PERFORMANCE OF PRECAST BOLTED TUNNEL LINING THROUGH PHYSICAL AND NUMERICAL MODELLING

SITI NORAFIDA BINTI JUSOH

UNIVERSITI TEKNOLOGI MALAYSIA

PERFORMANCE OF PRECAST BOLTED TUNNEL LINING THROUGH PHYSICAL AND NUMERICAL MODELLING

SITI NORAFIDA BINTI JUSOH

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

NOVEMBER 2016

DEDICATION

This thesis is dedicated to my husband, Mohd. Nazrul, our daughters, Nur Naqiyah and Nur Najwa. I give my deepest expression of love and appreciation for the encouragement that you gave, the sacrifices and patience for all of you made during this graduate programme. May Allah bless us with Jannatul Firdaus.

> “Indeed, your Lord is most knowing of who has gone astray from His way and He is most knowing of the [rightly] guided.”
>
> (al-Quran, 68:7)

ACKNOWLEDGEMENTS

In the name of Allah, the Almighty who gives us enlighten, the truth, the knowledge and with regards to Prophet Muhammad S.A.W for guiding us to the straight path. We thank Allah for giving us the ability and strength to complete this task and to continue our good deeds to the community in this field.

I must thank both my parents for their love and support throughout my entire life. Thank you to my husband and daughters for giving me the strength to reach for the stars and chase my dreams. My brothers and little sisters deserve my wholehearted thanks as well.

Sincere gratitude and appreciation to my supervisors, Associate Professor Dr. Hisham bin Mohamad, for his guidance, support and patience throughout this study, especially for the opportunity to expose to the new knowledge. I would also like to thank Professor Dr. Aminaton Marto for serving as a co-supervisor and accepting me to join the Soft Soil Engineering Research Group (SSRG). I am grateful for the discussion and interpretation of some results presented in this thesis with the help of SSRG members.

Appreciation is also due to Associate Professor Dr. Sarifuddin bin Saad, Dr. Mariyana Aida Ab. Kadir and Dr. Abdullah Zawawi Awang, thank you for sharing knowledge especially in structures field and encouragement in my many moments of crisis. Lastly, I would like to thank all who have either involved directly or indirectly in completing this task.

ABSTRACT

Designing a tunnel is significantly different from designing a normal building. Tunnels not only require maximum strength but also need for stability due to movement which incorporate stress redistribution in the surrounding soil. To allow tunnel deformation, a number of precast concrete segments are lined together and joined with curved bolts to form a tunnel ring. Due to jointing conditions and the curving shape of the segment, complex flexural movement in the segment joints is not yet fully understood. It is crucial to examine angular joint stiffness as previous researchers assumed that each segment joint has a unique value, even though they change non-linearly. This study examines angular joint stiffness in lining segments to produce a realistic model of soil-structure interactions. The behaviour of individual (non-jointed) segments and dual-jointed segments were investigated in the laboratory with a transversal vertical line load supported by two different boundary conditions to attain a moment reduction factor, M_R and angular joint stiffness, k_ω. M_R was in the range of 0.132 - 0.85 for pin-roller and 0.62 for pin-pin. The k_ω of dual-joints for pin-pin conditions was 6000 to 7000 kNm/rad and k_ω for pin-roller conditions was 1035 kNm/rad. Three-dimensional segmental lining models were developed using ABAQUS 6.10 software. Initial results were validated with an analytical Unit Load method for selected load and support conditions. The model was compared with laboratory data. It was observed that the segmental tunnel lining model with nonlinear jointed stiffness for hinge interaction matched laboratory results. The simulation was successfully extended into a full soil-tunnel model for a case study. Validation was carried out with published field data from a case study for Mass Rapid Transit (MRT) Circle Line Projects in Singapore. A new level of understanding for tunnel linings was achieved from the effect of segment lining joints. When compared to a continuous ring model (tie-model), less tangential bending was observed in the simulated segment tunnel model (hinge-model), indicating a reduction in joint stiffness with increased loads and a significant effect on overall tunnel responses. A practical method to solve the soil-structure interaction of segmental bolted tunnel linings using nonlinear angular joint stiffness was achieved from this study.

