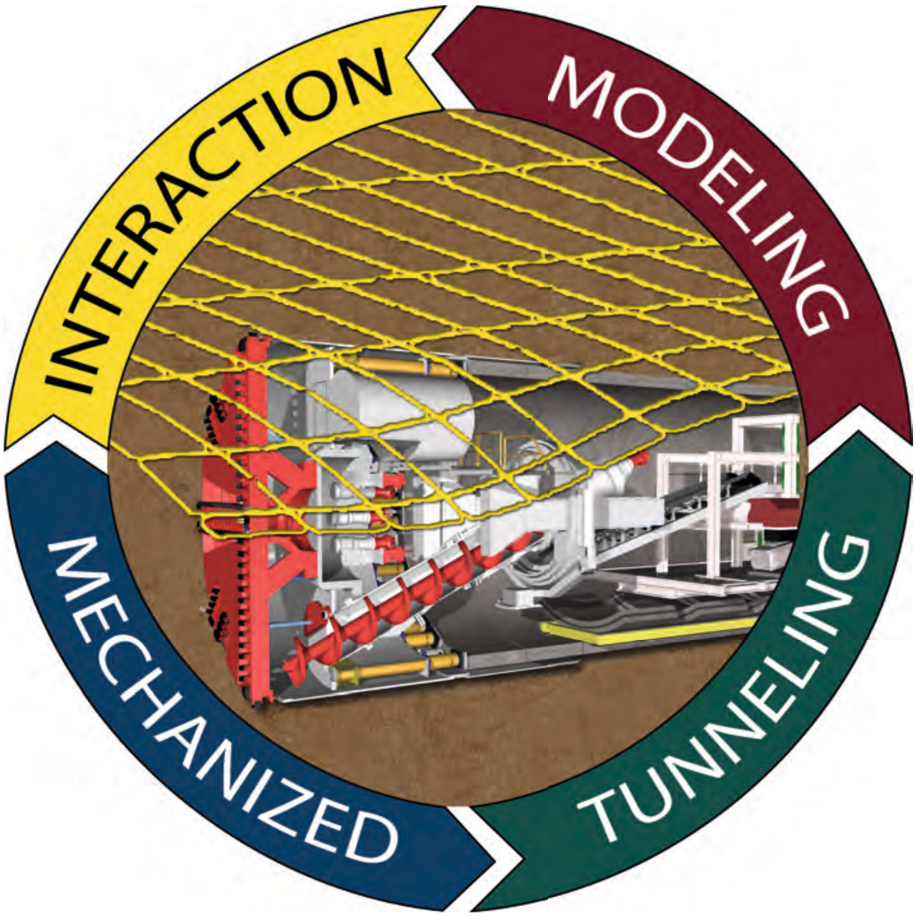
Collaborative Research Center 837

Interaction Modeling in Mechanized Tunneling



SFB 837 Brochure 2015

RUHR UNIVERSITY BOCHUM

CONTACT

COLLABORATIVE RESEARCH CENTER 837

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THE SFB 837 - INTERDISCIPLINARY FUNDAMENTAL RESEARCH IN TUNNELING

Mechanized Tunneling has proven itself as an economical and flexible construction method that continues to undergo a dynamic evolution process; shield diameters are constantly increasing, and the range of scenarios in which tunnel boring machines are deployed is continuously expanding, from clays to granular soils to highly fractured or monolithic rock masses, from partially to fully saturated ground, and from alpine mountain ranges with high overburden pressures to sensitive urban areas with low overburden. Today, the application range of tunnel boring machines is being extended to an ever increasing variety of geotechnical conditions.

In order to maintain low settlements, remain economically feasible, and to ensure an environmentally friendly construction process, the modern mechanized tunneling process requires realistic and reliable numerical models during the planning and construction stages. These models become especially critical in difficult geotechnical environments as well as under special boundary conditions, such as driving under existing constructions. A prerequisite for a reliable numerical prognosis is the accurate assessment of the interactions between the components involved in mechanized tunneling, the surrounding site, the ground, and any pre-existing structures. Heterogeneous geological conditions and often only approximated ground parameters create, in contrast to other engineering projects, special demands. This and the constant expansion of the range of deployment of shield-supported tunneling as well as the tendency to ever larger shield diameters necessitate new insights to new problems that can only be effectively solved through truly interdisciplinary research. Open problems demanding fundamental research arise in almost all aspects of the mechanized tunneling process. Examples are the distribution of the face support pressure in EPB shields, the actual mechanism in which water infiltrates the face support fluid and the grout, the relationship between the excavation at the tunnel face and cutter head wear, the effectiveness of measurements with respect to the quality of prognosis, the real-time support of the tunneling processes through continuously updated numerical models, the optimization of logistics processes or the robustness of segmental lining and the effectiveness of the grout between the lining and the ground.

In this context, the German Research Foundation (DFG) established the Collaborative Research Center "Interaction Models for Mechanized Tunneling" (SFB 837) at the Ruhr-University in Bochum in 2010. Collaborative Research Centers are interdisciplinary scientific research groups in which cooperative research is conducted under the umbrella of a central research theme. They have the potential to be funded for a period of up to 12 years, and are evaluated in 4-year intervals. With a research budget of ca. 10 Million Euros for the second 4-year funding period, the SFB 837 is currently the largest research group conducting fundamental research in tunneling-related topics worldwide.

The research team compromising the SFB 837 is composed of 13 project leaders along with approximately 35 scientific assistants, at the doctoral as well as postdoctoral level, with a background in various disciplines within the fields of civil engineering, geosciences and mechanical engineering. Within a total of 15 subprojects, design concepts,

