

Zdenek Zizka

Stability of slurry supported tunnel face considering the transient support mechanism during excavation in non-cohesive soil



SFB 837
Interaktionsmodelle für den
maschinellen Tunnelbau

Schriftenreihe des Instituts für
Konstruktiven Ingenieurbau, Heft 2019-03

Doctoral Thesis

STABILITY OF SLURRY SUPPORTED TUNNEL FACE CONSIDERING THE TRANSIENT
SUPPORT MECHANISM DURING EXCAVATION IN NON-COHESIVE SOIL

submitted in fulfilment of the requirements for the degree of Doctor of Engineering
(Dr.-Ing.) to the Department of Civil and Environmental Engineering of the Ruhr-
Universität Bochum

BY

ING. ZDENEK ŽIZKA

Reviewers:

Prof. Dr.-Ing. Markus Thewes

Institute for Tunnelling and Construction Management, Ruhr-Universität Bochum (Germany)

Prof. Dr. Adam Bezuijen

Laboratory of Geotechnics, University of Gent (Belgium)

Date of submission: 16th October 2018

Date of oral examination: 13th February 2019

Schriftenreihe des Instituts für Konstruktiven Ingenieurbau

Herausgeber:
Geschäftsführender Direktor des
Instituts für Konstruktiven Ingenieurbau
Ruhr-Universität Bochum

Heft 2019-3

Zdenek Zizka

**Stability of slurry supported tunnel face
considering the transient support mechanism
during excavation in non-cohesive soil**

Shaker Verlag
Düren 2019

Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über <http://dnb.d-nb.de> abrufbar.

Zugl.: Bochum, Univ., Diss., 2019

Copyright Shaker Verlag 2019

Alle Rechte, auch das des auszugsweisen Nachdruckes, der auszugsweisen oder vollständigen Wiedergabe, der Speicherung in Datenverarbeitungsanlagen und der Übersetzung, vorbehalten.

Printed in Germany.

ISBN 978-3-8440-6940-2

ISSN 1614-4384

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Telefon: 02421 / 99 0 11 - 0 • Telefax: 02421 / 99 0 11 - 9

Internet: www.shaker.de • E-Mail: info@shaker.de

PREFACE

The present study was developed in my time as research assistant at the Institute for Tunnelling and Construction Management ("TLB") of the Ruhr-Universität Bochum.

My special thanks goes first to Prof. Dr.-Ing. Markus Thewes for his guidance of the thesis. Further, I want to thanks to Prof. Thewes for his intensive scientific support and the trust placed in me during my work at the institute. To Dr.-Ing. Britta Schoesser and deceased Prof. Dr.-Ing. habil. Tom Schanz, I want to thank for their intensive promotion and scientific leading of the "SFB 837 subproject A6", in frame of which, this thesis was developed. Additionally, I explicitly acknowledge Prof. Dr. Adam Bezuijen for his deep interest in my work, the countless and informative discussions, and his active participation in my examination. To Prof. Dr. Markus Knobloch I thank for his friendly willingness to take on the tasks of a non-specialist examiner.

Furthermore, I have to thank my colleagues at the TLB for outstanding years of co-working. Numerous discussions, sharing time together and mutual help when solving any problems were amazing. The same can be said to the colleagues from the Collaborative Research Center SFB 837. In particular, I thank to Dr.-Ing. Jakob K pferle for his collaboration on joint experiments conducted with the RUB tunnelling device. Another special thank goes to Dr.-Ing. Anna-Lena Hammer for countless discussions during the last phases of the thesis writing. Experimental investigation needs experimental devices. Therefore, I want to thank also to the technicians involved in the construction of the experimental equipment that I have used for the investigation in this thesis.

Additionally, the work of numerous students and the support of the student assistants has to be acknowledged here. Especially, I would like to thank to my student assistant Samy Tong for his invaluable help during development of this thesis.

A big thank goes also to my former colleagues from the company MTC - Maidl Tunnelconsultants GmbH & Co. KG where I had the pleasure to work simultaneously

during the time at the TLB. This developed thesis has significantly benefited from the practical knowledge I have obtained during my work in the company.

Last but not least, I thank to my parents for their endless support and encouragement for working abroad in Germany. Within the time in Bochum, I met a lot of great people among them also my girlfriend Gabriela. To her I want to express my deep thanks for always motivating me to finish this thesis.