ABSTRAK

Mereka bentuk sebuah terowong adalah sangat berbeza berbanding dengan mereka bentuk bangunan biasa. Terowong tidak hanya memerlukan kekuatan maksimum tetapi juga memerlukan kepada kestabilan disebabkan pergerakkan dengan mengambil kira pengagihan semula tegasan dalam tanah sekelilingnya. Untuk membenarkan ubah bentuk berlaku kepada terowong, sejumlah pelapik segmen konkrit pratuang disusun bersama disambungkan dengan bolt keluk bagi membentuk satu lingkaran terowong. Disebabkan oleh keadaan sambungan dan bentuk segmen yang melengkung, pergerakkan lenturan yang kompleks pada penghubung segmen masih belum difahami sepenuhnya. Adalah penting untuk memeriksa kekukuhan sendi bersudut memandangkan pengkaji sebelum ini mengambil kira sendi penghubung mempunyai satu nilai yang malar sedangkan ia sebenarnya berubah secara tidak selanjar. Kajian ini mengkaji kekukuhan sendi bersudut pada pelapik segmen untuk menghasilkan model interaksi tanah-struktur yang realistik. Tingkahlaku individu (tidak-terhubung) segmen dan dwi-terhubung segmen telah dikaji di dalam makmal dengan dikenakan beban melintang menegak lurus yang disokong oleh dua keadaan sempadan yang berbeza untuk mendapatkan faktor pengurangan momen, M_R dan kekukuhan sendi bersudut, k_ω. M_R adalah di antara 0.132 – 0.85 untuk pin-rola dan 0.62 untuk pin-pin. k_ω untuk kajian dwi-terhubung bagi keadaan pin-pin ialah 6000 ke 7000 kNm/rad dan k_ω untuk keadaan pin-rola ialah 1035 kNm/rad. Tiga-dimensi model pelapik segmen juga telah dibangunkan menggunakan perisian ABAQUS 6.10. Keputusan awal telah disahkan dengan analisis kaedah Beban Unit untuk beban dan keadaan sokongan yang tertentu. Model yang sama dibandingkan dengan keputusan makmal. Telah didapati bahawa model pelapik segmen terowong bersama kekukuhan sendi tidak selanjar menggunakan interaksi engsel telah berjaya dipadankan dengan keputusan makmal. Simulasi tersebut kemudiannya dikembangkan dengan jaya kepada model penuh tanah-terowong untuk sebuah kajian kes. Pengesahan telah dilakukan dengan data lapangan yang telah diterbitkan bagi kajian kes daripada Projek Circle Line Mass Rapit Transit di Singapura. Tahap baru kefahaman dalam terowong berdasarkan kesan sambungan pelapik segmen telah dicapai. Apabila dibandingkan dengan model lingkaran berterusan (model-terikat), momen lentur tangen yang lebih kecil telah diperolehi daripada model tunnel bersegmen (model-engsel), yang menunjukkan pengurangan kekukuhan sendi dengan bertambahnya beban dan sangat memberi kesan kepada keseluruhan reaksi terowong. Kaedah praktikal untuk menyelesaikan interaksi tanah-struktur bagi pelapik segmen terowong berbolt menggunakan kekukuhan sendi bersudut tidak selanjar telah tercapai melalui kajian ini.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACI	-	American Concrete Institute
ASCE	-	America Society of Civil Engineers
BMD	-	Bending moment diagram
BS	-	British Standard
BOTDR	-	Brillouin Optical Time Domain Reflectometer (Optical Fibre Strain Analyser); tools to identify localized sections of differential strain distributed along an optical fibre
CDP	-	Concrete damage plasticity
DAUB	-	German Tunnelling Committee
DJPP	-	Dual-jointed pin-pin
DJPR	-	Dual-jointed pin-roller
EPB	-	Earth Pressure Balance tunnel type
FEM	-	Finite Element Method
ITA	-	International Tunnel Association
LTA	-	Land Transport Authority
LVDT	-	Linear variable differential transformer
JSCE	-	Japan Society of Civil Engineers
MC	-	Mohr Coulomb
MPC	-	Multi point constraints
MS	-	Malaysian Standard
NATM	-	New Austrian Tunnelling Method
NJPR	-	Non-jointed pin-roller
NJPP	-	Non-jointed pin-pin
OT	-	Outer Bound
ÖVBB	-	Österreichische Vereinigung für Betonund Bautechnik

(Working Group on Concrete in Tunnel Construction of the Austrian Association for Concrete and Construction Technology)

PCTL - Precast concrete tunnel lining
RC - Reinforced Concrete
SFD - Shear force diagram
SFRC - Steel fibre reinforced concrete
SG - Strain gauge
SGCB - Strain gauge of curve bolt
SLS - Serviceability Limit State
TBM - Tunnel Boring Machine
ULS - Ultimate Limit State
1D - One dimensional
3D - Three dimensional

LIST OF SYMBOLS

A - Cross-sectional area

b - Width of segments

c - Soil cohesion

d - Unsupported excavation length

e - Distance from centroidal axis to neutral axis measured towards centre of curvature

E - Young’s modulus of the concrete

EI - Bending rigidity of tunnel lining

F - Flexibility ratio; flexural stiffness ratio between the ground and lining

h - Height of joint interfaces

I - Moment of inertia of the tunnel lining with complete cross-section

k - Subgrade modulus

K - A set of joint stiffness that consists of flexural, axial and shear stiffness (K_θ, K_δ and K_r)

L - Beam span length

M - Bending moment at x due to actual loading

m	-	Bending moment at x due to virtual unit load applied at point of deflection that interest, i
N	-	Number of segments in a ring ($n > 4$)
P	-	Load
p	-	Initial yield for value of the pressure invariant
q	-	Ratio of the second stress invariant on the tensile meridian
R	-	Radius of the centroid of the cross section of lining
t	-	Thickness of gauge base plus adhesive layer
r	-	Radius of gauge-bonded surface
W	-	Section modulus of the joint
w	-	Uniformly distributed load
y	-	Vertical height of arch at angle of interest, θ
c_r	-	Constant rotational stiffness
c_{ri}	-	Rotational stiffness in the segment’s joint
D_1	-	Distortional ring diameter of staggered segment tunnel
D_2	-	Distortional continuous ring diameter
E_s	-	Young’s modulus of the soil
E_L	-	Young’s modulus of the lining
F_n	-	Concentrated normal force at the joint
f'_c	-	Compressive strength of concrete at 28 days
f_y	-	Steel yield strength properties
G_c	-	Shear modulus of intact concrete
$\hat{G}$	-	Reduced shear modulus of cracked concrete
I_e	-	Effective equivalent lining stiffness
I_j	-	Moment of inertia at the joint which affected mainly by the contact zone

I_L - Area moment of inertia of arch cross section about the principal axis perpendicular to the plane of the arch

k_θ - Rotational joint coefficient

k_ω – Angular joint stiffness

k_x - Lateral earth factor horizontally

k_y - Lateral earth factor vertically

k_v - Coupling stiffness

K_A - Axial spring

K_c - Parameter of failure surface in deviatoric cross section; a ratio of the distances between the hydrostatic axis and respectively the compression meridian and the tension meridian in the deviatoric cross section

K_E - Element stiffness matrix

K_0 - Lateral earth factor, $1 - sin\ \phi$

K_θ - Bending moment per unit length required to develop a unit rotation angle along the joint of the assembled segments/flexural joint stiffness/rotational spring

K_δ, - Axial stiffness per unit length required to develop a unit axial displacement

K_r - Shear stiffness; shear force per unit length required to develop a unit shear deformation

K_r - Joint rotational stiffness

K^I_θ - Rotational stiffness

K^I_α - Axial stiffness

K^l_{sr} - Shear stiffness in radial direction

K^l_{st} - Shear stiffness in tangential direction

L_d - Distance between two LVDTs measures segment vertical movement

l_t - Contact area height in the longitudinal joint

M_{ad} - Additional moment

M_i - Tangential bending moment in segment’s joint *i*

M_R - Moment reduction factor

R_A - Reaction force at left of segment

R_B - Reaction force at right of segment

v_c - Poisson’s ratio of the concrete

v_L - Poisson’s ratio of the lining

v_s - Poisson’s ratio of the soil

α - Angle of end segment to the midpoint of segment

ε - Strain

ζ - Additional rate ratio of bending moment distribution in circumferential joints