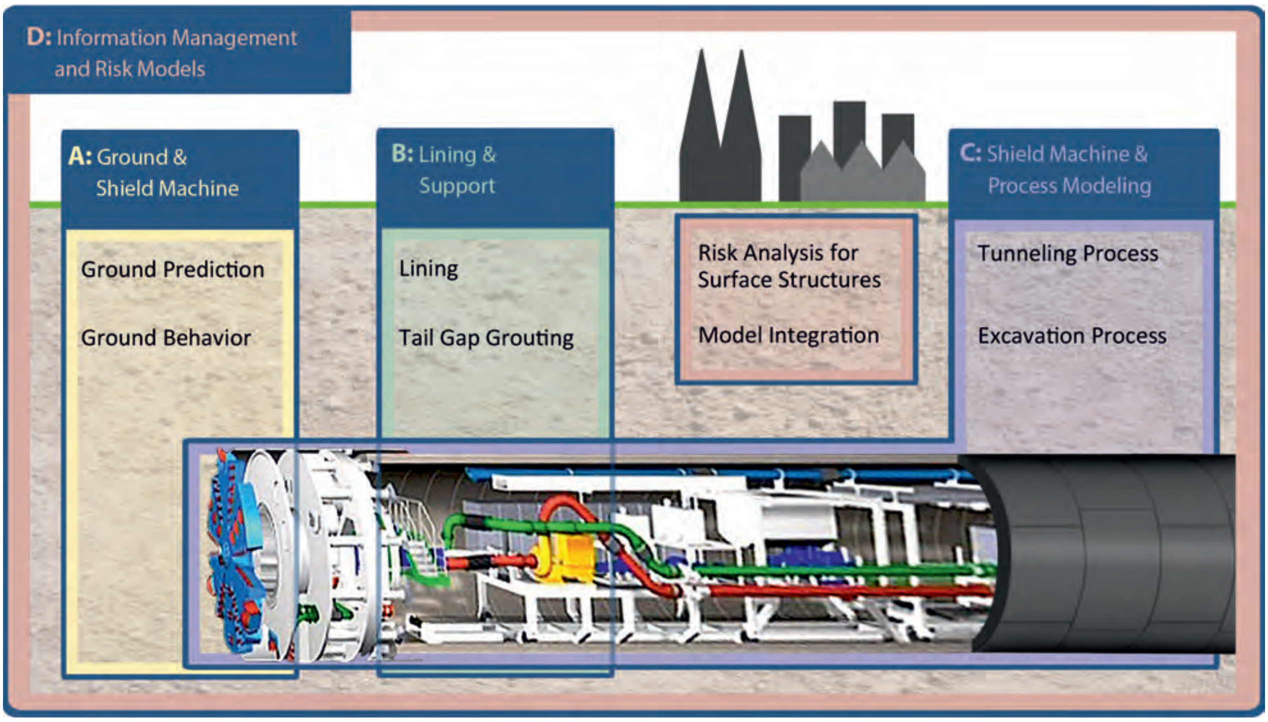


Fig. 1: Components and processes involved in mechanized tunneling and their representation within 4 project areas in the SFB 837

numerical models and new excavation technology concerning mechanized tunneling are being developed. The Coordinator of the SFB 837, along with a four-member Executive Board is responsible for the leadership of the SFB. Further administrative support is provided by an assistant coordinator as well as by an administrative assistant responsible for day-to-day organization. To support the SFB in strategic planning decisions, especially in the context of relevant challenges encountered in tunneling practice, an advisory board was established that is composed of six representatives from consultant offices, engineering firms, machine producers, and from city and state administrations. This advisory board is invited to a yearly event sponsored by the SFB in which the advisory board constructively critiques the research progress of the SFB. This has always resulted in a highly profitable exchange of ideas for the SFB.

The research goals of the SFB 837 are concerned with various relevant planning and construction aspects of the many components of the mechanized tunneling process. They are organized into 4 project areas (Fig. 1). Project area A is concerned with the characterization and modeling of the in-situ ground and the disturbed ground conditions in the vicinity of the cutting wheel as well as with advance exploration methods. The topic of research in project area B is the modeling of novel segmental lining designs with enhanced robustness and the interaction between the grout and the surrounding soil. Project area C is concerned with the simulation of the advancement process and real time prognosis methods to support the TBM steering, optimal monitoring strategies, the simulation of logistics processes and the modeling of the cutting process and the material transport into the excavation chamber. Finally, the last project area D is concerned with research on risk analysis in urban tunneling and model integration. These research themes are each supported by computational models and are all included in an SFB encompassing tunnel information model that was developed in the first period of the SFB. Furthermore, in the first phase, interaction groups were formed in order to integrate and combine the results of different submodels and analyses. These originated partially through prototypical cause-and-effect relationships, and partially through the highly successful Wehrhahnlinie metro line project.

A further important element of the SFB 837 is the cooperation with companies directly involved in tunnel engineering projects, as well as the intensive cooperation with national and international scientific institutions. Through cooperation with the Wehrhahnlinie subway project in Düsseldorf, the Brenner Base Tunnel SE and the German Railways as well as various engineering firms, construction companies and a TBM manufacturer, the SFB 837 has built up a large number of scientific partnerships. Currently, the academic partnerships include the School of Engineering of Tongji University in China, the Cambridge Innovation and Knowledge Center of Cambridge University in the UK and the Universities of Graz and Leoben in Austria. The internationalization of the SFB 837 was supported in the first phase by international stays of Ph.D. and postdoctoral researchers in renowned international universities including the Bulgarian Academy of Sciences, the Politecnico Torino in Italy, The University of Kyoto and Kumamoto in Japan, Chalmers University in Sweden, the University of Alberta in Canada, and Brown University, MIT, Princeton University, and the University of Delaware in the USA. The SFB 837 endeavors to greatly expand this international presence in the second period of the SFB.

The brochure at hand is meant to provide a short overview of the current and future research activities of the SFB 837. It includes a list of the 15 subprojects of the SFB 837 as well as a list of all the academic publications published so far within the SFB. The SFB 837 continues to lead to a fruitful and invigorating exchange of ideas between partners in tunnel engineering practice and in academics, and would kindly like to invite to you contact us.

Günther Meschke,

Coordinator of the SFB 837

EXECUTIVE BOARD

Prof. Dr. techn. Günther MESCHKE

Structural Mechanics

SFB 837 Coordinator,
Leader of subprojects:
B2, C1, C4

Prof. Dr. techn. Günther Meschke is the head of the Institute for Structural Mechanics of the Ruhr University Bochum and coordinator of the SFB 837 as well as of the Research Department "Subsurface Modeling & Engineering". His research is in the field of computational structural mechanics with an emphasis on multifield and multiscale models for porous and fiber-reinforced materials, numerical simulation models for underground construction (tunneling, geothermal energy systems), and lifetime oriented analysis of structures.

Prof. Meschke studied Civil Engineering (with a specialization in structural engineering) at the Vienna University of Technology, and in 1989, he received his doctorate from the Technical University of Vienna. After a post-doctoral period at the Vienna University of Technology and a research fellowship at Stanford University (USA) he became an Associate Professor at Vienna University of Technology in 1996 and later was appointed Professor of Structural Mechanics at the Ruhr University Bochum in 1998.

Prof. Meschke is an Ordinary Member of the German Academy of Science and Engineering (acatech), the North Rhine-Westphalian Academy of Sciences, Humanities and the Arts and an associate member of the Austrian Academy of Sciences. He is the author of over 260 scientific publications.

Prof. Dr.-Ing. Markus THEWES

Tunnelling and
Construction Management

SFB 837 Vice Coordinator,
Leader of subprojects:
A4, C3

Prof. Dr.-Ing. Markus Thewes is the head of the Institute for Tunnelling and Construction Management since 2005. He studies Civil Engineering at the RWTH Aachen University and received his doctorate at the University of Wuppertal in 1999. Between 1993 and 2005, he practiced in the tunneling industry in various positions. Among these were working as a design engineer for the technical department of a contractor, as a construction manager on international tunnel projects, as a geotechnical engineer for a TBM manufacturer, and as a design engineer for subway planning. His fields of research at the Ruhr University Bochum are mechanized tunneling machine technologies, sprayed concrete, simulation of construction processes, safety and security in the underground space, risk management and operation and rehabilitation of tunnels. He was First Vice President of the International Tunnelling and Underground Space Association, is an elected member of the German Tunnelling Committee, and member of the supervisory board of the Institute for Underground Infrastructure. He member of the editorial boards for the journals 'Tunnelling and Underground Space Technology', 'Geomechanics and Tunnelling' and the German 'Tunnelling Pocketbook'. He is author of more than 130 publications in journals and conferences.

