EFFECTS OF STRESS-RATIO ON CRACK INTENSITY IN TUNNEL LINING

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DEDICATION

Dedicated to my late teacher/mentor Dr. Mahmood Arshad who motivated and inspired me before embarking on this journey of exploring the mysterious world.

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ABSTRACT

Tunnels after serving period over time needs to be inspected and maintained for them to perform without any structural failure and posing no hazard to the ongoing traffic. Structural health assessment of tunnel lining is carried out to investigate and mitigate the cause of defects in tunnel lining to ensure user safety. In conjunction with other tunnel liner defects, liner cracks were found to be considered as the most critical defect because of their potential to trigger subsequent defects and cause tunnel instability. Until now, the relationship between the developing anomalies in tunnel liner and their cause is still unclear and studies have addressed the cause of liner crack due to topography (in terms of overburden) on the stability of tunnel liner, especially for the varying overburden. The research mainly aims at understanding the effect of varying overburden on liner cracks. For this purpose, visual inspection was conducted and cracks in the tunnel liner were mapped and quantified and numerical analysis was performed to see the effect of varying topography (overburden) using parameter Stress-Ratio (*K*) on the intensity of liner in terms of state of stress-displacement using Induced Stress (IS) and Stress Concentration Factor (SCF) as a performance evaluation criteria's. The result from this study shows the shift in magnitude as well as position of crack density along different portions of tunnel liner with varying overburden depth. Moreover, based on the regional diversity of crack along longitudinal profile of tunnel for advances in tunnel assessment, tunnel was divided into zones based on the varying overburden with a view to identify varying intensity of crack on tunnel liner. The crack density increased with increasing overburden depth such as shallow zone is ranging from 0 to 96 m overburden depth with crack density (575 m to 628 m), while transition zone has range from 97 to 160 m having density (650 m to 700 m) whereas the overburden depth for deep zone with denser cracks at vertical wall and lower hance portion ranges from 161 to 204 m with crack density (704 m to 724 m). On the basis of results, the method applied for mapping and quantification of crack can serve inspectors and owners of tunnels for technical guidance to conduct health assessment of tunnel liner.

ABSTRAK

Terowong, selepas suatu tempoh masa operasi, perlu diperiksa dan diselenggara agar terowong ini dapat beroperasi tanpa kegagalan struktur dan tidak menimbulkan bahaya kepada lalu lintas. Penilaian kesihatan struktural pelapik terowong dilakukan untuk menyiasat dan mengurangkan punca kerosakan pada pelapik terowong bagi memastikan keselamatan pengguna. Bersama dengan kecacatan pelapik terowong lain, keretakan kapal didapati dianggap sebagai kecacatan paling kritikal kerana berpotensi mencetuskan kecacatan berikutnya dan menyebabkan ketidakstabilan terowong. Sehingga kini, hubungan antara anomali yang berkembang pada pelapik terowong dan penyebabnya masih belum jelas dan kajian mengenai penyebab keretakan pelapik terowong oleh faktor topografi (dari segi tanggungan atas) terhadap kestabilan pelapik terowong, terutamanya untuk taggungan atas yang berbeza-beza. Tujuan utama kajian ini adalah untuk memahami kesan tanggungan atas pelbagai pada retakan pelapik terowong. Untuk tujuan ini, pemeriksaan visual dilakukan dan retakan pada pelapik terowong dipetakan, diukur dan analisis numerik dilakukan untuk melihat kesan topografi yang berbeza-beza (tanggungan atas) menggunakan parameter nisbah tegasan *(K)* pada intensiti pelapik dari segi keadaan tekanan-anjakan menggunakan Induced Stress (IS) dan Stress Concentration Factor (SCF) sebagai kriteria penilaian prestasi. Hasil dari kajian ini menunjukkan perubahan magnitud serta kedudukan kepadatan retakan di sepanjang bahagian pelapik terowong pada kedalaman dan tanggungan atas yang berbeza-beza. Tambahan lagi, berdasarkan kepelbagaian keretakan di sepanjang profil membujur terowong, terowong dibahagikan kepada beberapa zon berdasarkan tanggungan atas yang bervariasi dengan tujuan untuk mengenal pasti pelbagai intensitas retakan pada pelapik terowong. Kepadatan retakan bertambah dengan peningkatan tangungan atas, di mana zon cetek berkisar antara kedalaman 0 hingga 96 m tanggungan atas, dengan kepadatan retakan (575 m hingga 628 m), sementara zon peralihan berkisar di antara 97 hingga 160 m dengan kepadatan (650 m hingga 700 m), manakala kedalaman tanggungan atas untuk zon dalam dengan retakan yang lebih padat pada dinding menegak dan bahagian *hance* yang lebih rendah berkisar antara 161 hingga 204m dengan kepadatan retakan (704 m hingga 724m). Berdasarkan hasil kajian, kaedah yang digunakan untuk pemetaan dan pengukuran retak ini dapat membantu pemeriksa dan pemilik terowong sebagai garis panduan teknikal untuk menjalankan kerja-kerja penilaian kesihatan pelapik terowong.