$\varnothing$ - Subtended angle of the arch from middle span to the point of load (Roark’s formulations)

η - Bending rigidity (stiffness) reduction factor

λ - Joint stiffness ratio (introduced by Lee et al., 2001)

θ - Angle of end segment to the point of interest

φ - Rotation angle around the ring centre axial axis ($\varphi = 0$ at the top of the ring)

σ - Normal stress

μ - Viscosity parameter / shear retention parameter

ψ - Dilation angle

δ_I - Deflection at point interest, *i*

Δd_E - Increment of nodal displacement connected to an element

Δd_G - Increment of nodal displacement connected to a global

Δl - Unsupported excavation length in front of the tunnel lining

ΔR_E - Increment of nodal forces connected to an element

ΔR_G - Increment of nodal forces connected to a global

Δu_i - Deformation difference of the coupling at position i; depends on the deformation from the rotations in longitudinal joints due to the bending moments

ε_c - Compression strain

ε_{cu} - Ultimate compression strain

ε_{max} - Strain at which the parameter μ reduces to zero

θ_i - Rotation in the longitudinal joint i

σ_{b0}/σ_{c0} - Ratio of the strength in the biaxial state to the strength in the uniaxial state.

σ_{11} - Horizontal effective stress at a point specific

σ_2 - Radial ovalisation stress

σ_{33} - Effective stress as the vertical stress

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

The evolution of construction techniques and trend towards integrated use of structure design nowadays are to promote reliable and economic construction. By designing a structure into competitive prefabricated element, time of construction can be speed up especially in term of assembly times and in the same time reduce design costs and the structural weight. Construction of prefabricated elements also reduced site facilities and become less disruption thus reduce long-term operational cost. This lead to an early return on the client’s investment. A precast reinforced concrete segment tunnel lining is one of its kinds. Linings constituted of prefabricated reinforced concrete (RC) segments are routinely used in circular tunnels bored by earth pressure balance (EPB) or slurry machines because they are easily assembled inside the shield (Bilotta and Russo, 2013). The uses of segmental tunnel lining lead to an intensive industrialization of construction process and give an accurate control of the segments quality (Arnou and Molins, 2011). Segment is laid in the excavated soil one by one and jointed in various joint patterns to form a complete ring. Successive rings then laid aside either in parallel straight joint pattern or staggered joint pattern. With this integrated tunnel lining design, lining gives flexibility to allow flexural movement of tunnel, lead to adaptable and safety to the tunnel in overall. This is also a good effort of sustainability practice.

Design of tunnel lining is not straightforward. Tunnel lining design process should be approached by iterative process to gain an appreciation of how the ground and lining are likely to interact. Soil stiffness, flexibility or rigidity of lining, interaction of soil-lining and response of joint mechanism were the included factors that should be taking into account in bending moment investigation to achieve an accurate prediction (Yanzhi *et al.,* 2014). Variation in the structural forces in successive rings along the tunnel axis has been found in staggered segmental tunnel lining (Blom *et al.,* 1999; Hudoba, 1997; Do *et al.,* 2013b) which lead to a necessity to investigate the effect of joints pattern to the overall tunnel performance. Therefore, the stability of the tunnel lined by the precast concrete segments thus depends on a continuous support (*i.e.,* joint) and pressure around the ring. An important aspect of any integrated design construction is the joint connection. In tunnel, despite the general use of continuous lining, segmental joint lining are introduced to reduce the moment resisting connections which can be achieved by various types of joint pattern. Connections joint from segment to segment and from ring to ring are introduced to make sure tunnel is capable of resisting relatively high moments but also effectively flexible to allow movement against surrounding soil.

Circumferential lining joints are relatively straightforward to analyse and quite easily to understand in terms of their behaviour pattern. However, different manner of investigation is needed for longitudinal joints. Previous researchers concluded that longitudinal joint is crucial to investigate but complex analysis to fulfil (Blom *et al.,*1999 and Cavalaro *et al.,*2011). Issues in lining are not merely about the strength, but how much the tunnel allows to flexure to overcome the ground movement. The effect of the joints on the internal forces and deformations should be taken into consideration in the design of the tunnel linings. This relates much to the importance of understanding more on tunnel behaviour, how much tunnel lining is allowed to bend and to understand their load-displacement curve. By neglecting the structural stiffness in the tunnelling-structures analysis, it yields to significant overestimation of internal forces in the structural members (Mroueh and Shahrour, 2003).

1.2 Problem Statement

Klappers *et al.* (2006) mentioned that the behaviour of joints has to be modelled in a proper way because joints will highly affect the results. The effect of the joints on the internal forces and deformations should be taken into consideration in the design of the tunnel linings (Schulze and Duddeck, 1964; Muir Wood, 1975; Liu and Hou, 1991; Hashash *et al.,* 1998; Koizumi and He, 2000; Lee and Ge, 2001). Hudoba (1997) found out that it is very important to know the detailed earth loading characteristics since the detailing of lining element's interstices has a decisive influence of the lining stresses and deformations. It was also found that bending moment could increase with the increase of number of joint (Hudoba, 1997). Stiffness of lining may be affected; when bending moment is increased, the stiffness of lining also increased (Liao *et al.,* 2008). Xiaochun *et al.* (2006) study the effects of cushion; both sealing cushion and transmission cushion and concluded the joint stiffness is greatly reduced by the transmission packing material (*i.e.,* joint conditions). These shown that joint investigation is a crucial part of tunnel lining, thus research on this topic is significant to be carried out.

Considerable research on displacement field movement for a single and multiple tunnels has been undertaken (Schulze and Duddeck, 1964; Muir Wood, 1975; Peck, 1964; Sagaseta, 1987; Verruijt, 1997; Louganathan and Poulos, 1998; Park, 2004; Blom *et al.,* 1999; Franzius and Potts, 2005; Möller, 2006; Mohamad, 2008). However, lack of investigation still exists when accounting detailing of structural response (*i.e.,* flexural bending moment in tunnel lining) and the behaviour of the joints condition in segment's joints. Therefore, research was carried out to fulfil the lack of structural response knowledge in tunnel lining field.

