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, $k_{\omega}$. $M_R$ was in the range of 0.132 - 0.85 for pin-roller and 0.62 for pin-pin. The $k_{\omega}$ of dual-joints for pin-pin conditions was 6000 to 7000 kNm/rad and $k_{\omega}$ 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 pergerakan 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, pergerakan bentuk yang kompleks pada penghubung segmen masih belum difahami sepenuhnya. Adalah penting untuk memeriksa kekuatan sendi bersudut memandangkan pengkajian sebelum ini mengambil kira sendi penghubung mempunyai satu nilai yang malar sedangkan ia sebenarnya berubah secara tidak selanjar. Kajian ini mengkaji kekuatan 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 menunggak melintang menegak yang disokong oleh dua keadaan sempadan yang berbeza untuk mendapatkan faktor pengurangan momen, $M_R$ dan kekuatan sendi bersudut, $k_{\omega}$. $M_R$ adalah di antara 0.132 – 0.85 untuk pin-rola dan 0.62 untuk pin-pin. $k_{\omega}$ untuk kajian dwi-terhubung bagi keadaan pin-pin ialah 6000 ke 7000 kNm/rad dan $k_{\omega}$ 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 didapat bahawa model pelapik segmen terowong bersama kekuahan 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 kekuukan 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 kekuukan sendi bersudut tidak selanjar telah tercapai melalui kajian ini.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td>ii</td>
<td></td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iii</td>
<td></td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iv</td>
<td></td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>vi</td>
<td></td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
<td></td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
<td></td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiv</td>
<td></td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xxvii</td>
<td></td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>xxix</td>
<td></td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xxxiv</td>
<td></td>
</tr>
</tbody>
</table>

1 INTRODUCTION 1

1.1 Background 1
1.2 Problem Statement 3
1.3 Objectives 5
1.4 Scope of Study 6
1.5 Significant of Study 7
1.6 Hypotheses 8
1.7 Thesis Outline 8

2 LITERATURE REVIEW 10

2.1 Introduction 10
2.2 Tunnelling-Induced Ground Movements 14
2.3 Soil-Tunnel Interaction 16
2.4 Tunnel Lining Design 18
   2.4.1 Ultimate Limit State (ULS) 19
   2.4.2 Serviceability Limit State (SLS) design 22
   2.4.3 Recommended Distortion Ratios for Soft Ground Tunnels 26
2.5 Design Method in Shield – Driven Tunnels in Soft Ground 26
2.6 Influences of Segmental Joint on Internal Forces 29
   2.6.1 Existing Approach in Segmental Tunnel Lining Design 31
   2.6.2 The Theory of Joint Rotational Calculation in Segment's Joints 33
   2.6.3 Segment’s Joint Model in Various Tunnel Lining Investigation: Application in Geotechnical Engineering 43
2.7 Tunnel Joint Configurations Effects 59
2.8 Summary of Literature Review 61

3 METHODOLOGY 63

3.1 Introduction 63
3.2 Laboratory Testing Programme 65
3.2.1 Phase 1: Non-Jointed Pin-Roller (NJPR) 69
3.2.2 Phase 2: Non-Jointed Pin-Pin (NJPP) 71
3.2.3 Phase 3 and 4: Dual-Jointed Pin-Pin (DJPP) and Dual-Jointed Pin-Roller (DJPR) 73

3.3 Laboratory Testing Setup 76
3.3.1 Support Systems 76
3.3.2 Load on the Lining 79
3.3.3 Conducted Measurements 80
3.3.4 Experimental Conditions 89
3.3.5 Calculation Method 91

3.4 Numerical Model Development 93
3.4.1 General Steps in Finite Element Method 93
3.4.2 ABAQUS Program 95
3.4.3 Structural Modelling in ABAQUS 96
3.4.4 Verification of Model 97
3.4.5 Straight Beam with Uniform Distributed Load and Closed Form Solution 99
3.4.6 Curve Beam's Element Model and Unit Load Method Verification 100
3.4.7 Beam and Shell Model Verification 104
3.4.8 Description of FE Segmental Tunnel Model Development by Using Shell Element in ABAQUS 107
3.4.9 Summary for Numerical Analysis Model Development 120

