JACK FORCE EFFECT TO TUNNEL STABILITY

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

School of Civil Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

OCTOBER 2021

ACKNOWLEDGEMENT

I would like first to thank Allah almighty who pleased me by his guidance, patcient, knolwedge and strength to complete this degree. Then to my wife who without her constant support and encouragement I would not be able to make it this far.

I would like also to show my deepest sense of gratitude to my supervisors Dr. Siti Norafida Binti Jusoh and Ir. Dr. Rini Asnoda Abdullah for their constant advice, support and valuable assists which resulted in completing this work successfully.

I am sincerely thankful to all my friends, especially to my dearest fiends Alaa Awad, Abubaker Gabr, Mohamed Sabry and Noureldeen Essam who supported me in many occasions. I would like also to thanks my local friend Vinoth Kumar, who eased my staying and introduce me to the warm culture of this beautiful country.

Finally, I would like to give my thanks to everyone who cooperated and helpedme to complete this degree.

ABSTRACT

The construction process of a bored tunnel is a complex process. During tunnel construction, loads were acting on tunnel and to support excavation, tunnel lining were installed with application of jack force (Fj). Jack force is exerted as a thrust force to ensure advancement of tunnel construction and to enhance tunnel face stability. However, the complexity of Fj to the variation of segment's thickness to ensure the overall tunnel stability is not fully studied yet. The impact of jacking force on segmental tunnel lining and surrounding soil during the tunnel construction also yet to be definedin certain. Therefore, effect of tunnel lining thickness applied with a variation of jack forces in the tunnel-boring machine (TBM) in different soil formations is investigated here in. This research presents a three dimensional (3D) numerical modelling of tunnelsoil-jack force by using ABAQUS software. From the findings, the ground surface andsubsurface reaction, and reaction force in segment lining were presented. It is found that, from the initial model, longitudinal and transverse surface settlement shows a similar results with previous research work thus verified the work. Next, from the simulation, loads case applied caused stress on the tunnel face which must be encountered by a certain thrust magnitude to advance the tunnel. The face pressure values changed respective to the soil formations, which recorded a different maximumvalues in the range of 360 MPa to 500 MPa in different soil formations. The jack force calculated from the face pressures of three different lining thicknesses (0.135 m, 0.275 m, and 0.375 m). Jack force of each lining thickness in different soil formations is ranging from 4000 kN, 2000 kN and 1000 kN for the lining thickness of 0.135 m, 0.275 m and 0.375 m, respectively. From the extended complex model, results show the subsurface soil settlement presents a heaving behaviour at the beginning of the excavation and induced a gradually increase of settlement once tunnel stabilise its excavation. The subsoil stress of the soil above the tunnel crown reaches its plastic behaviour at the end of shield contact to cause the final soil displacement. When investigate the effect of jack force to the tunnel lining reaction, a tunnel lining thicknessof 0.135 m, 0.275 m and 0.375 m show a maximum reaction force in range of 20000 kN to 40000 kN, 27400 kN to 22700 kN, and 22400 kN to 27700 kN, respectively. This reaction force was varied due to the soil formations and staggered tunnel configurations. It is also found that, the lining thickness of 0.275m (t/D = 0.0458) showsthe most stable uniform distribution of reaction force (RF) and thus presents none of critical segments (i.e., safe condition). The segment configuration and angle shows the favourable angle of 5 segment rings is when the staggered started at the angle 32.5°. To sum up, all factors including the geological condition, face pressure, redistribution of sub surface soil stress and jack force variation are crucial in tunnel stability, hence the tunnel lining selection should be done accordingly.