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LIST OF ABBREVIATIONS

NATM	-	New Austrian Tunnelling Method
2D	-	2-Deimentional
ASTM	-	American Society for Testing and Material
BEM	-	Boundary Element Method
BS-EN	-	British Standard European Norm
CCD	-	Charge-coupled Device
CIRIA	-	Construction Industry Research and Information Association
DEM	-	Digital Elevation Model
DEM	-	Discrete Element Method
DFN	-	Discrete Fracture Network
DXF	-	Drawing Interchange Format
EPBM	-	Earth Pressure Balance Machine
ER	-	Electrical Resistivity
ESRI	-	Environmental System Research Institute
FDM	-	Finite Difference Model
FEM	-	Finite Element Modelling
FHWA	-	Federal Highway Administration
FL	-	Fast Lane
GCP	-	Ground Control Point
GIS	-	Geographical Information system
GPR	-	Geological Point Radar
GSI	-	Geological Strength Index of Rock
H-d	-	Lower Hance
H-u	-	Upper Hance
IS	-	Induces Stress
ISRM	-	International Society of Rock Mechanics
JUPEM	-	Jabatan Ukur Dan Pemetaan Malaysia
KML	-	Keyhole Marked-Up Language
KMZ	-	Keyhole Marked-Up Language Zipped
NDT	-	Non-Destructive Test

RQD	-	Rock Quality Designation
SCF	-	Stress Concentration Factor
SCL	-	Sprayed Concrete Lining
SL	-	Slow Lane
T1	-	Tunnel 1
T2	-	Tunnel 2
TBM	-	Tunnel Boring Machine
UCS	-	Uniaxial Compression Strength
UCT	-	Universal Compression Test
UPV	-	Ultrasonic Pulse Velocity
UTM	-	Universal Testing Machine
V	-	Vault
VW	-	Vertical Wall

LIST OF SYMBOLS

σ_v	-	Vertical In-situ Stress
σ_h	-	Horizontal In-situ stress
σ_1	-	Major Principal Stress
σ_3	-	Minor Principal Stress
σ_2	-	Intermediate Stress
σ_n	-	Normal Stress
τ	-	Shear Strength
γ	-	Unit Weight of Rock
Z	-	Overburden Depth
K	-	In-situ Stress Ratio
σ_c	-	Intact Compressive Strength of Rock
E_h	-	Deformation Modulus of Rock
E_{rm}	-	Rock Mass Modulus
E_i	-	Intact Rock Modulus
μ	-	Poison's Ratio
D	-	Blasting induced Disturbance Factor
C	-	Cohesion Strength
φ	-	Internal Frictional Angle
Kis, cyl	-	Correction Factor
Λ	-	length to Diameter Ratio
$F_{is\ corr,\ cyl}$	-	In-situ Concrete Strength
f_c	-	Core Strength
f_{cm}	-	Mean Compressive Strength
f_{ck}	-	Characteristic Cylindrical Strength
E_{cm}	-	Young's Modulus
P	-	Compressive Strength
F	-	Failure Load
L_h	-	Shear Load
P_h	-	Horizontal Pressure

P_v	-	Vertical Pressure
A_p	-	Area of Piston
A_s	-	Gross Contact Area
A	-	Cross-Sectional Area
V	-	Pulse Velocity
T	-	Time Travel by pulse
σ_1	-	Post-Excavation Stress
σ^0	-	Pre-Excavation Stress

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The role of construction industry in the development of any country cannot be ignored. A nation's competitiveness can be seen and realized in terms of its infrastructure. Being a developing nation Malaysia has realized the role of construction industry not only from economic perspective but also in the quality-of-life standard of its people. The increasing interest and inevitable need of construction industry is due to vision 2020. According to which, Malaysia must maintain GDP of 6% by the end of 2020 to be recognized one of the developed nations. The main purpose of vision 2020 is to turn Malaysia into developed, strong, economically healthy and vigorous nation by the end of 2020, which has resulted in the execution of many civil infrastructures including tunnels in Malaysia [2].