3.5 3D Segmental Tunnel-Soil Model Development 121

3.6 Summary of Methodology 123

4 LABORATORY RESULTS AND DISCUSSION 125
4.1 Introduction 125
4.2 Non-jointed Testing Results 127
4.3 Dual-Jointed Segmental Tunnel Lining Results 132
4.4 Mechanical Behaviour of Segmental Tunnel Lining 137
   4.4.1 Moment Response of Non-Jointed Testing 137
   4.4.2 Moment Response of Dual-Jointed Testing 142
4.5 Superimpose Lining Response 147
4.6 Stress-Strain Results 153
4.7 Summary 154

5 NUMERICAL MODEL RESULTS 156
   5.1 Introduction 156
   5.2 Individual Segmental Tunnel Model Analyses 157
      5.2.1 Pin Support Model Designation 158
      5.2.2 Segment to Support Interactions Calibration Model 161
      5.2.3 Non-Jointed Pin-Pin Simulation Results 163
      5.2.4 Roller Support Model Designation 165
      5.2.5 Non-Jointed Pin-Roller Simulations Results 168
   5.3 Dual Jointed Segmental Tunnel Model Development 170
   5.4 Summary 176

6 3D SEGMENTAL TUNNEL-SOIL INTERACTION MODELLING 177
   6.1 Introduction 177
   6.2 Development of Full Soil-Tunnel Model 178
      6.2.1 Boundary Condition Assignment 180
      6.2.2 Model Discretization 181
      6.2.3 Interactions Model in Full Soil-Tunnel Model 182
      6.2.4 On The Initial Stress 184
      6.2.5 Sequential Construction Process in 3D FEM 185
      6.2.6 Simplified model 186
   6.3 Results and Discussions 189
## LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Failure mechanisms in tunnel lining design (ITA, 2000)</td>
<td>19</td>
</tr>
<tr>
<td>2.2</td>
<td>Mechanisms of limit state design in tunnel (ITA, 2000)</td>
<td>20</td>
</tr>
<tr>
<td>2.3</td>
<td>Standard specifications for tunnelling: Shield tunnels - for serviceability limit state (SLS) design by Japan Society of Civil Engineering (JSCE, 2007)</td>
<td>24</td>
</tr>
<tr>
<td>2.5</td>
<td>Distortion ratio in flexible ring linings design verification in variety of ground conditions (after Schmidt, 1984)</td>
<td>26</td>
</tr>
<tr>
<td>2.6</td>
<td>Summary of tunnel lining investigation with adopting various segment’s joint model</td>
<td>44</td>
</tr>
<tr>
<td>3.1</td>
<td>Segments and respective experimental tests</td>
<td>68</td>
</tr>
<tr>
<td>3.2</td>
<td>Listings of strain gauges and their position onto extrados and intrados of segmental linings</td>
<td>87</td>
</tr>
<tr>
<td>3.3</td>
<td>Plasticity material parameter used in ABAQUS</td>
<td>115</td>
</tr>
<tr>
<td>4.1</td>
<td>Summary of testing programme</td>
<td>126</td>
</tr>
</tbody>
</table>
4.2 Mid-section deflection in segments  