Ruhr-Universität Bochum, October 2018

Zdenek Zizka

ACKNOWLEDGEMENTS

The German Research Foundation DFG (Deutsche Forschungsgemeinschaft) facilitated this research financially through subproject A6 “Locally transient face support within hydroshield excavation” as part of the Collaborative Research Center 837 “Interaction modeling in mechanized tunneling” at the Ruhr-Universität Bochum.

This support is gratefully acknowledged.

ABSTRACT

Tunnel face stabilization is one of the three key elements of the soft ground tunnelling. Slurry shields are known to be a reliable excavation method in non-cohesive soils under groundwater level. In such conditions, they can actively support the tunnel face while minimising of the support pressure fluctuations. Two fundamental conditions must be fulfilled to stabilize a tunnel face: A sufficient face support pressure in the excavation chamber and an efficient pressure transfer of slurry excess pressure onto the soil skeleton. At the time of introduction of the slurry shield, the theories to describe the pressure transfer were transferred from diaphragm wall technology, in which the bentonite slurry supports the open trench. In the past, however, increased pore water pressures above the hydrostatic level were measured in front of the tunnel face during excavation. The measurements could not be explained by the pressure transfer theories from diaphragm wall technology. The increased pore pressure significantly reduces the efficiency of the face support. It is expected that the increased pore pressures result from the continuous disturbance of the pressure transfer mechanism by rotating cutting tools at the tunnel face during excavation. The objectives of this thesis are to understand the consequences of simultaneous slurry penetration and tool excavation process at the tunnel face. A further aim is to characterize the pressure transfer and resulting tunnel face support efficiency for various combinations of slurry penetration and excavation scales.

Considering the state of the art of slurry face support and of face stability assessment, two hypotheses about the pressure transfer during slurry shield excavation resulting from the interaction between cutting tools and pressure transfer mechanism are formulated. Case A and Case B of the interaction at the tunnel face are introduced based on local comparison between slurry penetration and tool cutting depth. The Case A stands for higher cutting depth than slurry penetration depth, while Case B represents shallower cutting depth than slurry penetration depth. It is concluded that each case requires different approach of characterization due to repeated primary slurry penetration in Case A and slurry re-penetration in Case B. To obtain the basis for

the further comparison with slurry penetration scale, the typical relationship between cutting depth of a tool and the timespan between subsequent tool passing was determined from reference excavation projects. Following on this the slurry penetration was investigated experimentally. Time-dependent permeability of soil for slurry and slurry penetration depth were evaluated for the Case A of interaction. In contrast, the focus of the investigation for Case B was set on the distribution and development of pore pressure and effective stress inside and outside of slurry penetrated zone during the slurry penetration. The investigations for both cases were conducted using originally designed column tests. Case B was additionally investigated using the RUB tunnelling device. A transient FE seepage analysis utilizing the experimentally determined transient permeability coefficients for slurry was necessary to determine the pressure transfer in Case A due to mutual cutting tracks interaction. In Case B, the slurry stagnation gradient determined in the experiments could be directly transferred to the tunnel face conditions to assess the transfer due to presence of slurry re-penetration.

It is concluded that the pressure transfer efficiency in Case A is significantly reduced due to increased pore water pressures outside of slurry penetrated zone during excavation. The methods originating from diaphragm wall technology to predict pressure transfer are not valid in Case A. Based on the obtained results, it is recommended to conduct the excavation with a type of interaction according to Case B. Finally, an integrated approach for the design of minimal required slurry pressure to stabilize the tunnel face is suggested.

INDEX

Preface	I
Acknowledgements.....	III
Abstract	V
Index.....	VII
1. Introduction	1
1.1 Motivation.....	1
1.2 Problem statement and objectives.....	3
1.3 Methodology and structure.....	4
2. Face stability of slurry shield driven tunnels.....	7
2.1 Fundamentals of slurry shield tunnelling method	8
2.1.1 Slurry shield construction and application range	9
2.1.2 Fundamental requirements for the support medium and pressure.....	11
2.1.3 Cutting tools used in slurry shield tunnelling	12
2.2 Failure modes of the slurry supported tunnel face	14
2.2.1 Local failure modes	14
2.2.2 Global failure modes.....	15
2.3 Local stability assessment.....	15
2.4 Global stability assessment.....	16
2.4.1 Limit equilibrium solutions	17
2.4.2 Limit state solutions.....	19
2.4.3 Comparison and evaluation of the models	22

