UNIVERSITY OF SOUTHERN QUEENSLAND

# USING TOPOLOGY OPTIMISATION IN TUNNEL REINFORCEMENT DESIGN

A dissertation submitted by

**TIN NGUYEN**

B.Eng., Danang University of Technology, Vietnam, 2005

M.Eng, Asian Institute of Technology, Thailand, 2009

For the award of the degree of

**Doctor of Philosophy**

2015

# Dedication

*To my family*

# Abstract

In tunnel reinforcement design, having a suitable tool which is able to capture complex ground material and various tunnelling conditions is definitely significant. Since early stages of tunnelling engineering, empirical approaches using rock mass classification and accumulated experiences have been commonly used. Nevertheless, as developed from long-term accumulated knowledge in older projects, it is not always applicable to new ground conditions and also hardly guarantees a best design to be obtained. Analytical method is another tool to provide explicit calculations, however, its applications are limited to only some simple scenarios such as circular tunnel. It is also noted that these two approaches are only applicable to free-field conditions. Owing to the ability in modelling complex ground conditions with consideration of discontinuities or adjacent structures, numerical simulations has been constantly developing and applying in tunnel excavation design in the last decades. An appropriate incorporation of numerical analysis and optimisation techniques, if applicable, would provide a powerful tool for obtaining an optimal tunnel design.

In spite of effectiveness of topology optimisation theory, which is proved to work effectively in a broad range of engineering disciplines, its applications in geotechnical engineering and specifically in tunnelling design is fairly humble. Some research works have already attempted to incorporate topology optimisaton techniques in tunnel reinforcement design and proposed some initial achievements in the area. However, simple assumptions on the material models and modelling techniques of geomaterials and reinforcement materials have essentially limited its applications and practicality in a complicated structure like underground excavations.

This thesis explores the incorporation of topology optimisation methods in tunnel reinforcement design. The main focus of the study is to improve some critical shortcomings of the previous works on reinforcement optimisation and propose new optimisation algorithms in searching for the best distribution of reinforcement material.

As the first step in this study, material nonlinearities are accounted for in optimisation techniques to improve the linear elastic material model assumption of previous studies. Practical behaviours of material, hence, can be captured. The Bidirectional Evolutionary Structural Optimisation (BESO) method is extended to consider nonlinear material behaviour. An elastic perfectly-plastic Mohr-Coulomb model is utilised for both host ground and reinforced material. External work along the tunnel wall is considered as the objective function. Various *in situ* stress conditions with different horizontal stress ratios and different geostatic stress magnitudes are investigated through several examples. The outcomes show that the proposed approach is capable of improving tunnel reinforcement design. Also, significant difference in optimal reinforcement distribution for the cases of linear and nonlinear analysis results proves the importance of the influence of realistic nonlinear material properties on the final outcome.

Another serious shortcoming of the previous studies is that reinforced areas were modelled as homogenised isotropic elements. Optimisation results, therefore, do not clearly show reinforcement distributions, leading to difficulties in explaining the final outcomes. In order to overcome this deficiency, a more advanced modelling technique in which reinforcements are explicitly modelled as truss elements embedded in rock mass media is employed. Corresponding optimisation algorithm are proposed to seek for an optimised bolt layout. Also, a topology optimisation technique is employed to simultaneously optimise all bolt parameters including pattern for bolts, spacing between the bolts and size of the bolts. The external work along the opening is selected as the objective function with a constraint on volume of bolt. To demonstrate the capabilities of the methods, numerical examples of nonlinear material models are presented. Various tunnelling characters and geological conditions with presence of discontinuities in the host rock have been successfully investigated in numerous examples, showing the broad applicability and usefulness of the proposed approaches.

In reality, minimisation of certain displacements such as heave issues or ground displacements in shallow tunnel is sometimes of concern. Extending optimisation methods to capture these objective functions is crucial. A general displacement-based objective function is introduced with a constraint on a bolt volume. Sensitivity analysis is conducted and details on identification of necessary parameters are provided. Using the presented optimisation algorithm, an example on optimising bolt layout to minimise a heave function is performed. It is shown that the displacement-based objective function can be effectively captured by the proposed optimisation technique.

This study focuses on applying topology optimisation in tunnel reinforcement design to take advantage of both numerical analysis and optimisation methods. The presented techniques are applicable to any material models of host ground and reinforcements and provides clear and practical final outcomes. Using the proposed methods, all significant factors including geological conditions, construction sequences and tunnel characters can be taken into account to obtain an optimised reinforcement distribution. It is also demonstrated that various objective functions can be employed and usefully optimised by the methods. The obtained results proves that the optimisation techniques presented in this thesis are promising tools to reinforcement design of underground excavations.

# Certification of Dissertation

I certify that the idea, experimental work, results and analyses, software and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award.

Tin NGUYEN | Date

ENDORSEMENT

Dr. Kazem GHABRAIE, Principal supervisor | Date

Prof. Thanh TRAN–CONG, Co-supervisor | Date

# Acknowledgements

Firstly, my sincere thanks are extended to Prof. Thanh Tran-Cong for giving me an opportunity to pursue my PhD at the University of Southern Queensland (USQ), opening up a new and bright chapter of my academic career. His financial and academic support are also appreciated. I would like to express my profound gratitude to my principle supervisor, Dr. Kazem Ghabraie, for his invaluable supervision, fruitful discussions, useful writing corrections and inspirations during the period of my PhD research.

I owe this work to my dear parents. Their endless love, unconditional lifetime sacrifices and continued encouragements are invaluable sources that constantly keeps me move forward.

My sincere appreciations are due to my beloved wife for being beside me through the ups and downs, sharing many tough times in our personal life and especially giving a birth of our little daughter, Emma. Without her supportive encouragement, I have never made this to the end. Special thanks are also due to my lovely daughter for all much happiness she has brought to me during my period of intensive research.

I would like to extend my gratitude to all members of my parents-in-law's family, my brother, Thien, my sister-in-law, Nhung and my nephew, Duc Trong, for their warm love and selfless support.

The project was jointly funded by the University of Southern Queensland (USQ), Faculty of Health, Engineering and Surveying (FHES), and the Computational Engineering and Science Research Centre (CESRC). This financial support is gratefully acknowledged.

# Papers resulting from the Research

## Journal papers

1. **Nguyen, T.**, Ghabraie, K., and Tran-Cong, T. (2014). Applying Bi-directional Evolutionary Structural Optimisation method for tunnel reinforcement design considering nonlinear material behaviour. *Computers and Geotechnics,* 55, 57-66.
2. **Nguyen, T.**, Ghabraie, K., Tran-Cong, T., and Fatahi, B. (2015). Improving Rock Bolt Design in Tunnels Using Topology Optimisation. *International Journal of Geomechanics (accepted 9 Jan 2015).*
3. **Nguyen, T.**, Ghabraie, K., and Tran-Cong, T. (2015). Simultaneous pattern and size optimisation of rock bolts for underground excavations. *Computers and Geotechnics (accepted 10 Feb 2015).*

## Conference papers

1. **Nguyen, T.**, Ghabraie, K., and Tran-Cong, T. (2012). Tunnel Reinforcement Optimization for Nonlinear Material. *The 4th International Conference on Computational Methods (ICCM2012)*, Gold Coast, Australia, November 2012.

# Contents

# List of Figures

# List of Tables