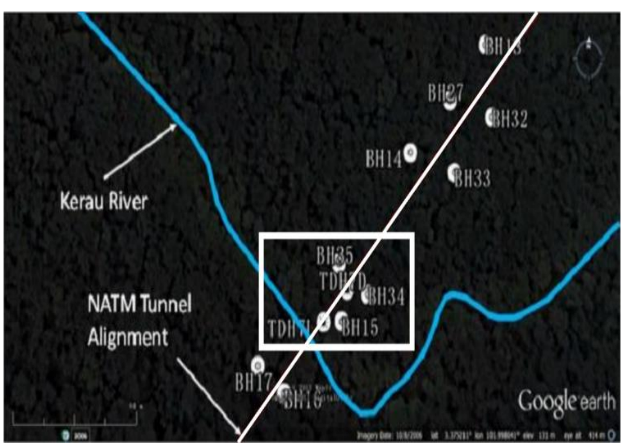


Figure 2 Location of boreholes and tunnel alignment in Google™ Earth

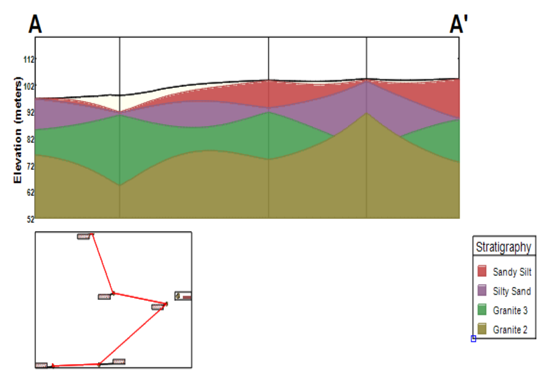


Figure 3 Simplified stratigraphy profile generated in EnviroInsite 2014

4.0 FINITE ELEMENT SIMULATION SETUP

The finite element model is based on a simplified layered geological sequence as observed in PSRWT tunnel using RS³ program by Rocscience [7]. The thickness of layers in the sequence was also slightly adjusted to allow a regular size of element to be used within the modelled mesh with a view to reducing the complexity and number of elements used in constructing the mesh.

4.1 Geometry Setup

The geometry in RS[3] is based on simplified stratigraphy profile as shown in Figure 3. Figure 4 shows the constructed geometry model. The simplified lithological sequence here only incorporates the near tunnel lithology. The external boundary was constructed using 'Add External Boundaries' option. The layers from top to bottom represent the Sandy Silt (colour brown), Silty Sand (colour green), Granite Grade III (colour pink), and Granite Grade II (colour blue) respectively. The 'Add Material Boundaries' option was used to distinguish the soil and rock layers.

The dimension of the tunnel is based on NATM typical section design sheet provided by KeTTHA. The 'Add Excavation Boundaries' option was used to construct the horseshoe shaped tunnel. The tunnel width is 5.2 m and the total height is 5.2 m (sidewall height of 2.7 m and roof arc radius of 2.7 m).

The model dimension in x-direction is 218 m. The external boundary was set as approximately 20 times of the tunnel width from both sides of the tunnel excavation boundary. In y-direction the tunnel is located 20 m below the top surface in terms of overburden. The dimension in z-direction is 20 m which reflects the selected tunnel section considered for this study.

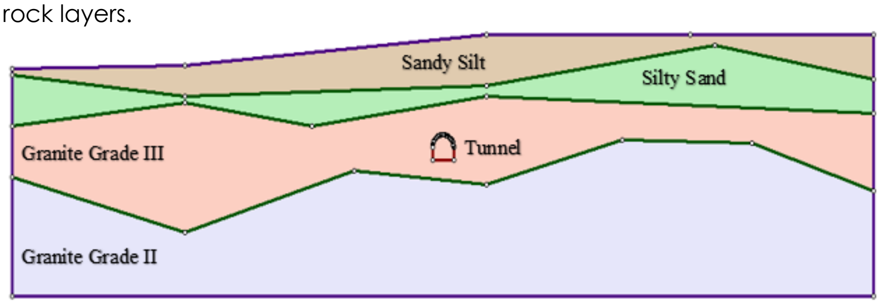


Figure 4 Constructed geometry in RS[3]

4.2 Modelling Parameters

'Material Properties' option of RS[3] was used for assigning the mechanical properties and different parameters. The input parameters of soil and rock layers are shown in Table 3. Some of the parameters were adopted from typical values from literatures. Others were based on correlations, equations and data obtained from KeTTHA. BH34 borehole log data was adopted to obtain parameters. Unavailability, limited access and confidentiality of some data were significant constraints. Laboratory tests data of borehole TDH7 which is situated near distant tunnel section were used in this situation to reflect the same weathered granite. The m_b, s and *parameters* of rock were calculated from integrated GSI (Geological Strength Index) calculator feature of RS[3]. As the NATM segment of PSRWT tunnel was excavated by controlled drill and blast, the disturbance factor was set to zero (D=0) as recommended by Hoek *et al.* (2002) [8]. Elastic rock modulus (E_{rm}) was calculated using Generalized Hoek-Diederichs method [9].