ABSTRAK

Proses pembinaan untuk terowong korekan adalah proses yang rumit. Semasa pembinaan terowong, beban telah bertindak ke atas terowong dan untuk menyokong pengorekan, pelapik terowong telah dipasang dengan penggunaan daya bicu (Fj). Daya bicu dikenakan sebagai daya tujahan bagi memastikan kemajuan pengorekan dan untuk meningkatkan kestabilan pintu terowong. Walaubagaimanapun, kerumitan Fj terhadap variasi ketebalan segmen untuk memastikan kestabilan keseluruhan terowong belum dikaji sepenuhnya. Kesan daya bicu kepada segmen pelapik terowong dan tanah sekeliling sewaktu pembinaan terowong juga masih belum dapat dijelaskan dengan pasti. Oleh itu, kesan ketebalan pelapik terowong dengan variasi daya bicu di dalam mesin pengorekan terowong di dalam formasi tanah yang berbeza telah dikaji di sini. Kajian ini membentangkan model berangka tiga dimensi (3D) terowong-tanah-daya bicu menggunakan perisian ABAQUS. Daripada keputusan, reaksi tanah di permukaan dan subtanah serta reaksi pelapik segmen dibentangkan. Didapati, dari model awal, mendapan melintang dan membujur menunjukkan keputusan yang sama seperti kajian lepas dan ini mengesahkan model ini. Kemudian, daripada simulasi, kes-kes beban yang dikenakan telah menyebabkan tekanan kepada muka hadapan terowong yang memerlukan tindakan daripada sejumlah daya tujahan untuk meneruskan korekan. Nilai tekanan muka berubah berdasarkan formasi tanah, yang mana direkodkan pada nilai maksimum yang berbeza iaitu dalam anggaran 360 MPa kepada 500 MPa di dalam tanah yang berbeza. Daya bicu telah dikira dari tekanan muka untuk tiga jenis ketebalan pelapik (0.135 m, 0.275 m, dan 0.375 m). Daya bicu untuk setiap ketebalan pelapik dalam formasi tanah yang berbeza adalah dalam anggaran 4000 kN, 2000 kN dan 1000 kN untuk masing-masing ketebalan pelapik 0.135 m, 0.275 m dan 0.375 m. Daripada model kompleks, keputusan menunjukkan bahawa enapan tanah subpermukaan menunjukkan tingkah laku lambung pada permulaan pengorekan dan menghasilkan pertambahan mendapan apabila terowong mula mencapai kestabilan dalam pengorekan. Tekanan subtanah dalam permukaan di atas kepala terowong mencapai tingkahlaku plastik pada pengakhiran pelindung yang menyebabkan pergerakan akhir tanah. Apabila dikaji tentang kesan daya bicu kepada reaksi terowong, dengan ketebalan pelapik terowong 0.135 m, 0.275 m and 0.375 m, daya reaksi maksimum adalah didapati pada anggaran 20000 kN to 40000 kN, 27400 kN kepada 22700 kN, dan 22400 kN kepada 27700 kN, masing-masing. Daya reaksi adalah bervariasi disebabkan oleh formasi tanah dan konfigurasi terowong yang berperingkat. Juga didapati, ketebalan pelapik 0.275 m (t/D = 0.0458) menunjukkan keadaan paling stabil dengan pengedaran seragam daya reaksi (RF) dan menunjukkan tiada segmen yang kritikal (keadaan selamat). Corak konfigurasi segmen dan sudut menunjukkan sudut yang paling baik untuk 5 segmenialah apabila kecondongan peringkat bermula pada sudut 32.5 º . Sebagai rumusan, kesemuafaktor termasuklah keadaan geologi, tekanan muka, pengagihan tegasan subtanah, dan variasi daya bicu adalah penting di dalam kestabilan terowong. Oleh itu, pemilihan pelapikterowong perlulah dilakukan dengan sewajarnya.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

FEM	-	Finite Element Method
3D	-	Three Dimension
EPB	-	Earth Pressure Balance
ULS	-	Ultimate Limit State SLS
SLS	-	Serviceability Limit State
TBM	-	Tunnel Boring Machine
UTM	-	Universiti Teknologi Malaysia
LRFD	-	Load and Resistance Factor Design
RF	-	Reaction Force