EXECUTIVE BOARD

Prof. Dr.-Ing. Holger STEEB

Continuum Mechanics

Leader of subprojects:
A4, B4

Prof. Dr-Ing. Holger Steeb is the head of the Institute for Continuum Mechanics of the Ruhr University Bochum. His research interests are focused in the field of continuum mechanics of single and multi-phase materials, porous materials and materials with intrinsic microstructure. He works on numerical homogenization techniques for scale bridging and on discretization schemes like finite elements or Smoothed Particle Hydrodynamics (SPH). In Prof. Steeb's lab, experimental tools like X-ray micro-tomography, opto-rheometer and dynamical testing devices are available.

Prof. Steeb studied Civil Engineering at the University of Stuttgart. In 2002, he received his doctorate from the University of Stuttgart. After a post-doctoral period and a research fellowship at the National Technical University of Athens (NTUA, Greece) he got his habilitation at the Saarland University, Saarbrücken in 2008. In 2009 he was a (tenured) assistant Professor (UD) for Multi-Scale-Mechanics at the University of Twente, Enschede, NL and was appointed as Professor for Continuum Mechanics at the Ruhr University Bochum in 2009.

He is editor of the book series „Advances in Geophysical and Environmental Mechanics and Mathematics“ and member of the editorial board of „Applied and Computational Mechanics“. He is author of over 150 scientific publications.

Prof. Dr.-Ing. Rolf BREITENBÜCHER

Building Materials

Leader of subprojects:
B1, B3

Prof. Dr.-Ing. Rolf Breitenbücher is the head of the Institute for Building Materials at the Ruhr University Bochum. His research interests are mainly focused on the experimental investigation of concretes, especially in tunneling and traffic areas, on the durability of concrete at chemical exposure, the effect of cyclic stresses on the microstructure, as well as on shotcrete and fiber-reinforced concrete. He is the speaker of the DFG-research group FOR 1498 "Alkali-Silica-Reactions in concrete structures under cyclic stresses and simultaneous supply of external alkalis".

Prof. Breitenbücher studied civil engineering (major: structural engineering) at the Technical University of Munich. He received his PhD at the TU Munich in 1989. He was the chief of the central materials laboratory of the Philipp Holzmann AG in Frankfurt/Main from 1992 to 2002. In 2003, he was appointed Professor for building materials at the Ruhr University Bochum.

Prof. Breitenbücher is a member of several panels for standardization. He is chairman of the European standardizing committee for "Concrete" and also of the national DIN-committee "Beton". Furthermore, he has published more than 125 scientific papers.

PROJECT LEADERS

Prof. Dr. Michael ALBER

Engineering Geology / Rock Engineering

Leader of subproject: C5

Prof. Dr. Michael Alber is the head of Engineering Geology / Rock Engineering in the Faculty of Geosciences. His research interests are mechanized excavations, the quantitative description of soil and rock properties and the mechanisms associated with "hydraulic fracturing" in jointed geologic media. After receiving his diploma in geology from Stuttgart University, Prof. Alber was owner and operator of a drilling company for geotechnical site investigations. He went 1990 to the Pennsylvania State University where he received the MSc in Mining Engineering (rock mechanics). After 2 years in applied research in the US and 1 year as a senior geotechnical engineer on a construction site he went to the Technical University of Berlin. He received his PhD for research on hard rock tunnel boring machines in 1996. Since 2001 he is Professor for Engineering Geology and rock engineering at the Ruhr University Bochum.

Dr.-Ing. Steffen FREITAG

Structural Mechanics

Leader of subproject: C1

Dr. Steffen Freitag is a Junior Research Group Leader at the Institute for Structural Mechanics at Ruhr University Bochum. His research interests are Computational Intelligence, Numerical Simulation with Uncertain Data, and Structural Reliability.

Dr. Freitag studied Civil Engineering focusing on structural engineering and mechanics at the Technische Universität (TU) Dresden from 2000 to 2005. Afterwards, he worked as a research assistant at the Institute for Structural Analysis at TU Dresden within the Collaborative Research Center 528 "Textile Reinforcements for Structural Strengthening and Repair". In 2010, he obtained the academic degree Dr.-Ing. (PhD) from TU Dresden. From 2011 to 2012, he was a visiting scholar within the Center for Reliable Engineering Computing at Georgia Institute of Technology.

Since 2015, Dr. Freitag is a member of the "Junges Kolleg" at the North Rhine-Westphalian Academy of Sciences, Humanities and Arts.

PROJECT LEADERS

Prof. Dr. rer. nat. Wolfgang FRIEDERICH

Geophysics - Seismology

Leader of subproject:
A2

Prof. Dr. rer. nat. Wolfgang Friederich leads the Seismology working group at the Geoscience Faculty of Ruhr University Bochum. His research focusses on forward and inverse modeling of seismic wave propagation on various spatial scales.
Prof. Wolfgang Friederich studied physics and geophysics at Karlsruhe University. He received his PhD from Karlsruhe University and his postdoctoral qualification (habilitation) from Stuttgart University. After a 2 year period of teaching and research at Frankfurt University he holds the chair of geophysics at Ruhr University Bochum since 2004. From 2005 to 2011 he was spokesperson of the Collaborative Research Center (SFB) 526 "Rheology of the Earth - from the upper crust to the subduction zone".

Prof. Dr. rer. nat. Klaus HACKL

Mechanics of Materials

Leader of subprojects:
A2, C4

Prof. Dr. rer. nat. Klaus Hackl leads the Chair of Mechanics of Materials at the Ruhr University Bochum. He is chairman of the DFG-research group FOR 797, Microplast (Analysis and Computation of Microstructures in Finite Plasticity) and director of the international master-program "Computational Engineering" at the Ruhr University Bochum. He is member of the GAMM-activity group "Analysis of microstructure", which he chaired for many years. He is member of the editorial board of several international journals and author of more than 200 scientific publications. Prof. Hackl develops models for the behavior of complex materials and implements those into numerical schemes. A focus of his work lies on variational methods. Specifically, he works on processes in geo-materials, shape-memory alloys and dislocation microstructures.
Prof. Hackl studied physics and mathematics at the universities in Karlsruhe and Heidelberg. He obtained his PhD at RWTH Aachen in 1989. From 1989 until 1992 he worked as fellow of the A. v. Humboldt-foundation at the University of Delaware, USA. From 1992 until 1997 he was assistant professor and later associate professor at the Technical University of Graz, Austria. There, he completed his habilitation in mechanics in 1997. Since 1999 he is full professor at the Ruhr University Bochum.

PROJECT LEADERS

Prof. Dr.-Ing. Markus KÖNIG

Computing in Engineering

Leader of subprojects:
C2, C3, D1, D3

Prof. Dr.-Ing. Markus König is professor at the Chair of Computing in Engineering at the Ruhr University Bochum. His research focuses on process modelling, building information modelling, heuristic optimization methods, the simulation of construction and logistics processes, uncertainty as well as risk management and knowledge management in the construction industry.
Prof. König studied civil engineering and applied computer science at the University of Hannover. In 2003 he received his doctorate there in the field of product and process modelling. Between 2004 and 2009 he was Junior Professor of Theoretical Methods of Project Management at the Bauhaus-Universität Weimar before he was appointed professor of Computing in Engineering at the Ruhr University Bochum in 2009. Prof. König is chairman of the German Association of Computing in Civil Engineering (Arbeitskreis Bauinformatik).

