FOREPOLING PRE-SUPPORT APPLICATION IN THE SHALLOW TUNNELING THROUGH WEATHERED GRANITE

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Dedicated to my beloved family.

And those craving for unveiling this mysterious universe.

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ABSTRACT

Tunnel face stability and ground movements induced by excavation are of significant concern in shallow tunneling through weak ground. In conjunction with other support systems, various pre-support measures are applied to reinforce the ground prior to excavation for ensuring tunnel crown stability and construction safety in general. Among them, forepoling is the simplest form of umbrella arch pre-support method which is widely used in tunneling application. Until now, very few studies addressed the effect of forepoling design parameters on crown stability of shallow tunnel constructed in weathered rock and no study is available for weathered granite. This leads to conservative and uneconomical designs of basic forepoling design parameters. This study aims at quantitative understanding through numerical parametric analysis regarding the behavior of forepoling pre-support design parameters that affect the crown stability of a shallow tunnel constructed in weathered granite. The effect of three design parameters - forepole length, installation angle and spacing on crown stability were investigated by using 3D finite element analysis program RS3 by Rocscience; using Pahang-Selangor raw water transfer tunnel project as a reference case. These parameters were then optimized considering total displacement and induced major principal stress at tunnel crown as evaluation indicator of crown stability. The results show that, the total displacement at tunnel crown increases by 0.64% when the forepole length was increased from 5 m to 9 m. The induced major principal stress at tunnel crown decreases by 1.02% when the length is varied from 3 m to 8 m. The total displacement at tunnel crown decreases by 0.23% when the installation angle of forepole is varied from 5° to 9°. From this study, it was found that length of 3 and 4 m; with angle of 5° to7°, and spacing of 300 mm are optimum forepoling design parameters under given tunneling condition.

ABSTRAK

Kestabilan muka terowong dan pergerakan tanah yang disebabkan oleh penggalian harus diambil berat terutamanya apabila melibatkan terowong cetek di dalam tanah yang lemah. Dengan kaedah sistem sokongan, pelbagai langkah pra-sokongan digunakan untuk mengukuhkan tanah sebelum penggalian bagi memastikan kestabilan bumbung terowong dan keselamatan pembinaan secara amnya. Antaranya, kaedah *forepoling*, di mana merupakan kaedah pra-sokongan yang paling mudah di dalam sistem kaedah pra-sokongan payung gerbang dan digunakan secara meluas di dalam aplikasi terowong. Sehingga kini, sangat sedikit kajian mengambilkira kesan parameter reka bentuk *forepoling* terhadap kestabilan bumbung terowong cetek yang dibina di dalam batu terluluhawa, dan tiada kajian dilakukan untuk granit terluluhawa. Ini seterusnya, membawa kepada reka bentuk konservatif dan tidak ekonomi dalam reka bentuk asas *forepoling*. Kajian ini bertujuan untuk memahami dari sudut kuantitatif melalui kaedah analisis parametrik berangka mengenai tingkah laku parameter reka bentuk *forepoling* yang mempengaruhi kestabilan bumbung terowong cetek di dalam granit terluluhawa. Kesan daripada tiga parameter reka bentuk, iaitu panjang, sudut pemasangan dan jarak, kestabilan bumbung terowong telah dikaji dengan menggunakan program RS3, iaitu kaedah unsur terhingga 3D oleh Rocscience; dengan mengambil kira projek Terowong Pemindahan Air Mentah Pahang-Selangor yang telah siap sebagai kes rujukan. Parameter-parameter ini kemudian dioptimumkan dengan mempertimbangkan jumlah anjakan dan tegasan prinsipal utama di bumbung terowong sebagai petunjuk penilaian kestabilan bumbung. Keputusan menunjukkan bahawa, jumlah anjakan pada bumbung terowong meningkat sebanyak 0.64% apabila panjang *forepole* telah ditingkatkan daripada 5m hingga 9m. Tegasan utama pada bumbung terowong berkurangan sebanyak 1.02% apabila panjang ditambah dari 3m kepada 8m. Manakala, jumlah anjakan pada bumbung terowong berkurangan sebanyak 0.23% apabila sudut pemasangan daripada forepole diubah dari 5° kepada 9°. Daripada kajian ini, didapati bahawa panjang 3m dan 4 m; dengan sudut sudut 5° kepada 7°, dan jarak 300mm adalah reka bentuk *forepoling* yang paling optimum merujuk kepada keadaan terowong tersebut.