5.1 Moment-rotation from Test 2 of dual-jointed pin-pin test  

6.1 Details of the ground properties for every layer of soil model in MRT Singapore (Osborne et al., 2008)  

6.2 Details of the ground properties for every layer of soil model in MRT Singapore (simplified from Osborne et al., 2008)
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Tunnel lining definitions (Do et al., 2013b)</td>
<td>13</td>
</tr>
<tr>
<td>2.2</td>
<td>Acting forces in tunnel lining (a) Forces in tunnel lining: axial forces, $F_A$ and Hoop/Tangential forces, $F_h$, and (b) Stresses within tunnel with radius, $r$: axial stress, $\sigma_a$, radial stress, $\sigma_r$ and Hoop/Tangential stress, $\sigma_h$</td>
<td>14</td>
</tr>
<tr>
<td>2.3</td>
<td>Ground settlement through as a result of tunnelling (Kim, 2008)</td>
<td>16</td>
</tr>
<tr>
<td>2.4</td>
<td>Ultimate limit strength analysis in BS 8110-3: 1985: Chart no 47</td>
<td>21</td>
</tr>
<tr>
<td>2.5</td>
<td>Standard specifications for tunnelling in shield tunnels’ for serviceability limit state (SLS) design (JSCE, 2007)</td>
<td>23</td>
</tr>
<tr>
<td>2.6</td>
<td>Design methods in shield-driven tunnels in soft ground by International Tunnelling Association (ITA) (Duddeck, 1988)</td>
<td>27</td>
</tr>
<tr>
<td>2.7</td>
<td>Janssen model (a) reality and (b) model simplification (Janssen, 1983)</td>
<td>34</td>
</tr>
<tr>
<td>2.8</td>
<td>Moment-rotations relation model by considering the nonlinear stress distribution over the cross-section of flat surfaces (Gladwell, 1980)</td>
<td>36</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>2.9</td>
<td>Three stages of segment’s joints behavior: Tangential bending moments as a function of rotation in the segment’s joints (Blom, 2002)</td>
<td></td>
</tr>
<tr>
<td>2.10</td>
<td>Balanced of force at the joint area (Koyama, 2003)</td>
<td></td>
</tr>
<tr>
<td>2.11</td>
<td>(a) Concept of the additional rate of bending rigidity and (b) Concept of the efficient ratio of bending rigidity (Koyama, 2003)</td>
<td></td>
</tr>
<tr>
<td>2.12</td>
<td>Tunnel lining modelling (Koyama, 2003)</td>
<td></td>
</tr>
<tr>
<td>2.13</td>
<td>Modelling of (a) pedestal longitudinal support boundary and contact surfaces and (b) dual half jointed segment in meshed condition with seat pad (Chen and Mo, 2009)</td>
<td></td>
</tr>
<tr>
<td>2.14</td>
<td>(a) Segment joint (b) Set of stiffness joint characteristic consist of rotational spring ( K_\theta ), axial spring ( K_A ) and radial spring ( K_R ) (Do et al., 2013b)</td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Flowchart of research methodology</td>
<td></td>
</tr>
<tr>
<td>3.2</td>
<td>An individual segment lining ready to set up (a) a sample of segmental tunnel lining with tunnel dimensions (b) Close up view of precast segment tunnel lining, embedded with interlocking cushion transmission</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>Reinforcement arrangement in segment, (a) width cross section and (b) side view</td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>Dual-jointed segment cut into half, rearranged and joined with curved bolts</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>Test arrangement for segmental lining of Phase 1: NJPR</td>
<td></td>
</tr>
</tbody>
</table>
3.6 Schematic testing view of NJPR with load, support system and conducted measurement (a) cross section and (b) side view

3.7 Schematic testing view of NJPP with load, support system and conducted measurement (a) cross section and (b) side view

3.8 Test arrangement for dual-jointed tunnel lining

3.9 Schematic testing view of DJPP with load, support system and conducted measurement (a) cross section and (b) side view

3.10 Schematic testing view of DJPR with load, support system and conducted measurement (a) cross section and (b) side view

3.11 Triangular beams supports (a) pin and roller supports with two bolted holes to allow segment attachment, (b) rear view of steel support

3.12 Support interaction (a) a special manufactured design wall plug of 25 mm of diameter and 90 mm in length with 50 mm thread used to fasten the segment onto the steel support and (b) Segment has been setup with triangular beam roller support and wall plugs

3.13 In Phase 1 and Phase 4, view of pin end support system consist of triangular welded beam with wooden layers and I-beam steel, steel plates and anchored bolt to floor

3.14 In Phase 2 (NJPP) and Phase 3(DJPP), I-beam steel, steel plates and steel boxes with rod bolt anchor to the floor to restrained the support position in pin-pin support test

3.15 Load applied on segment
3.16 Schematic diagram for loading system

3.17 Strain gauge bonded on curved surface (Kyowa, 2015)

3.18 Strain gauge installation

3.19 Phase 1 (NJPR) strain gauges position, (a) segment’s extrados (SG1 to SG4), (b) segment’s intrados (SG11 to SG15) (Notes: All units are in mm)

3.20 Phase 2 (NJPP) strain gauges position, (a) segment’s extrados (SG1 to SG4) and (b) segment’s intrados (SG6 to SG9) (Notes: All units are in mm)