Dr.-Ing. Arash Alimardani LAVASAN

Foundation Engineering,
Soil & Rock Mechanics

Leader of subproject:
A5

Dr. Arash Alimardani Lavasan is a junior research group leader and project leader at the chair of Foundation Engineering, Soil and Rock Mechanics at the Ruhr University Bochum. In the framework of the SFB 837, his research interests are "Adaptive constitutive modeling of soil with special consideration of anisotropy and destructuration" and "Numerical simulations of interactions in mechanized tunneling".
Dr. Lavasan studied civil engineering (Bachelor) from 1998 to 2002 at Shiraz University, Iran. He finished his Master degree with special honors in geotechnical engineering in 2005 at K.N.Toosi University of Technology in Teheran, Iran. Subsequently, he started his doctoral research with the title "Experimental and numerical investigation of load-deformation behavior of interfering shallow foundation on reinforced sand". He obtained his Ph.D (with special honors) in geotechnical engineering in 2010. In 2012, Dr. Lavasan received the Alexander von Humboldt Foundation award for Post-doctoral research at Ruhr University Bochum.

PROJECT LEADERS

Prof. Dr.-Ing. Peter MARK

Concrete Structures

Leader of subprojects:
B1, D3

Prof. Dr.-Ing. habil. Peter Mark is professor at the Institute of Concrete Structures and director of the Institute of Structural Engineering at the Ruhr University Bochum. Main areas of his research are development of calculation and design strategies for concrete structures, maintenance and strengthening of civil engineering structures, industrial structures, design of reinforced and pre-stressed concrete bridges, fibre reinforced concrete structures and lifetime-oriented structural design.

Prof. Mark obtained his doctorate in 1997 and his postdoctoral lecture qualification in 2006 at the Ruhr University Bochum. Since 2007, he is partner at Grassl Consultant Engineers, Düsseldorf, and particularly responsible for the fields of bridge engineering, industrial construction and independent checking of structural analysis. Since 2007, Prof. Mark is a certified consulting engineer and, since 2008, Independent Checking Engineer (ICE) for concrete and composite structures. Since 2009, he holds the professorship for Concrete Structures at the Ruhr University Bochum. Prof. Mark participates in national as well as international committees, including the VGB PowerTech Scientific Advisory and the German Tunnelling Committee (working group "Lining Segment Design"). Furthermore, he is chairman of Deutscher Ausschuss für Stahlbeton (DAfStb) committee on fibre reinforced concrete and member of CEN/TC250/SC2/WG1/TG2 "Fibre Reinforced Concrete".

Prof. Dr.-Ing. Tamara NESTOROVIĆ

Mechanics of Adaptive Systems

Leader of subproject:
A2

Prof. Dr.-Ing. Tamara Nestorović is professor for Mechanics of Adaptive Systems at Ruhr University Bochum, Germany. Her research fields are overall design and control of smart structures, active vibration and noise reduction, experimental identification and real-time control, development of robust controllers based on FE-models, inversion methods and reconnaissance in mechanized tunneling, damage detection and machine diagnosis.

She graduated in 1994 from Mechanical Engineering (Control Systems) at the University in Niš, Serbia and got her "Magistar" Degree in Control Systems at the same Faculty in 2000. After obtaining her Ph.D. in 2005 at the Otto-von-Guericke University in Magdeburg, Germany (awarded by the Association of German Engineers VDI as best Ph.D. thesis) she researched at the same University and at the Fraunhofer Institute for Factory Operation and Automation IFF, Magdeburg as project leader in the field smart structures and virtual reality. In 2008 she was appointed a full professor at Ruhr University Bochum. Prof. Nestorović is author of over 150 scientific publications.

PROJECT LEADERS

Dr.-Ing. Arne RÖTTGER

Materials Technology

Leader of subproject:
C5

Dr.-Ing. Arne Röttger is group leader at the Chair of Materials Technology at the Institute of Materials of the Ruhr University Bochum. His research topics can be found in the field of wear resistant materials like hard alloys and metal matrix composites.
From 2001 to 2005 Arne Röttger studied mechanical engineering with course specialization in plant engineering and construction at the University of Applied Science Südwestfalen. Beginning 2005 to 2007 he studied mechanical engineering at the Ruhr University Bochum with the focus on materials. From 2008 he worked as research assistance at the chair of materials technology. Thereby, he was dealing with the topics like thermal spraying of Fe-base materials by means of HVOF and the investigation of the Fe-rich corner of the ternary system Fe-C-B. Based on these investigations he submitted his PhD-thesis in 2011.

Prof. Dr.-Ing. Tom SCHANZ

Foundation Engineering, Soil & Rock Mechanics

Leader of subprojects:
A5, A6, C2

Prof. Dr.-Ing. Tom Schanz is head of the Chair for Foundation Engineering, Soil- and Rock Mechanics at the Ruhr University Bochum. He received his PhD at ETH Zurich and the subsequent habilitation at the University of Stuttgart. The focus of his research covers the complete range of geotechnical engineering with a strong expertise on theoretical and experimental soil mechanics. Major objective is the constitutive description of geomaterials based on the multi scale understanding of the underlying mechanical, physico-chemical and hydraulic principles. This constitutive understanding is considered in the frame of numerical modelling of geomechanical problems for complex coupled multi physics systems. The chair operates an excellent equipped laboratory with equipment developed by our research group. Based on our research experience we are able to measure and control state parameters for both saturated and partially saturated multiphase materials. An additional focus of our work is the design of smart materials which we adopt to the specific conditions under which they are used in typical applications as underground repositories for highly toxic waste, the use of the subground for the storage of energy for further geoenvironmental applications. In this light we understand mechanised tunnelling as a transient multi field process to be modelled on different scales with adequate complexity considering inherent uncertainty and heterogeneities typical for geomechanical problems.

PROJECT LEADERS

Dr.-Ing. Britta SCHÖßER

Tunnelling and Construction Management

Leader of subproject: A6

Dr. Britta Schößer is team leader at the Institute for Tunnelling and Construction Management. Her research topics contain the application of bentonite suspensions as support, lubrication and transport medium in hydro shield tunneling and pipe jacking. The rheology of bentonite suspensions and experimental investigations on the range of application of their use under consideration of geological and hydrogeological boundary conditions are part of her research scope.
In 1997, Dr. Schößer was working as project engineer at the engineering office of Prof. Maidl, Bochum and at Deutsche Montan Technologie (DMT), Essen. From 1998, she was a research assistant at the Working Group Pipeline Construction and Construction Management of Prof. Stein and obtained her PhD in 2004. In the time 2005 - 2007 Dr. Schößer worked as project manager at the Joint Venture “ARGE emscher:kanal”. Since 2008, she is senior researcher and head of the bentonite laboratory at the Institute for Tunneling and Construction Management. In cooperation with tunneling experts, she developed the suspension concept of LDSM (low density support medium) and HDSM (high density support medium) for tunneling projects in challenging geological conditions beginning in 2011.