LIST OF SYMBOLS

$T_{v(x)}$	-	Settlement at distance (x) from the tunnel axis
T_{vmax}	-	Maximum settlement above the axis of the tunnel
i	-	Horizontal distance between the central tunnel axis and the Inflection point of the curve
V_s	-	Volume of ground settlement per unit length through
V_L	-	Volume Ground loss
D	-	Tunnel diameter
t	-	Tunnel thickness
R	-	Radius
x	-	Lateral distance tunnel from excavation
z_0	-	Depth of tunnel
S''	-	Vertical displacement induced by tunnel
K	-	Earth coefficient
j	-	Maximum thrust force for jack pair
F_j	-	Jack force
T_{MAX}	-	Maximum total thrust of TBM
N_j	-	Jack pairs
f_R	-	Friction resistance
T_{Burst}:	-	Bursting force of bursting force from face of section as shown in Figure
d_{burs}	-	Centroid distance of bursting force from face of section figure
P_{pu}:	-	The jacking force applied on each jack pad
h_{anc}:	-	The length of contact zone between jack shoes and the segment face
h	-	The depth of cross section.
e_{anc}	-	The eccentricity of jack pads with respect to the centroid of cross section
σ_{jc}	-	Compressive stress
a_l	-	Transverse length of contact zone between jack shoes

		and segment face
$\$_{c}^{\$}$	-	Allowable compressive stresses
K_{Ro}	-	Rotational stiffness
K_A	-	Axial stiffness
K_{Ra}	-	Radial stiffness
F_l	-	Flexibility ratio
E	-	Young's modulus of the ground
V	-	Poisson's ratio of the ground
E_L	-	Young's modulus of the lining
V_L	-	Poisson's ratio of the lining
I_l	-	Effective moment of inertia of the lining
Il	-	The moment of inertia of the lining without joint
N	-	Number of segments
Ij	-	Second moment area at the joint
K_E	-	The element stiffness matrix
ΔD_E	-	The increments of nodal displacement connected to an element
ΔF_E	-	The increments of nodal forces connected to an element
K_G	-	The global stiffness matrix
ΔD_G	-	The increments of nodal displacement connected to a global
ΔF_G	-	The increments of nodal forces connected to a global
θ	-	Angle of friction
c	-	Cohesion
$\%_u$	-	Safety factor of buckling
$\%_w$	-	Average wet soil weight
E_c	-	Concrete Young's Modulus

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Overview

The classical excavation method such as the New Austrian Tunneling Method (NATM) has limitations for tunneling in urbanized areas; therefore, a Tunnel Boring Machine (TBM) is widely used especially in urban areas due to the advantage of limiting disturbances to the surrounding soil. In TBM method, tunnel lining is accumulated inside the shield of the boring machine and it consists of jointed rings and each ring consists of elements (segments). These segments are designed dimensions and shapes for specific purposes to ensure the resistance of tunnel lining to all possible loads during and after the tunnel construction. Besides that, the segment is important to hold over the longitudinal continuity with keeping the tunnel alignment as it is designed and constructing the lining with a fast rate and high level of safety (Maidl, 2013).

While the tunnel is advancing, the cutter head thrust on the segments to encounter the tunnel face pressure to cause thrust effect on the whole tunnel lining. longitudinal thrust effect is the main parameter to identify the jacks number, position, segments size and the loading effect from the excavation cutter head. The magnitude of the longitudinal thrust can be calculated by estimating the tunnel face pressure, calculating the earth and water pressure and friction, and/or adhesion between the ground and Tunnel Boring Machine (TBM) via soil mechanics principles. Besides, the thickness of the segments face should be considered to avoid the damaging of face edges and to avoid the joints position and thrust ram position being in the same position (Telford, 2004).

Another important factor concerned during the tunnel design is the effects of segmental joints on tunnel lining behaviour. The effect of the joints has been studied by many researchers through different methodologies (Do *et* al., 2014 a; Vervuurt, 2007; Jusoh, 2017).