3.21 Phase 3 and phase 4 strain gauges position, (a) segment’s extrados (SG9 to SG14) and (b) segment’s intrados (SG1 to SG6)

3.22 Curved bolts with engrave surface for strain gauge mounted (a) at extrados of bolt and (b) at intrados of bolt

3.23 LVDT 1 and 2 at the midsection of segment

3.24 LVDT 4 and 5 mounted at pin end side, capture position from different view angle; LVDT 4 is used to measure lateral movement (if any) and LVDT 5 is to measure settlement of plywood (if any)

3.25 Translational measurement (a) LVDT 3 - measure lateral roller support movement in NJPR and DJPR (b) LVDT 3 in the pin side of NJPP and DJPP test

3.26 Strain vs load in test 3 of dual-jointed pin-pin test shown linear path of strain results in four strain gauges measurement at the mid-section of specimen, both intrados and extrados of segment at left (SG6 and SG8) and segment at right (SG11 and SG12), respectively
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.27</td>
<td>ABAQUS Stages of complete simulation (ABAQUS, 2010)</td>
</tr>
<tr>
<td>3.28</td>
<td>Flowchart of numerical model verification process</td>
</tr>
<tr>
<td>3.29</td>
<td>Straight beam model with closed form solution</td>
</tr>
<tr>
<td>3.30</td>
<td>Non-jointed segment in hogging condition with one point load and pin-roller support system</td>
</tr>
<tr>
<td>3.31</td>
<td>Deflection $\delta y$ of one point load segment with pin-roller support condition</td>
</tr>
<tr>
<td>3.32</td>
<td>Verified a non-jointed single segment modelling of pin roller support system, (a) horizontal displacement at roller end vs. load and (b) deflection at segment's mid-span vs. load</td>
</tr>
<tr>
<td>3.33</td>
<td>Verified a non-jointed single segment with pin-roller support system for 100 kPa, (a) horizontal displacement with segment span length, and (b) vertical displacement with segment span length</td>
</tr>
<tr>
<td>3.34</td>
<td>Verified a non-jointed single segment with pin-pin support system: Result vertical displacement vs. load</td>
</tr>
<tr>
<td>3.35</td>
<td>Segment with support model</td>
</tr>
<tr>
<td>3.36</td>
<td>Characteristics of shell elements</td>
</tr>
<tr>
<td>3.37</td>
<td>$K_c$ parameter obtained the ratio of the second stress invariant on the tensile meridian, $\sigma$ to that on the compressive meridian, at initial yield for value of the pressure invariant $p$</td>
</tr>
<tr>
<td>3.38</td>
<td>Compressive material behaviour in concrete damage properties model</td>
</tr>
<tr>
<td>3.39</td>
<td>Concrete - tension stiffening model</td>
</tr>
</tbody>
</table>
3.40 Hyperbolic surface of plastic potential in meridional plane
3.41 Shear retention parameter
3.42 Effect of mesh refinement on the nodal surface normal (after ABAQUS 6.12, Simulia, 2014)
3.43 Mesh generation for segment and support designation
4.1 Load vs. deflections measured in experimental testing of non-jointed tests
4.2 Lining after non-jointed pin-roller experiment (a) the ruptured segment (b) cracks at the critical section of segment (c) transversal crack easily seen in the intrados of lining in the mid span of segment
4.3 Global response of lining movement measure by 5 LVDTs (L1 to L5) in Phase 1: NJPR. A is pin support and B is roller support. Maximum load of Test 1 = 130 kN (T1), Test 2 = 360 kN (T2) and Test 3 = 420 kN (segment failed) (T3)
4.4 Global response of lining movement measure by LVDTs at 5 different positions in Phase 2: NJPP. A and B both are pin support. Maximum load of Test 1=130 kN (T1) and Test 2 =360 kN (T2)
4.5 Combination result of test 1, test 2 and test 3 for NJPR, (a) B-B’section, (b) E-E’ section (Note: Test 1 = 0 – 130 kN; Test 2 = 0 – 360 kN; Test 3 = 0 -422 kN)
4.6 Strain gauge results at segment midspan (C-C’) for non jointed pin-pin test (Phase 2) (Notes: T1= 0-130 kN; T2= 0 360 kN)
4.7 Load vs Deflection for dual-jointed segment lining
4.8 Global response of lining movement measure by LVDTs at 5 different positions in Phase 3: DJPP. A and B are pin support. Maximum load of Test 2 = 100 kN (T2) and Test 3 = 130 kN (T3) 134