Prof. Dr.-Ing. Werner THEISEN

Materials Technology

Leader of subproject: C5

Prof. Dr.-Ing. Werner Theisen is the chair holder of Materials Technology at the Institute of Materials at the Ruhr University Bochum.
Beginning in 1977 to 1984 he studied mechanical engineering at the Ruhr University Bochum with the specialization subject “MATERIALS” and he received his PhD in 1988 about Ni- and Co-base alloys for wear protection applications. From 1988 until 1994 he was senior engineer at the chair of materials technology at the Ruhr University Bochum and did his post-doc (habilitated) in the field of machining of wear resistant alloys with respect to a materials-related consideration. From 1996 to 2000 he worked as the head of the technology division at the Maschinenfabrik Köppern in Hattingen and was appointed as a C4 professor at the chair of materials technology at the Ruhr University Bochum in 2000. In the period from 2011 to 2013 he was the dean of the faculty of mechanical engineering.

POST-DOCTORAL RESEARCHERS

Dr.-Ing. Mark Alexander AHRENS

Concrete Structures

Subproject:
B1

Dr. Mark Alexander Ahrens is a scientific assistant at the Institute of Concrete Structures at Ruhr University Bochum (RUB). His main areas of research are (residual) life-time prognoses of existent bridges made from reinforced and pre-stressed concrete, condition assessment methods and rehabilitation measures of infrastructure by means of structural health monitoring and experimental testing as well as precision assessment techniques and sensitivities of stochastically based forecasts.
Dr. Ahrens studied civil engineering from 1998 until 2004 at RUB with focus on structural engineering and informatics. When he had obtained his diploma he joined the collaborative research center 398 on “lifetime oriented structural design concepts” and worked on the subproject D1 entitled “reference structure: degradation and lifetime assessment of a pre-stressed road bridge made from reinforced concrete after 50 years of service”. In 2010 he finished his doctoral thesis “A stochastically based simulation concept for residual life-time prognoses of pre-stressed and reinforced concrete structures and its application on a reference structure”. Furthermore, he is a member of the International Association for Life-Cycle Civil Engineering (IALCCE) and the International Association for Bridge Maintenance and Safety (IABMAS).

Dr.-Ing. Christian BECKER

Continuum Mechanics

Subproject:
B4

Dr. Christian Becker is Post-Doc at the Chair of Continuum Mechanics of the Ruhr University Bochum. His research topics are modelling and numerical implementation of porous media.
Dr. Becker studied civil engineering from 1996 to 2001 with focus on construction engineering at the Ruhr University Bochum. From 2001 to 2007 he worked on a subproject of SFB 398 "Lebensdauerorientierte Entwurfskonzepte unter Schädigungs- und Deteriorationsaspekten", and finished his PhD in the field of numerical structural mechanics. After his work as a development engineer for a mechanical engineering enterprise Dr. Becker returned 2009 to Ruhr University Bochum.

POST-DOCTORAL RESEARCHERS

Dr.-Ing. Michael HOFMANN

Structural Mechanics

Subproject:
B2

Dr. Michael Hofmann is a research associate at the Institute for Structural Mechanics at Ruhr University Bochum. His research is focused on macromechanical models for different composite materials (reinforced concrete, fiber reinforced concrete, timber structures) and numerical methods for the simulation of coupled problems (solution algorithms).
Dr. Hofmann studied theoretical and applied mechanics at the Drepropetrowsk State University (Ukraine) from 1975 to 1980. Afterwards, he worked at the Chair of Theoretical and Applied Mechanics at Mariupol Technical University (Ukraine). In 1987, he defended his doctor's thesis in the Institute of Seismology (Alma-Ata, Kazakhstan). Since 2004, Dr. Hofmann is working in the Institute for Structural Mechanics at Ruhr University Bochum within different projects of basic and applied research in numerical structural mechanics.

Dr.-Ing. Dipl.-Inform. Karlheinz LEHNER

Computing in Engineering

Subproject:
D1

Dr. Karlheinz Lehner is a research associate at the Chair of Computing in Engineering at Ruhr University Bochum. His research focuses on both the use of knowledge-based technologies in product modeling and the use of optimization concepts in engineering tasks.
Dr. Lehner studied computer science at the Technical University of Dortmund between 1980-1986. He then worked at the Department of Computer Science in Civil Engineering at the Technical University of Dortmund where he defended his thesis "On the Use of Knowledge-Based Systems in Structural Optimization, as Exemplified by Truss Optimization" in 1991. Since 2010, Dr. Lehner has been working at the Chair of Computing in Engineering in various research projects.

POST-DOCTORAL RESEARCHERS

Dr.-Ing. Jelena NINIĆ

Structural Mechanics

Subproject:
C1

Dr. Jelena Ninić is a research associate at the Institute for Structural Mechanics at Ruhr University Bochum. Her research is focused on numerical methods for the simulation of the mechanized tunnelling process and soil structure interaction in real time.
Dr. Ninić studied structural engineering at the Faculty for Civil Engineering, University of Belgrade (Serbia) from 2003 to 2008. Afterwards, she worked at the same faculty as a teaching assistant at the Chair for Geotechnical Engineering. Since 2010, she is working as a research associate at the Institute for Structural Mechanics. In 2012, she was a visiting researcher at the Faculty of Civil and Environmental Engineering, Massachusetts Institute of Technology (MIT), USA. In 2015, she obtained her PhD degree with the thesis “Computational strategies for predictions of the soil-structure interaction during mechanized tunneling”.

DOCTORAL RESEARCHERS

Abdullah ALSAHLY
Subproject: C1

Adaptive computational modeling of tunnel boring machine advance

Supervisor: Prof. Dr. techn. Günther Meschke (Structural Mechanics)

Abdiel Ramon Leon Bal
Subproject: C4

Numerical modeling and simulation of the excavation process of soft soils in mechanized tunneling

Supervisor: Prof. Dr. techn. Günther Meschke (Structural Mechanics)

Thomas BARCIAGA
Subproject: A5

Constitutive modeling of structured soils with application to mechanized tunneling

Supervisor: Prof. Dr.-Ing. habil. Tom Schanz (Foundation Engineering, Soil & Rock Mechanics)

Hoang Giang BUI
Subproject: C1

Massive parallel computing in domain coupled problems in computational structural mechanics

Supervisor: Prof. Dr. techn. Günther Meschke (Structural Mechanics)

DOCTORAL RESEARCHERS

Ba Trung CAO
Subproject: C1

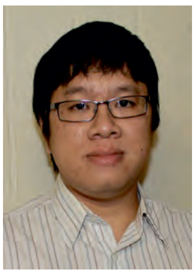
Parameter identification in numerical modeling of tunneling using model reduction techniques

Supervisor: Prof. Dr. techn. Günther Meschke (Structural Mechanics)

Alena CONRADS
Subproject: C3

Evaluation of maintenance concepts in TBM tunneling using process simulation

Supervisor: Prof. Dr.-Ing. Markus Thewes (Tunnelling and Construction Management)



Thai Son DANG
Subproject: C4

Numerical modeling and simulation of flow and fracture process at the tunnel face during mechanized tunneling