1.2 Problem Statement

Most of the previous researchers had modelled only the structure behaviour of tunnel lining without considering the effect of the surrounding soil, the effect of a certain pattern of joints on the segments' structure behaviour, and the effect of jack force and soil loads on the thickness of the segments at all. Although many studies have been conducted on ground movements and lining forces, while a relatively small body of research exists regarding the relationship between the jacking force (Fj) and the stresses in the lining.

As far as three dimensional (3D) numerical model is developed, some researchers have focused on studying the effect of the segments' joints on the tunnel lining behaviour, but not as a parameter in a full 3D model with the different soil loads and *Fj*. There is still not yet a full model, in a single face soil environment in which the presence of the varied value of jacking force during the tunnel advance is modelled, that allows ground displacement, structural lining forces, the pattern of the joints and thickness of segments to be considered.

1.3 Objectives

This research aims to fulfil the gap of the tunnel response due to the jacking force effect which is not yet fully explored. The results will show the reaction of each segment toward the force exerted by jacking the lining. This will lead to determining the highest suitable ring thickness that can resist the jacking force based on surrounding soil and exerted external load. Therfore, measure the settlement pattern alongside the tunnel axis and the lateral settlement that represent the volume loss produced by constructing the tunnel. The specific objectives of this study are to:

(a) Investigate the surface and subsurface settlement induced by the advancementof the tunnel via 3D model

(b) Measure the soil stress and face pressure to evaluate the jacking force requiredto advance linings with different thickness.

(c) Determine the effect of jack forces to the staggered segments reaction withdifferent tunnel lining thickness

1.4 Research Scope

The scope of the research is to generate a series of numerical model for segments tunnel lining with and without the effect of *Fj*, in different geological conditions. The geological setting assign based on the subsurface data of Mass Rapid Transit (MRT) tunnel lining project, in Singapore. The geological formation data separated to assign seven different formations, and the tunnel model simulated in each formation independently to unify the surrounding behaviour to focus on the tunnel behaviour findings. Besides, the scope of the research is to study the most suitable segments thickness based on the *Fj* that resulted from a single geological formation.

Therefore, a study shall be conducted on the relationship between the jacking force and the lining force of the tunnel lining considering the soil displacement; joints pattern will be the same for all models. The research outputs will be the tunnel rings behaviour that induced during the advance of the tunnel and the relation between the jacking force and settlement induced, the pressure acting on the tunnel face, the thickness of segments and the pattern of joints arrangements.

1.5 Limitation

The models discussed in this research does not simulate the full construction stages because of the computer limitation. In which for the full construction stages to be incorporated in the Finite Element (FE), it requires the fine element mesh generation to simulate elastoplastic behaviour of ground surrounding excavation face and linings supporting *Fj* directly. Secondly, the number of step-by-step analyses will increase as the construction stage is determine specifically. Also, some parameters in this research, which is the behaviour of grout material under load cases effect, creep and shrinkage phenomena for the lining is not been considered in this research. These limitations will not influence the main aim from this stage, where to measure the settlement pattern alongside the tunnel axis and the lateral settlement that represent the volume loss produced by constructing the tunnel.

1.6 Thesis Outline

This thesis consists of:

(a) Chapter (1): The general overview about TBM and the factors related to the search with the problem that will be discussed in this research, the objectives of this research and the scope of the research methodology.

(b) Chapter (2): Background, which discusses the previous study of the segmental design and the effect of the different kinds of joints on the tunnel lining resistibility for different kinds of loads, soil-tunnel interaction and the relation between the settlement and the segmental tunnel lining.

(c) Chapter (3): Details of research method which include the model flow chart that will lead to developing the 3D FEM model and the details of a case study that used in this research.

(d) Chapter (4): the analysing, verification and discussion of numerical analysis of three-dimensional (3D) finite element model.

(e) Chapter (5): The findings from the research that concluded and some recommendation for the future study proposed.

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