Since construction industry depends on the development of new infrastructure, but the condition of existing aging structures cannot be overlooked in terms of loss of revenue and disruption to industry and life of people. In addition, construction of new structure will cost more than that of reinstatement of already built structure. Tunnel is one of the major structures of civilization and an attractive civil infrastructure because of its advantage of providing better transportation facilities. After providing services over years, deterioration or other defects in the tunnels especially on the tunnel lining can be seen due to lack or improper maintenance, delay in repair or mainly due to aging, which results in decrease in the integrity of tunnel lining caused by the deterioration which may leads to tunnel collapse [3]. Hence the collapse of tunnel will seriously damage the socio-economic development and life quality of people in the city [4].

The deterioration of tunnel lining which is manifested in lining anomalies such as: crack, water-leakage, spalling or delamination, rusting of re-enforcement etc. Among them the most serious and damaging anomaly is liner crack. To avoid these unwanted situations to happen a monitoring system is required to identify, monitor, and determine the types of anomalies and cause of their development in the tunnel lining. Therefore, to ensure the durability of the tunnel the structural health assessment of tunnel lining is needed during its service life [5].

For the abovementioned problem, many approaches have been established in the past regarding finding the cause of development of liner cracks and their respective effects on tunnel liner for the health assessment of tunnel such as movement of neighbouring slope, difference of temperature in environments, geological condition, construction deficiencies and topography [6-9]. Among them effect of varying topography, in terms of overburden especially in tunnels buried under shallow overburden, has widely been studied for development of crack to ensure stability of tunnel [7]. Many researchers have studied effect of varying topography on liner in terms of subsidence or settlements of crown mostly in shallow tunnels, but no study is available on effect of varying overburden on the intensity of crack along the longitudinal profile of tunnel.

Numerical modelling is best way to demonstrate real life physical phenomenon in an idealized and simplified conceptual model. Although, result generated from numerical simulation are not exactly accurate, but they give approximation and aids knowledge in the understanding of solution of existing problem. Contrary to the previous studies constructing numerical model using horizontal ground surface to see the effect of topography, better result can be achieved using real topography.

1.2 Problem Statement

The realization of vision 2020 mentioned above shows the importance of development of new and maintenance of the existing civil infrastructures. Since tunnel is one of the significant underground structures which support transportation of goods and people, but tunnel deteriorate over period of time. And out aging of existing tunnels are inevitably expensive in terms of loss to national asset and life quality of people. The main reason of tunnel deterioration is the development of liner cracks which may leads to tunnel collapse if not properly addressed. Therefore, to avoid disruption to industry the health condition of existing tunnels needs to be maintained for which we need health assessment system. Usually, concept of topography is used to know the inducement of crack but there is lack of understanding about the effect of varying topography on behaviour of crack in terms of its intensity on tunnel liner. Therefore, novel approach is needed to understand the influence of varying overburden on crack with a view to use it as a practical tool to facilitate health assessment of tunnel liner.

1.3 Significance of Study

This study has given fair amount of understanding about the crack intensity along with their cause of inducements on tunnel liner for which health monitoring has received significant attraction. Especially, the effect of real topography on the tunnel liner was limited in previous literature with respect to behaviour of crack in terms of intensity along longitudinal profile of tunnel. This study validates and illustrates the application of proposed diagnostic approach in health assessment of tunnel by considering the effect of real topography on tunnel liner. The methodology presented and finding from this study may kick start serious efforts in providing technical guideline to the tunnel inspector and tunnel owners for the subsequent technical and maintenance program to increase the lifespan of tunnel. The results from numerical analysis may also give fair amount of idea to designers and engineers, keeping role of varying overburden in mind, during design and construction phase of tunnel. The outcome of this research will provide comprehensive knowledge and idea that can be pursued for future study.