Supervisor: Prof. Dr. techn. Günther Meschke (Structural Mechanics)

Vojtech Ernst GALL
Subproject: B2

Finite element simulation of segmented lining response to mechanized tunneling induced construction loads

Supervisor: Prof. Dr. techn. Günther Meschke (Structural Mechanics)

DOCTORAL RESEARCHERS

Mario GALLI
Subproject: A4

Rheological characterisation of EPB support medium composed of non-cohesive soil and foam

Supervisor: Prof. Dr.-Ing. Markus Thewes (Tunnelling and Construction Management)

Christopher GESING
Subproject: A4

Investigation of the rheology of conditioned soils under realistic conditions of EPB-tunneling

Supervisor: Prof. Dr.-Ing. Markus Thewes (Tunnelling and Construction Management)

Raoul HÖLTER
Subproject: C2

Optimal experimental design in the framework of mechanized tunneling

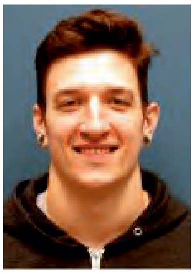
Supervisor: Prof. Dr.-Ing. habil. Tom Schanz (Foundation Engineering, Soil & Rock Mechanics)

Felix HEGEMANN
Subproject: D1

A hybrid ground data management concept for tunneling projects

Supervisor: Prof. Dr.-Ing .Markus König (Computing in Engineering)

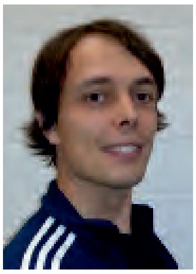
DOCTORAL RESEARCHERS



Jakob KÜPFERLE
Subproject: C5

Verschleißverhalten und Prognosen von TVM-Werkzeugen im Lockergestein

Supervisor: Prof. Dr.-Ing. Theisen (Materials Technology)



Lasse LAMBRECHT
Subproject: A2

Forward and inverse modeling of seismic waves for reconnaissance in mechanized tunneling

Supervisor: Prof. Dr. rer. nat Wolfgang Friederich (Geophysics)

Puviyarrasan MANICKAM
Subproject: D1

Interaction modeling for coupling simulations in a complex simulation system

Supervisor: Prof. Dr.-Ing. Markus König (Computing in Engineering)

Ahmed Marwan
Subproject: C1

Computational methods for optimization in mechanized tunneling

Supervisor: Prof. Dr. techn. Günther Meschke (Structural Mechanics)

DOCTORAL RESEARCHERS

Shorash MIRO
Subproject: C2

System identification in mechanized tunneling considering uncertainties

Supervisor: Prof. Dr.-Ing. Dietrich Hartmann (Computing in Engineering)

Khayal MUSAYEV
Subproject: A2

Frequency domain full waveform inversion in a tunnel environment

Supervisor: Prof. Dr. rer. nat. Klaus Hackl (Mechanics of Materials)

Thanh Luan NGUYEN
Subproject: A2

Filtering techniques for model calibration and waveform-based reconnaissance in mechanized tunneling

Supervisorin: Prof. Dr.-Ing. Tamara Nestorović (Mechanics of Adaptive Systems)

Aycan ÖZARMUT
Subproject: A4

Rheological properties of particle laden foam

Supervisor: Prof. Dr.-Ing. Holger Steeb (Continuum Mechanics)

DOCTORAL RESEARCHERS

Thomas PUTKE
Subproject: B1

Ein interaktives Optimierungs- und Entwurfskonzept für Tübbingschalen

Supervisor: Prof. Dr.-Ing. Peter Mark (Concrete Structures)

Tobias RAHM
Subproject: C3

Multi-method simulation of production and logistic processes in mechanized tunneling to assess the impact of disruptions on production performance

Supervisor: Prof. Dr.-Ing. Markus König (Computing in Engineering)

Kambiz SADRI
Subproject: C3

Simulation model for the planning of the logistic system of a mechanized tunneling jobsite

Supervisor: Prof. Dr.-Ing. Markus Thewes (Tunnelling and Construction Management)

Alexander SCHAUFLER
Subproject: B4

Ein Mehrphasen-Infiltrationsmodell für Ringspaltmörtel

Supervisor: Prof. Dr.-Ing. Holger Steeb (Continuum Mechanics)

DOCTORAL RESEARCHERS

Markus SCHEFFER
Subproject: C3

Simulationsgestützte Verfügbarkeitsanalyse von Tunnelvortriebsmaschinen

Supervisor: Prof. Dr.-Ing. Markus König (Computing in Engineering)

Fanbing SONG
Subproject: B1

Verhalten von Stahlfaserbeton unter Teilflächenbelastung

Supervisor: Prof. Dr.-Ing. Rolf Breitenbücher (Building Materials)

Jithender J. Timothy
Subproject: B2

Multilevel Micromechanics Modeling of Materials

Supervisor: Prof. Dr. techn. Günther Meschke (Structural Mechanics)

Nicola WESSELS
Subproject: C4

Discrete element simulation of cutting processes in soils

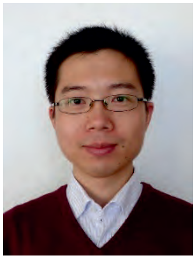
Supervisor: Prof. Dr. rer. nat. Klaus Hackl (Mechanics of Materials)

DOCTORAL RESEARCHERS

Bou-Young YOUN
Subproject: B3

Systematische Untersuchungen zum Entwässerungsverhalten von einkomponentigen Ringspaltmörteln im maschinellen Tunnelbau

Supervisor: Prof. Dr.-Ing. Rolf Breitenbücher (Building Materials)



Yijian ZHAN
Subproject: B2

Synthesis of multiscale modeling of fiber reinforced concrete and simulations of tunnel linings

Supervisor: Prof. Dr. techn. Günther Meschke (Structural Mechanics)

Zdenek ZIZKA
Subproject: A6

On the stability of slurry supported tunnel face considering transient support mechanism

Supervisor: Prof. Dr.-Ing. Markus Thewes (Tunnelling and Construction Management)

Chenyang ZHAO
Subproject: A5

Adaptive numerical modeling of mechanized tunneling in soft soil

Supervisor: Prof. Dr.-Ing. habil. Tom Schanz (Foundation Engineering, Soil & Rock Mechanics)

COMPLETED PhD THESES

Jelena NINIĆ

Subproject: C1
2015

Computational steering to minimize environmental impact in mechanized tunnelling

Steffen SCHINDLER

Subproject: D3
2014

Monitoringbasierte strukturmechanische Schadensanalyse von Bauwerken beim Tunnelbau

Trung Thanh DANG

Subproject: C3
2014

Analysis of microtunnelling construction operations using process simulation

Christoph BUDACH

Subproject: A4
2012

Untersuchungen zum erweiterten Einsatz von Erddruckschilden in grobkornigem Lockergestein

SUBPROJECTS OF THE SFB 837

DEVELOPMENT OF EFFECTIVE CONCEPTS FOR TUNNEL RECONNAISSANCE USING ACOUSTIC METHODS

A2

L. Lambrecht, K. Musayev, L. Thanh Nguyen, W. Friederich, K. Hackl, T. Nestorović

OUTLINE OF SUBPROJECT

The aim of this project is to develop new effective concepts for reconnaissance in mechanized tunneling using acoustic sounding methods to obtain highly resolved information on material properties of rock formations in front of the tunnel face with adequate effort. The presence of natural or man-made structures with direct bearing on tunnel excavation such as cavities, faults, erratic boulders or cut-off walls should be predictable from the results.