Research has been carried out on tunnel response but not investigate the joint response in specific via analytical analyses (Liu and Hou,1991; Lee and Ge, 2001; Yanzhi *et al.,* 2014; El Naggar and Hinchberger, 2008; El Naggar and Hinchberger, 2012), in laboratory (Nishikawa, 2003; Teachavorasinskun and Chub-uppakarn, 2010; and Caratelli *et al.*, 2011) and in-situ testing (Arnou and Molin, 2011). Several model tests and analyses had been carried out to examine the influence of joints on lining behaviour but in limited support design condition (*i.e.,* fix-fix condition in Teachavorasinskunand Chub-uppakarn(2010)) which not presenting the real phenomena in field. Whilst, analytical method had shown lot of contribution in basis formulation development of tunnel lining problems. However, when it comes to application, researchers tend to simplify the angular joint stiffness value into a constant linear value (which in real is a nonlinear in manner). Therefore, this research decided to improvise the angular joint stiffness findings by carried out laboratory testing with different type of support condition to closely imitate the behaviour of tunnel and in the same time to obtain the angular joint stiffness in nonlinear manner.

Recently, attempts had been performed by researchers to conduct simulation via Finite Element Analyses on tunnel lining response by taking into account the joint model (Hudoba, 1997; Blom *et al.,* 1999; Chen and Mo, 2009; Cavalaro *et al.,* 2011; Teachavorasinskunand Chub-uppakarn, 2010; Molins and Arnou, 2011; Wang *et al.,* 2011; Do *et al.,* 2013b and Yang *et al.*, 2014). However, Blom *et al.* (1999), Cavalaro *et al.* (2011) and Wang *et al.* (2011) did not modelled the connection in great details. On the other hand, Chen and Mo (2009) tried to fill the gap in the problem by including an actual shape of segments. However, they only verified their modelling with field crack measurement data and did not discussed into detail on findings of joint behaviour. In addition, common practices in simulation that assumed uniform rigidity in both ring and segment joint have resulting an overestimated tunnel design moment (Koyama, 2003). Despite of diversity of numerical simulation, models were also verified with laboratory testing or analytical analyses which take constant value of joint stiffness. Therefore it can be concluded that, abundant useful information were available in the literature, unfortunately the influence of segmental joint stiffness has not been fundamentally explored in detail and values in the joint stiffness adopted have not been verified properly. Therefore, this research tried to fulfil the gap by developed segment model in numerical analyses and validated with laboratory findings by means the nonlinear angular joint stiffness.

Discussions on joints in segmental tunnel lining by Janssen (1983) and Blom (2002) detailed the possible joint conditions to be analysed. However, the discussions were too “structural”, in a way the analyses lacked the geotechnical aspect. It is known that, in a tunnel ring, the earth forces acting to the tunnel such as ovalisation load (*i.e.,* soil with lateral and horizontal coefficient, and ground water table). The stress concentration from surrounding ground will induce lining segment cracking, joint bolts yielding, joint dislocation and joint tenon crushing, which all results in serious slurry and water leakage problems. Longitudinal ground settlements also lead to over-stress the tunnel concrete segmental lining (Wang *et al.*, 2014). Bear in mind that tunnels take beneficial condition flexible movement rather than higher strength. It is more beneficial to assure the high flexibility of lining to sustain hoop forces rather than to put higher safety of factor in moment (Bakker, 2003). Thus, interaction study of segmental tunnel lining with surrounding ground must be carried out to provide more certain knowledge in future. Therefore, this research focuses on bending moment of segmental tunnel lining as to gain benefit from flexible tunnel lining design in order to withstand the surrounding soil and additional unexpected range of future external loading for lining.

1.3 Objectives

Linings are assemble in segmental parts and connected with bolt and packing material, which give effect to the overall structural behaviour. Joints allow tunnel to rotate and allow deformation. It is an urge to carry out this research to fulfil the gap of understanding the behaviour of flexural moment in segmental lining (*i.e.*, segment's joint) as their performance are complex and not fully understood. This research is to fundamentally record and quantify the stiffness in joint of lining and to produce a realistic model of soil-structure interaction in segmental precast tunnel lining that taken into account the detailing of jointed lining system.

In specific, this research embarks the following objectives:

(a) to identify the behaviour of individual segment and jointed tunnel lining segment in laboratory test through moment reduction factor and to identify angular joint stiffness of segment's joint
(b) to perform simulation in three dimensional numerical model and to calibrate the model design with laboratory findings
(c) to establish the model of tunnel segment's joint by means moment-rotation
(d) to improvise the simulation into a full soil-tunnel modelling with establish segment's joint model through a case study

Research are carried out via laboratory testing, numerical modelling using Finite Element via ABAQUS 6.10 and verified with a case study. It is expected the new findings on jointed stiffness for segment lining can be used to model the tunnel interaction ground problems more accurately.

1.4 Scope of Study

The scope of study is limited to precast segment tunnel lining with and without curve bolt joints. This research focuses on flexural bending moment behaviour within segment's joint and discuss their effect to soil arching at tunnel periphery. Crack propagation is not taken into account as the scope of study limit the discussion on flexural bending moment response only. As segmental tunnel lining is built in curved shape, the complexity of joint condition from segment to segment must fundamentally be investigated. Comparison between simulated staggered tunnel ring with established segment's joint and circumferential ring tunnel without joint or simplified manner of joint (*i.e.,* tie constraint) were carried out in order to show significant effect of improved tunnel lining design method.

1.5 Significant of Study

This study intended to carry out a complete investigation on design method in tunnel lining with joint, by considering nonlinear joint stiffness - to able predict better the soil-tunnel interaction behaviour. Blom (2002) mentioned about moment rotation in joints, which can be divided into several stages; constant stiffness, reduced stiffness, reduced stiffness with plastic stress. Currently, past studies simplified the problem using the moment reduction factor (*i.e.,* assume constant stiffness, or reduced stiffness) and not considering the non-linear stage of stiffness reduction. Reviews of the related technical literatures also show that the numerical methods often simplify either the detailed structures of the tunnel or the external loads and boundary conditions. These simplified approaches are acceptable in most cases but may lead to some inaccuracies. Such as it may underestimate the dynamic stress of the tunnel, and it cannot reflect the joint width variation between tunnel linings. By taking into detail the tunnel joint parameters nonlinearly, this approach together with full soil-tunnel numerical analysis, will help to quantify the tolerance error when compare to simple simulation. The novelty of this research emphasized on the use of actual joint-connection parameter, the nonlinear angular joint stiffness. Quantifying the jointed stiffness parameter correctly is the first step to solve the interaction-ground problems in tunnel lining in more certainty. By doing this, it is also forecast to improve prediction on flexural moment behaviour in tunnel lining as well as surface settlement prediction near the tunnel.