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LIST OF ABBREVIATIONS

BEM	-	Boundary Element Method
CAD	-	Computer-Aided Design
DEM	-	Distinct Element Method
DFN	-	Discrete Fracture Network
FDM	-	Finite Difference Method
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
GSI	-	Geological Strength Index
JH	-	Japan Highway
ISRM	-	International Society for Rock Mechanics
MLD	-	Million Liter Per Day
NATM	-	New Austrian Tunneling Method
NGI	-	Norwegian Geotechnical Institute
PSRWT	-	Pahang-Selangor Raw Water Transfer
RMi	-	Rock Mass Index
RMR	-	Rock Mass Rating
RQD	-	Rock Quality Designation
TBM	-	Tunnel Boring Machine
UA	-	Umbrella Arch
UCS	-	Uniaxial Compressive Strength
UDEC	-	Universal Distinct Element Code
UTM	-	Universal Transverse Mercator

LIST OF SYMBOLS

F	-	Internal Forces
P	-	Applied Loads
J_a	-	Joint Alteration Number
J_n	-	Joint Set number
J_r	-	Joint Roughness Number
J_w	-	Joint Water Reduction Factor
m_b	-	Material Constant
ΔU	-	Nodal Displacements
σ_1	-	Major Principal Stress
σ_3	-	Minor Principal Stress
σ_{ci}	-	Intact Rock Uniaxial Compressive Strength
σ_n	-	Normal Stress
τ_f	-	Shear Stress
φ	-	Friction Angle

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

With the advent of urbanization and innovative technologies for infrastructure development, tunneling is becoming a sustainable practice recently. 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. Generally, the urban ground condition is not always favorable, and therefore is susceptible to major displacement due to tunneling process especially excavated in the soft soil and weak weathered rock formation (Watika *et al.*, 2004; Volkmann and Schubert, 2007; Latif *et al*., 2012). Rock masses situated at shallow depths exhibit weak mechanical behavior 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 (Hoek, 2004).

For the abovementioned 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 systems have widely been used to ensure stability during tunnel excavation by preventing tunnel face from collapsing especially in unfavorable subsurface conditions such as poor self-standing and/or weathered ground formation with a shallow overburden which are vulnerable to excessive displacement (Park *et al*., 2012; Latif *et al*., 2012).

The umbrella arch pre-support system installation procedure is less time intensive and more cost efficient compared to the abovementioned pre-support system. For these reasons, the use of umbrella arch pre-support systems have been increased over the last few years. However, there is still lack of comprehensive understanding and knowledge regarding the interaction between ground and pre-support systems related to umbrella arch system (Volkmann *et al*., 2006). The absence of widely accepted rules, formulas and clear guidelines for determining basic design parameters led the tunnel designers rely to on real life experience and common practices which may account for uneconomical and conservative design (Volkmann and Schubert, 2006, 2007).

Various previous literature emphasized on the significance of understanding the umbrella arch system behavior. In order to understand its behavior it is necessary to determine the influence of each umbrella arch design parameter on stability of tunnel face. Very few studies addressed the issue of design parameters (Song *et al*., 2006; Wang, 2012; Oke, 2014). However, no previous studies covered the parametric study of forepoling design parameters in weathered rock.

Generally numerical modeling illustrates a real life physical phenomena 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 modeling provides a simulation environment of probable uncertainties that might occur during tunnel excavation. Although results produced by numerical modeling are not entirely accurate, the results are still effective for aiding in understanding the existing underlying mechanisms and thus providing various options for ground improvement (Latif *et al*., 2012). Contrary to the construction experience obtained during real life tunnel excavation, the same tunnel can be excavated repeatedly by varying different parameters in numerical modeling.

1.2 Problem Statement

Over the past few years, the application of umbrella arch pre-support systems have significantly increased in shallow tunneling in weathered rock. Often, determining the basic design parameters of these pre-support systems are based solely on the experience of tunnel engineers as objective design guidelines are still not available. A standardized approach is required for determining these design parameters during tunnel designing process. Also, any civil engineering design needs optimization to ensure both safety and economic efficiency at the same time. However, there is a significant lack of understanding regarding the geotechnical behavior of umbrella arch pre-support system which may lead to the conservative and inefficient designs in terms of economy. Therefore, comprehensive fundamental knowledge regarding the interaction between weathered rock and umbrella arch pre-support is essential in order to optimize the design parameters. Hence, it is necessary to understand the influences of each design parameter on ground response with a view to providing an insight to the tunnel designers for making sound engineering judgment.