Applied imaging methods make use of inverse scattering theory, i.e. the inference of the spatial distribution of elastic and other material properties from reflected or refracted elastic waves. Forward computation of the elastic wavefield is done with fully numerical approaches that allow prediction of the elastic wavefield in complex geological environments. The inverse problem is tackled by full waveform inversion. The influence of material fluctuations is estimated using stochastic finite element methods. In addition, surrogate models are constructed by model reduction that allow fast inverse computations.

For validation of the methods, a laboratory experiment is planned where a down-scaled tunnel environment containing anomalous structures is equipped with acoustic sensors and emitters in various configurations. Scaling is on the order of 1:20 to 1:100. Finally, the developed methods will be applied to in-situ acoustic data.

FORWARD PROBLEM

In case of geologically simple media elastic wave propagation is modeled using the Spectral-Finite-Element-Method (SpecFEM) whereas for complex geological situations a nodel discontinuous Galerkin (NDG) (Fig. 1) approach is applied.

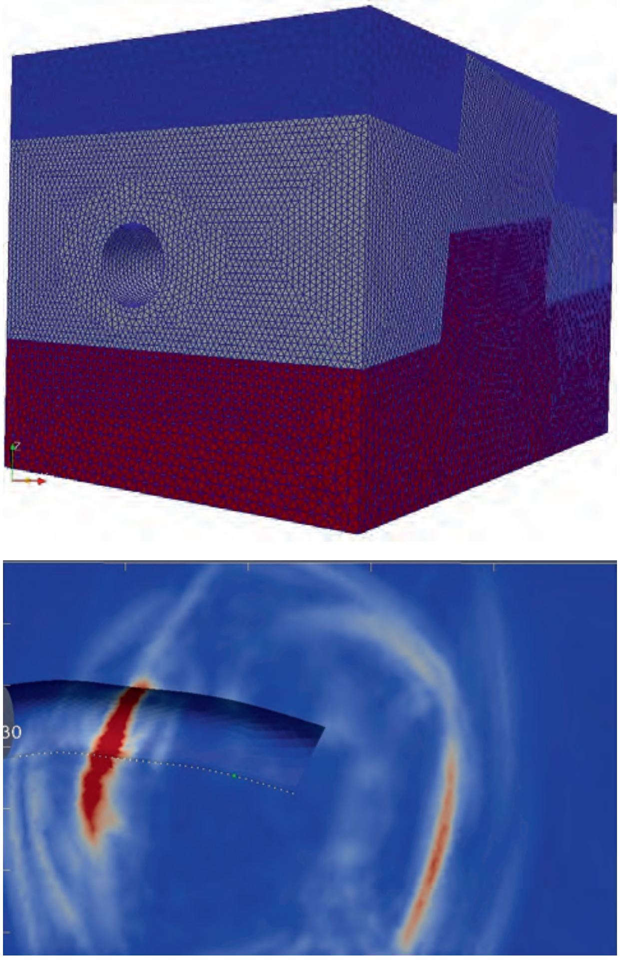
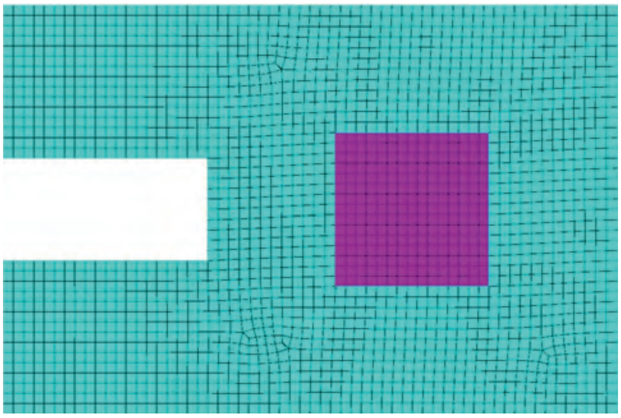


Fig. 1: Top: Tetrahedral mesh with curved tunnel, layer boundaries and steeply dipping faults perpendicular to the tunnel axis. Bottom: Snapshot of the seismic wavefield generated by source at the tunnel face

INVERSE PROBLEM

The inverse problem is tackled with full waveform inversion. The aim is to image the distribution of elastic material properties in front of the tunnel face from observations of the elastic wavefield. Up to now, 2D inverse computations were done in the time domain for the elastic wave equation (Fig. 2) and in the frequency domain for the acoustic wave equation (Fig. 3a and 3b).

The results indicate that an inversion in the frequency domain may possess better convergence behavior than an inversion in the time domain due to the reduced nonlinearity of the inverse problem.



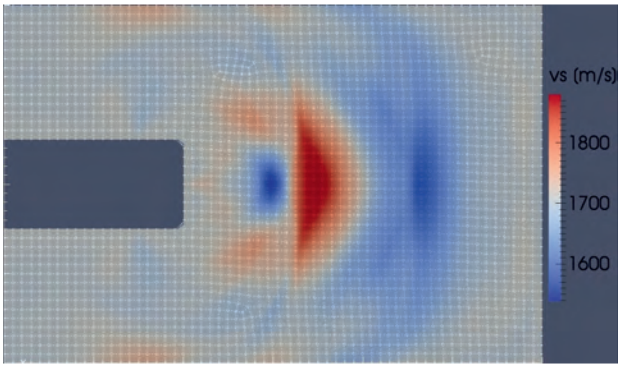


Fig. 2: Simplified test case for the 2D inverse problem in the time domain based on the elastic wave equation. Top: Sketch of the location of a square-shaped structural anomaly in front of the tunnel face. Elastic wavefields were calculated at receivers on the tunnel sidewalls generated by three sources located on the tunnel face. Bottom: Reconstruction of the anomaly using full-waveform inversion of waveforms recorded at the receivers

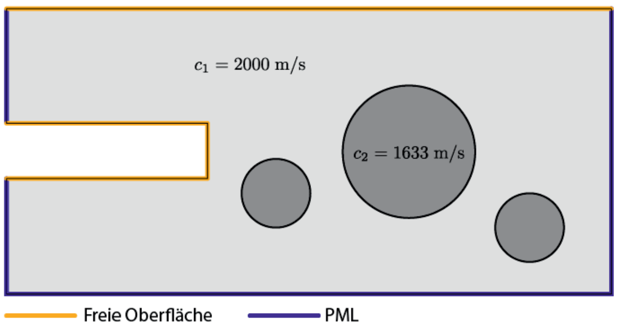


Fig. 3a: Simplified test case for the 2D inverse problem in the frequency domain based on the acoustic wave equation: Homogeneous test model with embedded structural anomalies