1.6 Hypotheses

Conventional lining design usually taken tunnel lining as a uniform rigidity ring model of lining by implying high partial safety factor on bending moment which is over estimated, due to incorrect assumptions (Koyama, 2003). Xiaochun *et al.* (2006) emphasized that joint rotational stiffness give great affect to the magnitude of bending moment of tunnel circumferentially. Moreover, Luttikholt (2007) emphasized that the influence of joints on the global lining behaviour is significant especially when the interaction between segments is included, more realistic tunnel lining response can be obtained. By considering segment's joint behaviour (which then effects the tunnel circumferential and longitudinal safety in overall), it is anticipated that full ring segments with nonlinear joint stiffness will observe greater restraint thus lower the moment flexural being generated. The new flexural bending moment and joint parameters established in this study will likely reduce the error and lead to much smaller in magnitude when compared to elastic joint stiffness model (angular joint stiffness introduce by previous researchers before). Nonlinear joint stiffness was also managed to be obtained which lead to more certainty prediction in soil tunnel interaction behaviour for tunnel lining with joint lining's bending moment themselves can cause by non-uniform ground pressures and joint eccentricities. From this point, more certainty of tunnel lining behaviour and displacement of the ground surrounding the tunnel can also be evaluated.

1.7 Thesis Outline

This thesis consists of seven chapters including the conclusions. In order to achieve contribution to the new level of certainty in soil-tunnel lining problems, the following chapters are presented.

Chapter 2 gives overview on soil-tunnel interaction that describes benefits of prefabricated segmental tunnel lining and joints in lining to obtain flexible condition as to bear the distortion and flexural bending moment. This chapter focused mainly on segmental tunnel lining design approach; continuous lining, segmental lining with reduction in bending rigidity and previous findings on numerical analyses regarding segmental joint solution. Then **Chapter 3** deals with methodology used in this thesis. It is divided into three main parts, laboratory set up of segmental tunnel lining, numerical modelling that carried out to simulate laboratory experiment and understand the structural response and deformations obtained from simulation models and the setup of three dimensional full soil-tunnel model of extended numerical model.

Chapter 4 presents and discusses the results obtained from the laboratory tests. Tangential bending moment of segmental tunnel lining plotted with rotations of segments lead to angular joint stiffness. By comparing the non-jointed and dual-jointed model, moment reduction factor is obtained for both type of support system.
In **Chapter 5**, the results of simulation models imitating laboratory testing are presented. The discussion on boundary conditions and interactions model adopted in the simulation model is described in details. From this chapter, angular joint stiffness interaction model was developed. **Chapter 6** then continues with assessment of the angular joint stiffness affect in full soil-tunnel lining model, by considering measured surface settlement and tangential bending moment of a case study. The three dimensional model are carried out with fast tunnel excavation method. The well-known Mohr Coulomb soil model is adopted to model seven layers of soil properties. In particular, it has been shown that the angular joint stiffness model could improve the variation of bending moment predictions in tunnel lining. Finally, **Chapter 7** summarizes the work present, arriving at conclusions and providing recommendations for future research.

REFERENCES

Abaqus 6.10.(2010). *User's manual*. Hibbitt, Karlson and Sorenson, Inc.Pawtucket, RI, USA

Abbasi, N. (2007). Finite Difference Approach for Consolidation with Variable Compressibility and Permeability. *Computers and Geotechnics*. 34: 41-52.

ACI Committee 318.(1999). *Building Code Requirements for Structural Concrete and Commentary (ACI 318-99),* American Concrete Institute, Detroit, MI.

Albertyn, H.L., Haas, T.N. and Dunaiski, P.E. (2014). Accounting for moment-rotation behaviour of connections in portal frames. *Journal of the South African Institution of Civil Engineering.* 56 (1)

Arnau, O. and Molins, C. (2011). Experimental and Analytical Study of the Structural Response of Segmental Tunnel Linings based on an In Situ Loading Test. Part 2: Numerical simulation. *Tunnelling and Underground Space Technology*, *26*(6), 778–788.

Arnau, O. and Molins, C. (2012). Three Dimensional Structural Response of Segmental Tunnel Linings. *Engineering Structures*, *44*, 210–221.

ASCE Task Committee on Concrete and Masonry Structure (1982). State of the art Report on finite Element Analysis of Reinforced Concrete, *ASCE.*

Bakhshi, M. (2015) Design of Segmental Tunnel Linings for Serviceability Limit State. Presentation for *AASHTO SCOBS T-20: Technical Committee for Tunnels.* New York.

Bakker, K.J. (2000). *Soil retaining structures, Development of models for structural analysis.* Taylor Francis. Rotterdam:Balkema

Bakker, K.J. (2003). Structural Design of Lining for Bored Tunnels in Soft Ground. *HERON* 48(1): 33-63. ISSN 0046-7316

Bathe, K.J.(1996). *Finite Element Procedures,* Prentice-Hall, New Jersey

Besseling, J.F. (1975). *Stiffness and Strength 2* (in Ducth). Oosthoek, Scheltema & Holkema.

Bickel, J.O., Kuessel, T.R. and King, E.H. (1996). Soft Ground Tunnel Support and Lining. *Tunnel Engineering Handbook; 2nd Edition*, Chapman and Hall, New York.

Bilotta, E., Ph, D. and Russo, G. (2013). Internal Forces Arising in the Segmental Lining of an Earth Pressure Balance-Bored Tunnel, (October), 1765–1780.

Blom, C. B. M. (2002). *Design Philosophy of Concrete Linings for Tunnels in Soft Soils* Ph.D. Thesis. Delft University, Netherlands.