1.3 Significance of the study

The study of umbrella arch pre-support is limited in rock engineering literatures, compared to other conventional support systems, such as shotcrete, rock bolt, and lattice girder. This study attempted to contribute to the knowledge of geotechnical behavior of pre-support in rock addressing the issues of dimensioning forepole design parameters. The result of numerical analysis of forepoling design parameters will provide a useful insight to the tunnel engineers and related policy makers for practical design optimization as well as decision making. The understanding of the influence of these design parameters to ground response will aid the designers to adopt a standard design guidelines avoiding overestimation as well as maintaining safety at the same time. The knowledge of rock and pre-support interaction will benefit policy makers and contactors related to tunnel construction for preparing contract documents and avoiding dispute. The outcome and recommendation of this study will provide future direction for further comprehensive and detailed study incorporating jointed rock model along with high quality field and laboratory test data.

1.4 Research Aim and Objectives

The research is aimed at quantitative fundamental understanding of the behavior of forepole pre-support design parameters that affect the crown stability of a shallow tunnel constructed in weathered granite by using numerical analysis. Hence, two main objectives to achieve the aim are as follows:

1. To identify the effect of three forepoling design parameters - forpole length, installation angle and spacing on crown stability of shallow tunnel in weathered granite.

2. To determine the optimized forepoling design parameters with a view to providing an insight for safe and economic design under given tunneling condition.

1.5 Scope and Limitations of the Study

The study takes Pahang-Selangor Raw Water Transfer (PSRWT) tunnel project as reference case. A 20 m long tunnel section belong to New Austrian Tunneling Method (NATM)-3 segment of PSRWT tunnel is considered for this study which was located within Chainage 5910 to 5930. The studied section is situated just before the Kerau River crossing area having a shallow overburden of 20 m. The tunnel section encountered weathered granite which had undergone full face excavation by controlled drill and blast technique. Among different categories of umbrella arch pre-support systems, forepoling was considered for this study focusing on mainly three design parameters: forepole length, installation angle, and spacing. Their effects on tunnel crown stability were investigated in terms of two indicators - total displacement and induced major principal stress. RockWorks 15 and EnvironInsite software were used for subsurface modelling. Parameters for subsurface modelling programs were adopted from the geological data of five boreholes. The numerical parametric studies are carried out using three dimensional (3D) finite element software RS^3 incorporating multi-stage excavation.

Required data were collected from various secondary sources such as Malaysian Ministry of Energy, Green Technology and Water (Kementerian Tenaga, Teknologi Hijau dan Air in Malay language, abbreviated as KeTTHA), project contractors, literature review and personal contact with tunnel related professionals. Unavailability of some data as well as unwillingness to share confidential data were significant constraints faced during this research. In these cases, derived data were used where some of the input data of the numerical analysis software were devised from correlations, engineering judgment, and typical values from previous literatures.

1.6 Organization of the Thesis

This thesis has been organized into five chapters. Chapter 1 discusses the background of the study and identifies the problem statement. It also highlights the main aim and objectives of the research as well as its scope and limitations. A brief overview of the forthcoming chapters is also provided here.

Chapter 2 presents comprehensive literature review of general concepts, theories, previous findings and overview of software relevant to this study. This chapter focuses on various NATM support systems including initial support systems and umbrella arch pre-support systems long with its design parameters. Value of three forepoling design parameters from previous projects and studies are summarized. The chapter also provides a general overview of stresses around excavation opening in rock, various rock mass classification systems, rock weathering classification, weathered granite material characteristics, different numerical analysis methods, Mohr-Coulomb and Generalized Hoek-Brown failure criteria.

Chapter 3 provides a flowchart and a brief overview of the research activities. A short description of the PSRWT tunnel project is provided which is used as a reference case for this study. This chapter also illustrates the technical descriptions, procedures and steps adopted for both subsurface modelling and numerical modelling. Firstly, it puts forward the input requirements of the modelling software extracted from collected data. After that it shows the step-by-step development of numerical model with two cases; Case 1- with forepole and Case 2 - without forepole.

Chapter 4 discusses the limitations and pitfalls in using the finite element software. It also illustrates the model verification by comparing simulation results based on analysis of Case 1 with field instrumentation data. After verification the analyzed results of numerical parametric study of Case 2 models are discussed to investigate the influence of three aforementioned forepoling design parameters on crown stability. Optimized values based on two crown stability indicators are illustrated. The findings of this study were compared with the relevant previous studies conducted by other researchers.

Finally, Chapter 5 presents the conclusive remarks on the study referring to the objectives which including summarized research findings. It highlights the main contributions made by this research, its practical applicability, and also sheds light into some areas where attention can be given in future for further advancement of this research.

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