1.4 Research Aim and Objectives

The aim of this study is to gain understanding of crack density at shotcrete tunnel liner by incorporating the influence of varying overburden factor on the intensity of crack. To achieve this aim, following objectives were needed:

i. To identify the cracks on tunnel liner.

ii. To quantify intensity of cracks mapped from visual inspection.

iii. To validate the effect of varying overburden on crack intensity using numerical simulation.

1.5 Scope and Limitations

The multi-arch tunnel Meru (T1) and Menora (T2) located at Jelapang, Perak, Malaysia on the North-South Expressway was chosen as case study. They are situated in the Kledang Range which comprises of granitic igneous rock. The tunnels are 800 m long in length. Different section of tunnel along tunnel length were chosen depending upon the crack intensity. The tunnel was constructed employing New Austrian Tunnelling Method (NATM) and liner of tunnel was built out of shotcrete. Among different types of anomalies in tunnel, cracks were chosen focusing on the intensity of these cracks on different portions of shotcrete tunnel liner such as wall, hance and vault. Moreover, the effect of varying overburden is studied on the intensity of cracks along the length of tunnel. Arc-GIS software was utilized to get elevation data to construct real topographical surface. Effect of varying topography in terms of induced stresses, stress concentration, and total displacement was studied incorporating two-dimensional (2D) Finite Element software RS2, used for 2D numerical simulation using Mohr-Coulomb failure criteria.

Required data for research was gathered by conducting series of field inspection i.e., visual and technical, as-build drawing, previous reports, liaising with project contractors and project owners, personal contact to government departments and related professionals for topographic map, literature review and laboratory testing. Serious constraints were faced conducting tunnel inspection and getting design data pertaining to construction of tunnel due to confidentiality which resulted in unavailability of some data. In these cases, some assumptions were made based on engineering judgement during numerical analysis.

1.6 Structure of Thesis

The thesis has been structured and organized in five chapters as:

Chapter 1: gives the background of study and outlined the research problem. It also discussed the objectives needs to achieve the aim of study. And then it illustrates the significance of study as well as scope and limitations. It also provides overview of forthcoming chapters.

Chapter 2: This chapter aims at providing previous literature review regarding general concepts, theories, procedure, standards, and overview of software utilized in this study. In this chapter overview of tunnel application, anatomy, types of tunnel based on construction method along with tunnel supports and failure history of tunnel is also presented. Moreover, understanding of stresses around opening during underground excavation is also given. And then types of anomalies on tunnel liner as well as cause of their inducement is presented focusing on varying topography. And then this chapter discussed the background studies of health assessment, laboratory testing procedure and different method of numerical analysis along with software employed.

Chapter 3: In this chapter flow chart of research activities is demonstrated. Brief description of geology and study area is also provided which is chosen as case study. Then this chapter explains technical procedures, descriptions adopted to conduct field inspections and further discusses laboratory testing conducted on core samples. This chapter also illustrates the method employed to extract elevation data using Arc-

GIS. And it puts forward the input of collected data and then explains the step-by-step procedure adopted to develop numerical model at different section of tunnel along its length.

Chapter 4: This chapter discusses results obtained from field inspection, material testing in laboratory and 2D numerical modelling of tunnel at different section along tunnel length. Moreover, this chapter elaborate effect of varying overburden on the intensity of crack by comparing and validating results from field observation and numerical analysis. In addition, this chapter also shed light on the findings of this study.

Chapter 5: The chapter summarize the conclusions derived from findings and results of numerical analysis and field inspection. Moreover, this chapter briefs practical applicability of the study conducted. And at the end recommendations for further study and future work is stated.

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LIST OF PUBLICATION

Conference Proceedings

1- Amber Islam, Rini Asnida Abdullah, Izni Syahrizal Ibrahim, Goh Thian Lai, Haryati Awang. Evaluation of Structural Health Assessment of Existing Multi-Arch Tunnel Lining. In 2019 Proceeding of VCRES-2019 ISRM Specialized Conference on Rock Mechanics and Engineering for Sustainable Energy. ISBN: 978-604-913-909-3