Blom, C. B. M., van der Horst, E. J., and Jovanovic, P. S. (1999). Three-dimensional Structural Analyses of The Shield-Driven "Green Heart" Tunnel of The High-Speed Line South. *Tunnelling and Underground Space Technology*. 14(2): 217–224.

Bloodworth, A.G. (2002). Three-Dimensional Analysis of Tunnelling Effects on Structures to Develop Design Methods, Ph. D. Thesis, Oxford Univ.

Bobet, A. (2003). Effect of Pore Water Pressure on Tunnel Support During Static and Seismic Loading. *Tunnelling and Underground Space Technology*. 18: 377–393.

Broere, W. and Brinkgreve, R.B.J. (2002). Phased simulation of a tunnel boring process in soft soil. *Numerical Methods in Geotechnical Engineering.* Presses de l'ENPC/LCPC, pp. 529–536.

Cao, W.H., Shen, W.Q. and Yang, Z.H., (2010). Large cross-section & long-distance sheild tunnel design—Engineering design of Shanghai Yangtze River Tunnel. *China Architecture & Building Press, Beijing, China*. (in Chinese).

Caratelli, A., Meda, A., Rinaldi, Z., and Romualdi, P. (2011). Structural Behaviour of Precast Tunnel Segments In Fiber Reinforced Concrete. *Tunnelling and Underground Space Technology*. *26*(2): 284–291.

Cavalaro, S. and Aguado, A. (2011). Packer Behaviour under Simple and Coupled Stresses. *Tunn Undergr Space Technol.* 28:159–173.

Cavalaro, S. H. P., Blom, C. B. M., Walraven, J. C. and Aguado, a. (2011). Structural Analysis of Contact Deficiencies in Segmented Lining. *Tunnelling and Underground Space Technology*. *26*(6): 734–749.

Chaudhari, S. V. (2014). Comparative study on Exterior RCC Beam Column Joint Subjected to Monotonic Loading. *International Journal of Computer Applications.* 102(3): 34–39.

Chen, J. S. and Mo, H. H. (2009). Numerical study on Crack Problems in Segments of Shield Tunnel Using Finite Element Method. *Tunnelling and Underground Space Technology*. *24*(1): 91–102.

Do, N.A. (2014). *Numerical analyses of segmental tunnel lining under static and dynamic loads*. PhD Thesis. Civil Engineering. INSA de Lyon. English. Hanoi, Vietnam.

Do, N. A., Dias, D., Oreste, P. and Djeran-Maigre, I. (2013a). 2D Numerical Investigation of Segmental Tunnel Lining Behavior. *Tunnelling and Underground Space Technology*. 37: 115–127.

Do, N.-A., Dias, D., Oreste, P. and Djeran-Maigre, I. (2013b). Three-dimensional Numerical Simulation for Mechanized Tunnelling in Soft Ground: The Influence of The Joint Pattern. *Acta Geotechnica*, 9(4): 673–694.

Duddeck, H. (1980). Empfehlungen zur Berechnung yon Tunneln im Lockergestein (in German). *Bautechnik*. 10: 349-356.

Duddeck, H., (1988). Guidelines for the Design of Tunnels (ITA WG 2 report). *Tunnelling and Underground Space Technology*. 3(3): 237–249.

Duddeck, H. and Erdmann, J. (1985).Structural design models for tunnels. *Underground Space*, 9: 5-6.

Einstein, H. (1979). Simplified Analysis for Tunnel Supports. *Journal of Geotechnical Engineering Division* 105 (GT4), 499–518.

El Naggar, H. and Hinchberger, S. D. (2008). An Analytical Solution for Jointed Tunnel Linings in Elastic Soil or Rock. *Canadian Geotechnical Journal*, 45(11): 1572–1593.

El Naggar, H. and Hinchberger, S. D. (2012). Approximate Evaluation of Stresses In Degraded Tunnel Linings. *Soil Dynamics and Earthquake Engineering*, 43: 45–57.

Franzius, J.N. (2004). *Behaviour of buildings due to tunnel induced subsidence.* PhD Dissertation, Imperial College, London, UK.

Franzius, J. N. and Potts, D. M. (2005). Influence of Mesh Geometry on Three-Dimensional Finite-Element Analysis of Tunnel Excavation. *International journal of geomechanics*. 5(3): 256-266.

Gladwell, G.M.L. (1980). *Contact problems in the classical theory of elasticity*. Sijthoff & Noordhoff International Publishers B.V. The Netherlands

Gerstle, K H (1988). Effect of connections on frames. *Journal of Constructional Steel Research*. 10:241-267.

Hashash, Y., Tseng, W.S. and Krimotat, A., (1998). Seismic Soil-Structure Interaction Analysis for Immersed Tube Tunnels Retrofit. *Proc. Geotechnical Earthquake Eng.Soil Dyn. III*, 2, 1380–1391.

Hashimoto, T., Ye, G. L., Nagaya, J., Konda, T., and Ma, X. F. (2009).Study on earth pressure acting upon shield tunnel lining in clayey and sandy grounds based on field monitoring. *Proc., Geotechnical Aspects of Underground Construction in Soft Ground.* C. W. W. Ng, H. W. Huang, and G. B. Liu, eds., Taylor and Francis, London, 307–312.

Hefny, a. M. and Chua, H. C. (2006). An Investigation into the Behaviour of Jointed Tunnel Lining. *Tunnelling and Underground Space Technology*. 21(3-4): 428.

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

Hudoba, I. (1997). Contribution to Static Analysis of Load-bearing Concrete Tunnel Lining Built by Shield-driven Technology. *Tunnelling and Underground Space Technology*. 12(1): 55–58.

International Tunneling Association. (1988). Guidelines for the Design of Tunnel. *Tunneling and Underground Space Technology*. 5: 237-249.

International Tunnel Association (ITA) Working Group 2. (2000). International Tunnelling Association Guidelines for The Design of Shield Tunnel Lining. *Tunnelling and Underground Space Technology*. 15(3): 303－331.

Janssen, P. (1983). *Tragverhalten von Tunnelausbauten mit Gelenktübbings.* Report-No. 83–41 University of Braunschweig, Department of Civil Engineering, Institute for Structural Analysis.