4.9 Global response of lining movement measure by LVDTs at 5 different positions in Phase 4: DJPR. A is pin support and B is roller support. Maximum load of Test 1 = 30 kN (T1) and Test 2 = 30 kN (T2) 134

4.10 Strain gauge results at segment mid section (a) dual-jointed pin-pin test of C-C’ section, (b) dual-jointed pin-pin of D-D’ section, (c) dual-jointed pin-roller of C-C’ section and (d) dual-jointed pin-roller of D-D’ section (Note: Test 1 = 0 -30 kN; Test 2 = 0 -100kN; Test 3 = 0 -130 kN) 135

4.11 Curve bolt strain data 136

4.12 Non-jointed pin-roller testing: bending moment versus angle (in radians) for selected load phase in test 1, test 2, test 3 and for maximum load in each test 138

4.13 Tangential bending moment in phase 2, NJPP for P = 100 kN and maximum load in each test 139

4.14 Tangential bending moment for NJPP and NJPR (load, P = 100 kN) 140

4.15 Simplified loading diagram 141

4.16 Design calculation of segment with applied load, (a) Shear force diagram (SFD) and (b) Bending moment diagram (BMD) 142

4.17 Comparison graph of strain gauge results for curve bolt and lining in test 2 DJPP 144
4.18 Moment versus rotation of curve bolt joint 144
4.19 Moment versus angle (in radian) for selected load phase in both DJPP 146
4.20 Tangential bending moment of Test 1 and Test 2 DJPR at load, $P = 30$ kN 146
4.21 Comparison of DJPP and DJPR moment response 147
4.22 Load vs deflections, (a) results of pin-pin tests and (b) results of pin-roller tests 148
4.23 NJPP-DJPP moment response at load, $P = 30$ kN 150
4.24 Moment-rotations for non-jointed and dual-jointed pin-pin 151
4.25 NJPR-DJPR moment response 152
4.26 Moment-rotation for non-jointed and dual-jointed pin-roller 152
4.27 Stress-strain diagram 154
5.1 Load-deflection results of NJPP compared between experimental deflection and FE deflections, measured at 0.25 m from segment’s mid span 158
5.2 Configuration of boundary conditional both supports, (a) support A (left side of segment) and at support B (right side of segment), (b) definition of triangular support part with support configuration; SC-1: PIN at bottom part and fix rotation at triangle part, SC-2: ENCASTRE at bottom part and fix rotation at triangle part, SC-3: ENCASTRE at bottom and PIN at triangle, SC-4: PIN at bottom with PIN at the edge of end bottom plate, SC-5: PIN at bottom with ENCASTRE at the edge of end bottom plate, SC-6: PIN ALL and (c) tangential bending moment results 161
5.3 Various types of interactions for joining support and segment

5.4 Ties interaction joins segment and support (without meshing element, assigned at wall plug location similar like in laboratory testing configurations)

5.5 Comparison result of non-jointed pin-pin support condition (NJPP) and numerical modelling (FEM-NJPP) by means SC-1 support join configurations and Tie constraints in segment-support joint interactions (a) Tangential bending moment and (b) Segment deflection at segment angle

5.6 Configuration of boundary condition at support B, (a) definition of triangular support part with support calibration; SC-1: ROLLER at bottom part and fix rotation at triangle part, SC-2: ROLLER at all outer part of support B, SC-3: ROLLER at bottom and PIN at triangle, SC-4: PIN at bottom with PIN at the edge of end bottom plate, SC-5: PIN at bottom with ENCASTRE at the edge of end bottom plate, SC-6 : PIN ALL (b) tangential bending moment results and (c) deflection of segment results

5.7 NJPR segment deflection ($\delta y$) measured by LVDT at 0.25 m from centre line of segments’ mid span, obtained by ABAQUS modelling