Table 3 Material properties in finite element model

Soil	Silty sand	Sandy silt	Source
Unit weight (MN/m³)	0.018	0.015	[10-11]
Poisson's ratio	0.35	0.3	[12-13]
Young's modulus (MPa)	20	20	[14-15]
Friction angle (°)	33 (Dense)	30	[10]
Cohesion (MPa)	0.022	0.067	[16]
Rock	**Granite Grade III**	**Granite Grade II**	
Unit weight (MN/m³)	0.027	0.028	[15]
Poisson's ratio	0.18	0.25	KeTTHA
Intact compressive Strength (MPa)	23	60	KeTTHA
GSI	25	63	KeTTHA
m_b parameter	0.686612	2.66754	GSI calculator
s parameter	0.00024	0.01639	GSI calculator
a parameter	0.531267	0.502287	GSI calculator
E_{rm}	1197.1	11755.2	GSI calculator

4.3 Boundary Conditions

Assignment of appropriate boundary conditions is essential as it influences the results to a great extent. The 'Loads and Restraints' option in RS^3 was used to assign the boundary conditions. Top surfaces were kept free from any restraints to allow displacement in this surface. The bottom surfaces were fully restrained in all directions so that the model remains stable under loading. The sides were restrained in x-direction. 'Use actual ground surface' was selected to take into account the effect of topography and vertical stress. Horizontal stress effect was considered by incorporating *k* value of 1.4 in the finite element model.

4.4 Multi-stage Excavation and Supports Installation

Multi-stage excavation approach was utilised in the finite element model for two cases of models:

1. Case 1–Without forepoles
2. Case 2–With forepoles

'Sequence Designer' option of RS^3 was utilised in order to achieve the sequential staging scenarios. In all the cases the advance rate was remained 1 m as the tunnel was excavated full face drill and blast method. The Case 1 excluded forepoles but included the conventional support systems like shotcrete, steel rib and rock dowel. The adopted sequential stages for Case 1 are shown in Figure 5. The Case 1 model was mainly constructed for verification purpose. The Case 2 included the forepoles and its sequential stages are shown in Figure 6. The Case 2 model can be used for parametric study of forepole design parameters by varying different parameter values.

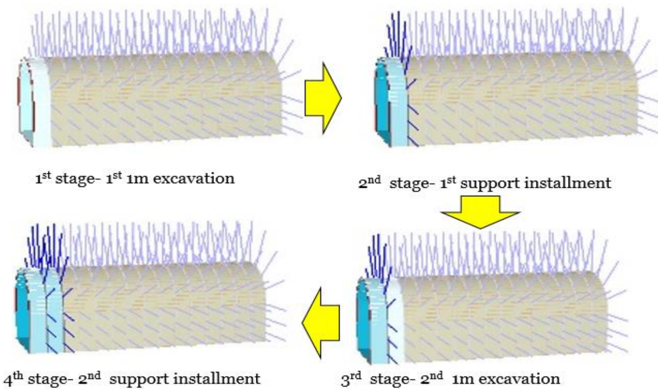


Figure 5 Multi-stage excavation sequence of Case 1–without forepoles model

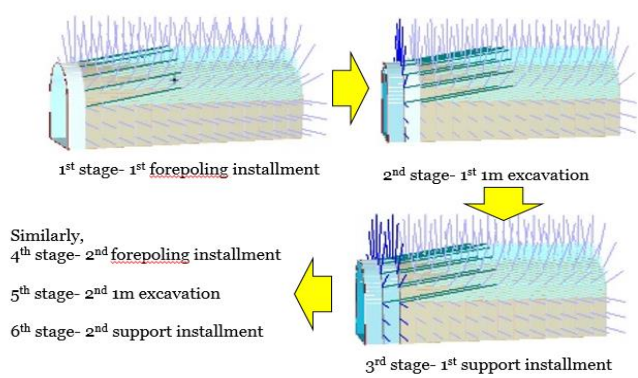


Figure 6 Multi-stage excavation sequence of Case 2–with forepoles model

4.5 Mesh and Discretization

Finer meshing provides more refined output results but it increases the computing time as well as hardware requirements. In addition to these, the mesh quality needs to be checked because low quality mesh will either cause the solution fail to convergence or produce unrealistic results. This can be done by modifying the boundary. In RS^3, two different types of mesh are available: graded and uniform. Graded meshing is suitable for subsurface excavations that incorporate clearly defined excavation boundaries. On the other hand, uniform meshing is more appropriate for surface excavations, slope stability analysis and groundwater models where excavation boundaries are not explicitly defined. Two types of solid element are available for each mesh type: 4-noded Tetrahedron and 10-noded Tetrahedron. Generally, elements with mid-side nodes such as 6-noded triangles or 8-noded quadrilaterals will increase the output accuracy but the cost will increase in terms of computing time and file sizes. In this study graded 4-noded tetrahedron mesh type was used for efficiency purpose.