Kachanov, L.M. (1958). On the time to failure under creep condition. Izv AN SSSR Otd Tekhn Nauk. 8: 26–31.

Kasper, T., Meshke, G. (2004). A 3D finite element simulation model for TBM tunnelling in soft ground. *International Journal for Numerical and Analytical Methods in Geomechanics*. 1 (28): 1441–1460.

Kasper, T and Meschke, G., (2006). A Numerical Study of the Effect of Soil and Grout Material Properties and Cover Depth in Shield Tunnelling. *Computers and Geotechnics*. 33: 234–247.

Kim, S-R. (2008). Some Experience From The Soft Ground Tunnelling In Urban Area. Seminar on *The State-of-the-art Technology and Experience on Geotechnical Engineering in Korea and Hong Kong.* Geotechnical Division, The Hong Kong Institution of Engineers. 71-109.

Klappers, C., Grübl, F., Ostermeier, B. (2006). Structural Analyses of Segmental Lining − Coupled Beam and Spring Analyses versus 3D FEM Calculations with Shell Elements. *Tunnelling and Underground Space Technology.* 21(3-4): 254-255.

Koizumi, A. and He, C.(2000). Dynamic behavior in longitudinal direction of shield tunnel located at irregular ground with considering effect of secondary lining. In: *12 World Conference on Earthquake Engineering*, Auckland, New Zealand.

Koyama, Y. (2003). Present status and technology of shield tunneling method in Japan. *Tunnelling and Underground Space Technology, 18*(2-3), 145–159. doi:10.1016/S0886-7798(03)00040-3

Kruger, T. S., Van Rensburg, B. W. J. & Du Plessis, G. M. (1995). Non-linear analysis of structural steel frames. *Journal of Constructional Steel Research,* 34(2-3): 285-206.

Kyowa (2015). Resistance Change of Strain Gauge Bonded to Curved Surface. *Kyowa Electric Instrument.* http://www.kyowa-ei.com/eng/technical/notes/technical_note/resistance_change.html

Lambrughi, A., Rodríguez, L.M., Castellanza, R. (2012). Development and validation of a 3D numerical model for TBM–EPB mechanised excavations. *Comput. Geotechnics*. 40: 97–113.

Lee, K. M. and Ge, X. W. (2001). The equivalence of a jointed shield-driven tunnel lining to a continuous ring structure. *Canadian Geotechnical Journal, 38*(3), 461–483.

Lee, K. M. R., Hou, X. Y., Ge, X. W. and Tang, Y. (2001). An analytical solution for a jointed shield-driven tunnel lining. *International Journal for Numerical and Analytical Methods in Geomechanics.* 25, 365–390.

Leonhardt F. and Reimann H. (1965). "Betongelenke – Versuchsbericht, Vorschlaege zur Bemessung und kontruktive Ausbildung: *Concrete hinges: Recommendations for structural analysis and design*. Deft. Berlin.

Liao, S.M., Peng, F.L. and Shen, S.L., (2008). Analysis of shearing effect on tunnel induced by load transfer along longitudinal direction. T*unnelling and Underground Space Technology.* 23: 421–430.

Liu, J.H. and Hou, X.Y. (1991). Shield-driven tunnels. *China Railway Press, Beijing, China.* 152-303 (in Chinese)

Loganathan, N. and Poulos, H. G. (1998). Analytical prediction for tunneling-induced ground movement in clay. *J. Geotech. Geoenviron. Engng.* 124(9): 846–856.

Lui, E. M. & Chen, W. F. (1987). Steel frame analysis with flexible joints. *Journal of Constructional Steel Research*. 8:161-202

Luttikholt, A. (2007). *Ultimate Limit State Analysis of a Segmented Tunnel Lining - Results of Full-scale Tests Compared to Finite Element Analysis.* Master Thesis. Delft University of Technology. Delft.

Menzies, B. (1997). Applying modern measures. *Ground Engineering*. 22-23.

Merritt, J.L., Monsees, J.E., Hendron, A.J. (1985). Seismic design of underground structures. In: Mann, C.D., Kelley, M.N. (Eds.), *Proceedings of the Rapid Excavation and Tunneling Conference*, Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, NY. 104–131.

Mo, H.H. and Chen, J.S.(2007). Study on inner force and dislocation of segments caused. *Tunneling and Underground Space Technology*.tust.2007.06.007

Mo, H. H. and Chen, J. S. (2008). Study on inner force and dislocation of segments caused by shield machine attitude. *Tunnelling and Underground Space Technology*. *23*(3): 281–291.

Mohamad, H. (2008). *Distributed Optical Fibre Strain Sensing of Geotechnical Structures,* Ph.D. Thesis. University of Cambridge.

Mohamad, H., Bennett, P. J., Soga, K., Mair, R. J., Lim, C.-S., Knight-Hassell, C. K. and Ow, C. N. (2007). Monitoring tunnel deformation induced by close-proximity bored tunnelling using distributed optical fiber strain measurements. *Proc. 7t Int. Symp. on Field Measurements in Geomechanics,* Boston.

Molins, C. and Arnau, O. (2011). Experimental and analytical study of the structural response of segmental tunnel linings based on an in situ loading test. *Tunnelling and Underground Space Technology*.26(6): 764–777.

Monsees, J.E. (1997). Soft Ground Tunneling. *Tunnel Engineering Handbook*. Bickel, J.O., Kuesel, T.R., King, E.H. 2nd Edition. Chapman and Hall. New York.

Morgan, H.D.(1961). A contribution to the analysis of stress in a circular tunnel. *Géotechnique*. 11 (1): 37–46.

Möller, S. (2006). *Tunnel induced settlements and structural forces in linings*. *Universitat Stuttgart, Mitteilung.* Ph.D. disertation, Stuttgart University.

Möller, S., Vermeera, P., and Bonnierb, P. (2003). A fast 3D tunnel analysis, *Second MIT Conference on Computational Fluid and Solid Mechanics*.1–4. Retrieved from http://www.uni-stuttgart.de/igs/content/publications/3Dtunnelanalysis.pdf

Mroueh, H. and Shahrour, I. (2003). A full 3-D finite element analysis of tunneling–adjacent structures interaction. *Computers and Geotechnics*. *30*(3): 245–253.