5.8 Segment’s displacement measured at edge of roller side in experiment compared with horizontal segment’s (U1) result from FE calculations

5.9 Tangential bending moment for non-jointed pin-roller (NJPR) with respectively numerical modelling result (FEM-NJPR) for selected load conditions
5.10 Tangential bending moment for non-jointed pin-pin support condition (NJPP) and non-jointed pin-roller (NJPR) with respectively numerical modelling result (FEM-NJPP and FEM-NJPR) at load P=100 kN 170

5.11 Parametric model of segment to segment interactions with (a) Spring and Tie model, (b) Various properties of Hinge-model and (c) Hinge with nonlinear angular joint stiffness properties which show the closest moment response in dual-jointed segments 174

5.12 Comparison of mid-span deflection of NJPP and DJPP, testing and simulation results 175

5.13 Results of dual-jointed pin-pin (DJPP) and dual-jointed pin-roller (DJPR) for tangential bending moment vs angle of segment 175

6.1 3D model of soil-tunnel system with respective boundary condition and meshing 179

6.2 Tunnel lining model: combination of three staggered rings and all-at-once (3S+AAO) tunnel lining 180

6.3 Tunnel lining three staggered rings with all-at-once lining model (with total rings are equivalence to 19 rings) with and without assigned meshes 182

6.4 Tie constrain of surface to surface type is assigned at the ring’s joint 183

6.5 Soil-tunnel interaction “master-slaves” formulation with surface to surface contact algorithm with contact interaction property, penalty friction of tangential behaviour; ‘master’ was represent by red colour and ‘slave’ in purple 183
6.6 Segment’s joint assigned with hinge nonlinear at two
different wire link node-to-node position in tunnel lining

6.7 Simplified tunnel lining model with three successive
staggered rings at angle of 11.25° rotated clockwise with
9072 linear quadrilateral elements of type S4R

6.8 Simplified extended soil block model of 63 m width x
43 m height x 80 m length with four layers soil
properties assigned with 13448 solid element of 8-node
brick linear hexahedron (C3D8P) with trilinear
displacement and trilinear pore pressure

6.9 Surface settlement obtained by tunnel lining with segment’s
joint of (a) FEM-hinge-model (3S+AAO), (b) FEM-tie
model (3S+AAO) (as comparison; i.e., continuous ring
model) and (c) FEM-hinge-model of 19 rings (Note:
Surface settlement path used to obtained results are
presented with red line at the ground surface)

6.10 FEM results of three staggered and all-at-once tunnel
(3S+AAO) of hinge-model, tie-model and FEM results of
19 rings hinge-model compared to field data of Outer
bound tunnel (OT) at R530 –R540 of Circle Line Stage 3,
Serangoon Interchange Station, MRT Singapore (Note:
G2407, G2408 and G2419 were surface settlement that
measured by settlement marker on OT tunnel; and R530
and R540 were settlement reading at the specific rings;
measured by BOTDR)

6.11 Tangential bending moment of Ring 2 by means of FEM-
hinge-model (3S+AAO model), measured at the end of the
excavation process
6.12 Tangential bending moment of Ring 2 by means of FEM-tie-model (3S+AAO model), measured at the end of the excavation process 194

6.13 Tangential bending moment of Ring 10 by means of FEM-hinge-model (19 Rings model), measured at the end of the excavation process (plotted via excel) 194

6.14 Section forces observed in FEM-hinge-model (3S+AAO model) 195

6.15 Section forces observed in FEM-hinge-model (19 rings model) (plotted via excel) 196

6.16 Ultimate limit strength analysis in BS 8110-3: 1985: Chart no 47 197

A.1 Deflection in arch by Roark’s formulation 212

A.2 A pin-roller arch definition 212

A.3 Load position definition: Concentrated vertical load 214

A.4 Half of segment’s span of roller side (B) 215

A.5 Half of segment’s span of pin side (A) 216

B.1 Combination result of test 1, test 2 and test 3 for NJPR, (a) A-A’ section, (b) B-B’ section, (c) E-E’ section and (d) F-F’ section 218

B.2 Combination result of Test 1 and Test 2 for NJPP, (a) A-A’ section, (b) B-B’ section, (c) E-E’ section and (d) F-F’ section 220