2.5	German safety concept for the face stability analysis.....	23
2.6	Practice oriented calculation of minimal support pressure in non-cohesive soils using Horn's failure mechanism	27
2.7	Conclusions about face stability assessment of slurry shield driven tunnels	34
3.	Slurry-soil interaction and the slurry pressure transfer	36
3.1	Basic properties of interacting materials.....	37
3.1.1	Definition of non-cohesive soils	37
3.1.2	Basic properties of bentonite slurries	38
3.2	Characterization of flow processes in soil by the theory of porous media..	47
3.2.1	Continuum approach of flow characterization in porous media	49
3.2.2	Capillary bundle approach of flow characterization in porous media	52
3.3	Fundamentals of suspension filtration and flow through porous media.....	55
3.3.1	General types of suspension filtrations	55
3.3.2	Standard blocking filtration (deep bed filtration)	57
3.4	Theories of support pressure transfer at the tunnel face	64
3.4.1	Theories not considering time factor	65
3.4.2	Theories considering time factor	76
3.4.3	Theories considering time factor and the interaction with cutting tools globalized over the entire tunnel face	81
3.5	Conclusion about state of the art of the slurry-soil interaction and the slurry pressure transfer	86
4.	Theoretical considerations concerning the adaptations of pressure transfer models.....	89
4.1	Case A - Tool penetration deeper than pressure transfer mechanism	91
4.2	Case B - Tool penetration shallower than pressure transfer mechanism	95
5.	Analysis of excavation scale	101
5.1	Analysis of tool layout on cutting wheels.....	103
5.2	Tool penetration and timespans between tool passes	104

6. Experimental investigations: Case A – shallow slurry penetration scale	109
6.1 Experimental set-up & methodology	109
6.2 Experimental programme and materials.....	113
6.3 Results and Interpretation	115
6.3.1 Experiments without back-pressure.....	115
6.3.2 Experiments with back-pressure	122
6.4 Comparison of tool cutting with slurry penetration scale for the Case A..	125
6.5 Summary of experimental investigation for the Case A.....	128
7. Experimental investigations: Case B – deep slurry penetration scale	131
7.1 Experimental set-up & methodology	132
7.1.1 Primary penetration of slurry	132
7.1.2 Re-penetration of slurry	134
7.1.3 Re-penetration of slurry with soil cutting – RUB Tunnelling device	137
7.2 Experimental programme and materials.....	139
7.2.1 Primary penetration and re-penetration.....	139
7.2.2 Re-penetration with soil cutting – RUB Tunnelling device.....	143
7.3 Results and Interpretation	145
7.3.1 Primary penetration of slurry within the column test	145
7.3.2 Re-penetration of slurry within the column test.....	157
7.3.3 Re-penetration with soil cutting – RUB Tunnelling device.....	163
7.4 Summary of experimental investigation for the Case B.....	170
8. Case A – Pressure transfer analysis and the implementation into tunnel face stability assessment	173
8.1 Methodology and the numerical models used in the pressure transfer analysis	173
8.1.1 Model for the parametric investigation of the tunnel face segmentation ..	174
8.1.2 Model for evaluation of the pressure transfer and simplified cutting wheel	179

8.1.3	Model for evaluation of the pressure transfer and realistic cutting wheel .	183
8.2	Results and interpretation for the pressure transfer analysis	185
8.2.1	Parametric study for investigation of the segmentation of the tunnel face	185
8.2.2	Investigation considering experimental results for slurry penetration and a simplified cutting wheel	186
8.2.3	Investigation considering experimental results for slurry penetration and a realistic cutting wheel	193
8.2.4	Comparison of the calculated pressure transfer with other theories ...	198
8.3	Face stability assessment for Case A	200
8.3.1	Face stability assessment for excavation with simplified and with realistic cutting wheels	200
8.3.2	Additional notes to the face stability in Case A.....	201
9.	Case B – Implementation of the experimental results into analytical face stability assessment	205
9.1	Conditions at the tunnel face during excavation and resulting model adaptation	206
9.1.1	Slurry penetration depth	206
9.1.2	Stagnation gradient development	208
9.1.3	Development of effective stress.....	213
9.2	Resulting adaptation of the face stability calculation model	214
9.3	Additional check of the self-bearing capacity of the wedge	217
9.3.1	Parametric study.....	218
9.3.2	Limitations of the additional check	219
10.	Recommendations for practice	221
10.1	Efficiency of the pressure transfer mechanism and measures to its increase.	221
10.2	Integrated design approach for the required face support pressure	224

10.2.1 Scenario with fixed parameters	225
10.2.2 Scenario without fixed parameters	230
11. Conclusion & outlook.....	231
References	XI
List of Figures	XXI
List of Tables	XXXI
List of Symbols	XXXV
List of Abbreviations	XLVII
Curriculum Vitae	XLIX
Appendix	LI