Mroueh, H. and Shahrour, I. (2008). A simplified 3D model for tunnel construction using tunnel boring machines. *Tunnelling and Underground Space Technology*. *23*(1): 38–45.

Muir Wood, A.M. (1975). The circular tunnel in elastic ground. *Géotechnique.* 25(1): 115–127.

Murayama, S. (1968). Earth pressure on vertically yielding section in sand layer (in Japanese). *Disaster Prevention Research Institute Annuals*, Kyoto University.11B: 123–138.

Namazi, E., Mohamad, H., Hong, A.K.B., Hajihassani, M., Jusoh, S.N. and Abad., S.V.A.N.K. (2012). Ground behaviour around a tunnel using various soil models. E*lectronic Journal Geotechnics Engineering (EJGE).* 17: 609-621

Nishikawa, K. (2003). Development of a prestressed and precast concrete segmental lining. *Tunnelling and Underground Space Technology*. 18(October 2002): 243–251.

Ohta, H., Shiotani, T., Sugihara, K., Hashimoto, T. and Nagaya, J. (1997). Consideration of Design Earth Pressure for Shield Tunnel Based on Measurement. *Proc. of Tunnel Engineering,* JSCE. Vol.9. pp.37–42. (in Japanese)

Osborne, N.H, Knight Hassell, C., Tan, L.C. and Wong. R. (2008). A review of the performance of the tunnelling for Singapore’s circle line project. *World Tunnel Congress 2008 - Underground Facilities for Better Environment and Safety*. India

Park, K. H. (2004). Elastic Solution for Tunneling-Induced Ground Movements in Clays. *Int. J. Geomech.* 4(4): 310–318.

Peck, R. B., Hendron, A.J. and Mohraz, B., (1972). State of the art of soft ground tunnelling. In: *Proceedings of the Rapid Excavation and Tunnelling Conference.*Chicago, IL, 1: 259–286.

Prinzl, F. and Gomez, A.R.A. (2001). TBM tunnel construction for the Bangkok RT: tunnelling through station Boo. *Singapore conference*.

Rabotnov, Y.N. (1969). *Creep problems in structural members.* North-Holland, Amsterdam.

Sagaseta, C. (1987). Analysis of Undrained Soil Deformations due to Ground Loss. *Geotechnique*. 37(3):301-320.

Schmidt, B. (1969). *Settlements and ground movements associated with tunnelling in soil.* Ph.D. thesis, University of Illinois.

Schmidt, B. (1984) Tunnel lining design – Do the Theories Work? *Proceedings, Australia/New Zealand Geomechanics Conference.* Perth, Western Australia.

Schulze, H. and Duddeck, H. (1964). Spannungen in schildvorgetrieben tunneln. *Beton and Stahlbetonbau.* 59(8): 169–175.

Shahrour, I., Khoshnoudian, F., Sadek, M. and Mroueh, H. (2010). Elastoplastic analysis of the seismic response of tunnels in soft soils. *Tunnelling and Underground Space Technology*. 25(4): 478–482.

Shalabi, F. I., Cording, E. J. and Paul, S. L. (2012). Concrete segment tunnel lining sealant performance under earthquake loading. *Tunnelling and Underground Space Technology*. 31: 51–60.

Son, M. and Cording, E.J. (2007). Ground-liner interaction in rock tunneling. *Tunneling and Underground Space Technology*. 22: 1–9.

Suzuki, M., Kamada, T., Nakagawa, H., Hashimoto, T. and Satsukawa,Y. (1996). Measurement of earth and water pressure acting on the great depth shield tunnel segments. *Geotechnical aspects of underground construction in soft ground*, IS-London, Mair & Taylor (eds). Balkema, pp. 613–619.

Tang, Y. (1988). *The mechanism study of the staggering assembly of shield-driven tunnel.* M. Phil. Thesis, Department of Geotechnics, Tongji University, China (in Chinese).

Terzaghi, K. (1950). Geologic aspects of Soft Ground Tunnelling. Chapter 11 in *Applied Sedimentation*. R. Task and D.Parker, eds. New York: John Wiley & Sons.

Teachavorasinskun, S. and Chub-uppakarn, T. (2010). Influence of segmental joints on tunnel lining. *Tunnelling and Underground Space Technology*. *25*(4): 490–494.

Timoshenko, S.P. and Gere, J.M. (1936). *Theory of Elastic Stability*. McGraw-Hill, Kogakushi ltd.

Vermeer, P., Bonnier, P. G. and Möller, S. C. (2002). On a smart use of 3D-FEM in tunnelling. *Numerical Models in Geomechanics Proceedings of the 8th International Symposium NUMOG VIII*.

Verruijt, A. (1997). A Complex Variable Solution for A Deforming Circular Tunnel in An Elastic Half-Plane. *International Journal for Numerical and Analytical Methods in Geomechanics*. 21:77–89.

Wang, L-Z., Wang, Z., Li, L-L. and Wang. J-C. (2011). Construction behavior simulation of a hydraulic tunnel during standpipe lifting. *Tunnelling and Underground Space Technology.* 26: 674–685

Wang, Z., Wang, L., Li, L. and Wang, J. (2014). Failure mechanism of tunnel lining joints and bolts with uneven longitudinal ground settlement. *Tunnelling and Underground Space Technology*. 40: 300–308.

Xiaochun, Z., Wei, Z., Zhengrong, H. and Yuewang, H. (2006). Effect of joint structure on joint stiffness for shield tunnel lining. *Tunnelling and Underground Space Technology*. 21(3-4): 407–408.

Yanzhi, Y., Weiwei, Z., Jianwei, W. and Zhihao, Y. (2014). Three-dimensional orthotropic equivalent modelling method of large-scale circular jointed lining. *Tunnelling and Underground Space Technology*. 44: 33–41.

Yuan, Y., Bai, Y. and Liu, J. (2012). Assessment service state of tunnel structure. *Tunnel. Under. Space. Tech*. 27: 72–85.

Zienkiewicz. O.C. and Taylor. R.L. (2005). *The Finite Element Method Set*, Butterworth-Heinemann, New York.