B.3 Combination result of test 1 and test 2 for DJPP, (a) A-A’ section, (b) B-B’ section, (c) C-C’ section, (d) D-D’ section, (e) E-E’ section and (f) F-F’ section 222
B.4  Strain measurement DJPR (a) Test 1 (b) Test 2  223

C.1  Results of NJPR (a) Test 1, (b) Test 2 and (c) Test 3  225

C.2  Results of NJPP (a) Test 1, (b) Test 2 and (c) Test 3  227

C.3  Results of DJPR (a) Test 1 and (b) Test 2  228

C.4  Results of DJPP (a) Test 1, (b) Test 2 and (c) Test 3  229

D.1  Curved beam subjected to pure bending  230

D.2  Curve beam cross section nomenclature  231
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACI</td>
<td>American Concrete Institute</td>
</tr>
<tr>
<td>ASCE</td>
<td>America Society of Civil Engineers</td>
</tr>
<tr>
<td>BMD</td>
<td>Bending moment diagram</td>
</tr>
<tr>
<td>BS</td>
<td>British Standard</td>
</tr>
<tr>
<td>BOTDR</td>
<td>Brillouin Optical Time Domain Reflectometer (Optical Fibre Strain Analyser); tools to identify localized sections of differential strain distributed along an optical fibre</td>
</tr>
<tr>
<td>CDP</td>
<td>Concrete damage plasticity</td>
</tr>
<tr>
<td>DAUB</td>
<td>German Tunnelling Committee</td>
</tr>
<tr>
<td>DJPP</td>
<td>Dual-jointed pin-pin</td>
</tr>
<tr>
<td>DJPR</td>
<td>Dual-jointed pin-roller</td>
</tr>
<tr>
<td>EPB</td>
<td>Earth Pressure Balance tunnel type</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>ITA</td>
<td>International Tunnel Association</td>
</tr>
<tr>
<td>LTA</td>
<td>Land Transport Authority</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear variable differential transformer</td>
</tr>
<tr>
<td>JSCE</td>
<td>Japan Society of Civil Engineers</td>
</tr>
<tr>
<td>MC</td>
<td>Mohr Coulomb</td>
</tr>
<tr>
<td>MPC</td>
<td>Multi point constraints</td>
</tr>
<tr>
<td>MS</td>
<td>Malaysian Standard</td>
</tr>
<tr>
<td>NATM</td>
<td>New Austrian Tunnelling Method</td>
</tr>
<tr>
<td>NJPR</td>
<td>Non-jointed pin-roller</td>
</tr>
<tr>
<td>NJPP</td>
<td>Non-jointed pin-pin</td>
</tr>
<tr>
<td>OT</td>
<td>Outer Bound</td>
</tr>
<tr>
<td>ÖVBB</td>
<td>Österreichische Vereinigung für Betonund Bautechnik</td>
</tr>
</tbody>
</table>
(Working Group on Concrete in Tunnel Construction of the
Austrian Association for Concrete and Construction
Technology)

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCTL</td>
<td>Precast concrete tunnel lining</td>
</tr>
<tr>
<td>RC</td>
<td>Reinforced Concrete</td>
</tr>
<tr>
<td>SFD</td>
<td>Shear force diagram</td>
</tr>
<tr>
<td>SFRC</td>
<td>Steel fibre reinforced concrete</td>
</tr>
<tr>
<td>SG</td>
<td>Strain gauge</td>
</tr>
<tr>
<td>SGCB</td>
<td>Strain gauge of curve bolt</td>
</tr>
<tr>
<td>SLS</td>
<td>Serviceability Limit State</td>
</tr>
<tr>
<td>TBM</td>
<td>Tunnel Boring Machine</td>
</tr>
<tr>
<td>ULS</td>
<td>Ultimate Limit State</td>
</tr>
<tr>
<td>1D</td>
<td>One dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three dimensional</td>
</tr>
</tbody>
</table>
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Cross-sectional area</td>
</tr>
<tr>
<td>$b$</td>
<td>Width of segments</td>
</tr>
<tr>
<td>$c$</td>
<td>Soil cohesion</td>
</tr>
<tr>
<td>$d$</td>
<td>Unsupported excavation length</td>
</tr>
<tr>
<td>$e$</td>
<td>Distance from centroidal axis to neutral axis measured towards centre of curvature</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s modulus of the concrete</td>
</tr>
<tr>
<td>$EI$</td>
<td>Bending rigidity of tunnel lining</td>
</tr>
<tr>
<td>$F$</td>
<td>Flexibility ratio; flexural stiffness ratio between the ground and lining</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of joint interfaces</td>
</tr>
<tr>
<td>$I$</td>
<td>Moment of inertia of the tunnel lining with complete cross-section</td>
</tr>
<tr>
<td>$k$</td>
<td>Subgrade modulus</td>
</tr>
<tr>
<td>$K$</td>
<td>A set of joint stiffness that consists of flexural, axial and shear stiffness ($K_\theta$, $K_\delta$ and $K_r$)</td>
</tr>
<tr>
<td>$L$</td>
<td>Beam span length</td>
</tr>
<tr>
<td>$M$</td>
<td>Bending moment at $x$ due to actual loading</td>
</tr>
</tbody>
</table>
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