5.0 RESULTS AND DISCUSSION

Any numerical model needs to be verified before carrying out sensitivity analyses for parametric study.

The verification was done by comparing simulated value with actual value obtained from field. Finite element analysis was performed on Case 1 model. The total displacement of tunnel crown at the location of 11 m (Chainage 5921) was considered for comparing with the actual displacement at tunnel crown. The actual displacement at tunnel crown measured at Chainage 5921 was 2.162 mm. The simulated value obtained from numerical analysis at this location was 1.88 mm which is 86.96% close to the actual measurement. The reason for this small deviation is obvious. Firstly, many assumptions were involved during numerical modelling. Another reason is that secondary data sources were used for input parameters instead of using primary data sources such as field measurements and/or laboratory tests. Some data were indirectly obtained from correlations and typical values from existing literatures.

6.0 CONCLUSION

This paper was aimed at developing a 3D numerical model of shallow tunnel incorporating multi-stage excavation and pre-support installation. The comparison between simulated and actual field measurement data shows good agreement which implies that the model is acceptable for parametric analysis by varying different parameter values. The verified model of this study is suitable especially for further parametric study of forepoling design parameters such as forepole length, installation angle and spacing as well as their optimisation with a view to aid the engineers in decision making process. This parametric study can be done using constructed Case 2 models.

Acknowledgement

The authors are very much grateful to the Malaysian Ministry of Energy, Green Technology, and Water (KeTTHA) and the contractor SNUI JV for providing necessary data to carry out this study.

References

[1] Wakita, S., Date, K., Yamamoto, T., Yanagisawa, H. and Uesugi, N. 2004. Effective Grouting Materials for Tunneling Through Unconsolidated Ground. *Proceedings Of The 30th ITA-AITES World Tunnel Congress Singapore, 22-27 May 2004*. 19(4-5): 509–510

[2] Volkmann, G. M. and Schubert, W. 2007. Geotechnical Model for Pipe Roof Supports in Tunneling. *Proc. Of The 33rd ITA-AITES World Tunneling Congress, Underground Space–The 4th Dimension Of Metropolises, 2007*. 755–760.

[3] Latif, M. F. A., Ismail, M. A. M., Selamat, M. R. and Ng, S. M. 2012. Effects of Pipe Roof Supports and the Tunnels Excavation on the Ground Settlement. *Electronic Journal of Geotechnical Engineering.* 18 (Bundle E): 1045–1056.

[4] Hoek, E. 2004. Numerical Modelling For Shallow Tunnels in Weak Rock. Unpublished Notes. Retrieved from https://www.rocscience.com/documents/pdfs/rocnews/Spring2003/ShallowTunnels.pdf

[5] Park, J.-J., Cho, I.-S., Lee, I.-M. And Lee, S.-W. 2012. Tunnel Reinforcement by Using Pressure-Induced Inflatable Pipes *Method. Journal of Geotechnical and Geoenvironmental Engineering.* 138: 1483–1491.

[6] Ismail, M. A. M., Azit, R., Ng, S. M., Zabidi, H., Bakhudin, N. and Nordin, Z. 2013. Evaluation Of Geological Conditions Ahead Of A Tunnel Face Using The Tunnel Seismic Prediction Method (TSP) Lesson Learned From The Pahang-Selangor Raw Water Transfer Tunnel, Malaysia. *Rock Mechanics for Resources, Energy and Environment.* CRC Press. 901–907

[7] RS^3 1.0. 2015. Rocscience Inc. www.rocscience.com

[8] Hoek, E., Carranza-Torres, C. and Corkum, B. 2002. Hoek-Brown Failure Criterion-2002 Edition. *Proceedings of NARMS-TAC, 1, 267–273.*

[9] Hoek, E. and Diederichs, M. S. 2006. Empirical Estimation of Rock Mass Modulus. *International Journal of Rock Mechanics and Mining Sciences.* 43: 203–215.

[10] Carter, M. and Bentley, S. P. 1991. *Correlations of Soil Properties.* London: Pentech Press Publishers.

[11] Coduto, D. P. 2001. *Foundation Engineering: Principles and Practices.* New Jersey: Prentice-Hall.

[12] Bowles, J. E. 1996. *Foundation Analysis and Design.* England: Mcgraw-Hill Book Company Limited.

[13] Das, B. M. 1994. *Principles of Geotechnical Engineering.* U.S.A: Cl Engineering.

[14] Obrzud, R. and Truty, A. 2012. *The Hardening Soil Model-A Practical Guidebook Z Soil*. Pc 100701 Report.

[15] Look, B. G. 2007. *Handbook of Geotechnical Investigation and Design Tables.* London: Taylor and Francis.

[16] NAVFAC. 1986. *NAVFAC Design Manual 7.2 - Foundations and Earth Structures. In: Command, N. F. E. (Ed.).* Virginia: Naval Facilities Engineering Command.