cr - Constant rotational stiffness

cri - Rotational stiffness in the segment’s joint

D1 - Distortional ring diameter of staggered segment tunnel

D2 - Distortional continuous ring diameter

Es - Young’s modulus of the soil

EL - Young’s modulus of the lining

Fn - Concentrated normal force at the joint

fc - Compressive strength of concrete at 28 days

fy - Steel yield strength properties

Gc - Shear modulus of intact concrete

Ĝ - Reduced shear modulus of cracked concrete

Ie - Effective equivalent lining stiffness

Ij - 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

$k_{\theta}$ - Rotational joint coefficient

$k_{\omega}$ - 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

$K_\theta$ - Lateral earth factor, $l - \sin \phi$

$K_{\theta}$ - Bending moment per unit length required to develop a unit rotation angle along the joint of the assembled segments/flexural joint stiffness/rotational spring

$K_\delta$ - 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

$K_r^\prime$ - Joint rotational stiffness

$K_{\theta}^\prime$ - Rotational stiffness

$K_a$ - Axial stiffness

$K_{sr}$ - Shear stiffness in radial direction

$K_{st}$ - Shear stiffness in tangential direction

$L_{vd}$ - 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

\( \nu_c \) - Poisson’s ratio of the concrete

\( \nu_L \) - Poisson’s ratio of the lining

\( \nu_s \) - Poisson’s ratio of the soil

\( \alpha \) - Angle of end segment to the midpoint of segment

\( \varepsilon \) - Strain

\( \zeta \) - 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)

\( \eta \) - Bending rigidity (stiffness) reduction factor

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

\( \theta \) - Angle of end segment to the point of interest

\( \varphi \) - Rotation angle around the ring centre axial axis \( (\varphi = 0 \text{ at the top of the ring}) \)

\( \sigma \) - Normal stress

\( \mu \) - Viscosity parameter / shear retention parameter

\( \psi \) - Dilation angle

\( \delta_i \) - Deflection at point interest, \( i \)

\( \Delta d_E \) - 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

\( \varepsilon_c \) - Compression strain
\( \varepsilon_{cu} \) - Ultimate compression strain
\( \varepsilon_{\text{max}} \) - Strain at which the parameter \( \mu \) reduces to zero
\( \theta_i \) - Rotation in the longitudinal joint \( i \)
\( \sigma_{b0}/\sigma_{c0} \) - Ratio of the strength in the biaxial state to the strength in the uniaxial state.
\( \sigma_{11} \) - Horizontal effective stress at a point specific
\( \sigma_2 \) - Radial ovalisation stress
\( \sigma_{33} \) - Effective stress as the vertical stress
# LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Analytical Analysis of Defining Deflection in Tunnel Lining</td>
<td>211</td>
</tr>
<tr>
<td>B</td>
<td>Results of Strain Gauge</td>
<td>217</td>
</tr>
<tr>
<td>C</td>
<td>Tangential Bending Moment Results</td>
<td>224</td>
</tr>
<tr>
<td>D</td>
<td>Segment Stress Distribution in Curved Member</td>
<td>230</td>
</tr>
</tbody>
</table>
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; Sagasea, 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


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


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