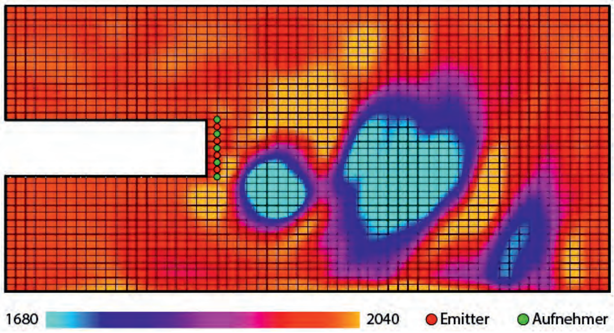


Fig. 3b: Simplified test case for the 2D inverse problem in the frequency domain based on the acoustic wave equation: Reconstruction of the structural anomaly by inversion of spectral amplitudes and phases at 20 frequencies recorded by 5 sensors on the tunnel face and generated by 5 sources on the tunnel face

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1. LAMBRECHT, L.; FRIEDERICH, W.: Forward and inverse modeling of seismic waves for reconnaissancein mechanized tunneling. In: Computational Methods in Tunneling and Subsurface Engineering (1), Aedificio Publishers, 769–777, 2013.
2. LAMBRECHT, L.; FRIEDERICH, W.: Forward and inverse modelling of seismic waves for reconnaissance in mechanized tunnelling. In: EAGE Near Surface. Waveform Inversion in Near-Surface Geophysics: Applications and New Developments (1), 13–16, 2013.
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4. MUSAYEV, K.; HACKL, K.; BAITSCH, M.: Frequency Domain Waveform Inversion in a Tunnel Environment. PAMM 13 (1), 323-324, 2013.
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MODEL DEVELOPMENT FOR THE CONDITIONED SOIL USED AS FACE SUPPORT MUCK OF EARTH-PRESSURE-BALANCE-SHIELDS

A4

M. Galli, C. Gesing, A.Ö. Özarmut, H. Steeb, M. Thewes

INTRODUCTION OF THE SUBPROJECT

The Earth Pressure Balanced Shield (EPB) is worldwide predominantly applied for mechanized tunneling in coarse-grained soils. The face support requires a conditioning of the medium, which mainly consists of the excavated soil, because of varying types of soil. High fluctuations of the support pressure during advance result from the effective rheological properties of the multi-phase support medium. The aim of this project is a development of regularized non-Newtonian constitutive models for EPB support media on the basis of scale-overlapping rheological experiments. For this purpose coordinated studies are conducted on the micro- and macro-scale. Moreover, the important question of pressure dependency of the support media´s rheological properties is investigated experimentally. The experimental results provide a basis to develop constitutive models of three-dimensional numerical simulations for the mixing and flowing processes in the excavation chamber of an Earth Pressure Balanced Shield.

EXPERIMENTAL RESULTS OF FIRST PHASE

On the micro-scale, the rheological experiments have been performed to determine rheological properties of dry-particle and surface wetted-particle-laden foam mixtures. In rheological experiments, polymer-stabilized liquid foam and glass beads (Silibeads Glass beads Type S) were used. In order to describe the rheological behavior of the mixtures, a modified Herschel-Bulkley-Papanastasiou model was fitted to experimental data (flow curve as well as oscillatory tests) of certain mixtures. The modification of this model is based on the inherent (regularized) yield stress, which depends on the volume fraction of dry and surface wetted-particles. Additionally, the flow curve tests (viscosity–shear rate curves) of the dry-particle and surface wetted-particle foam mixtures show that the viscosity decreases with increasing shear rate. This type of non-Newtonian behaviour is typical for shear thinning or pseudo-plastic materials.

On the macro-scale, foam penetration tests have been developed in order to investigate precisely the infiltration process at the tunnel face and to enable an analysis of the remaining water content in this area. The water content depends significantly on penetration time (advance rate) and geological conditions. The residual water content will be used as initial moisture for further investigations. Furthermore, the rheological experiments with realistic soil-foam mixtures have been conducted to support basically the phenomenological findings of the flow behavior of particle-foam mixtures on the micro-scale. Moreover, the interaction between different soils with foam of various contents could be assessed with regard to the flow behaviour. Thus, new results of the conditioning ability and therefore the range of EPB-shield applications in coarse-grained soils could be gained.

AIM OF THE SECOND PHASE & STATUS QUO

For the second phase, the subproject was divided into four Work Packages (WP). WP1 transitions from the rheological experiments of the first phase to heterogeneous experiments due to verification of the ascertained material parameters. In addition, "Smoothed Particle Hydrodynamics" (SPH), a Lagrangian mesh-free simulation method, will be used to provide numerical simulations of fluid flow with free surfaces. In order to calculate the model-inherent material parameters by using inverse analysis, the (heterogeneous) mini-slump-test - a

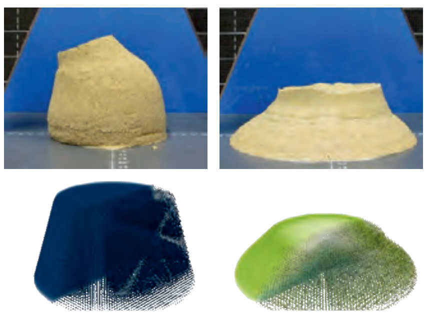

Fig. 1: Slump test – Experiment and simulation

simple and “cheap” rheological experiment - was performed to determine the flowability of the surface wetted-particle foam mixtures.

In WP2, rheological experiments will be performed for realistic particle-foam mixtures, too. The rheological investigations will be performed at different pressure conditions (atmospheric – 0.5 MPa), which are related to tunnelling. The supporting pressure, which effects the rheological properties of materials, can be determined by using a modified high-pressure Couette cell (Fig. 2, left). For the modified pressure cell, cub and bob geometries are used with smooth and rough surfaces taking into account wall slip effects (Fig. 2, middle and right). These geometries are used to obtain flow curves of foam with different volume fractions of particles at various pressure levels. Hence, the results will be compared with the flow curve data at atmospheric pressure.

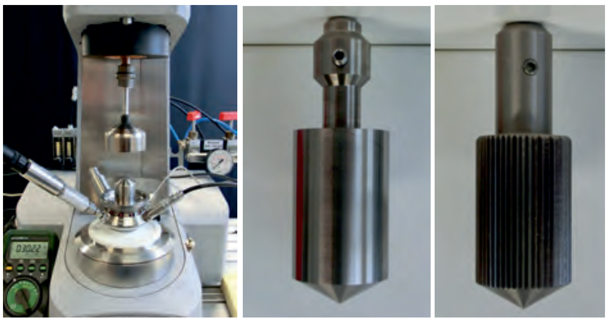

Fig. 2: Pressure cell (MC 301) (left), smooth Bob (middle) and ripped (rough) Bob (right)

In the course of WP3 these experiments will be extended onto the macro-scale with a practical range of grain distributions and conditioning agents. Thus, scale-overlapping rheological investigations of tunnelling foams with high amounts of soil particles will be conducted. First, the slump-test as well as rheological tests with cylinder and sphere configurations will be utilized. The transition of homogenous tests (micro-scale) to heterogenous tests (macro-scale) is ensured on the material level. Thus, the different mixture proportions of synthetic particle-foam mixtures can also be investigated in heterogenous testing configurations. In this manner the constitutive material model can be verified on the macro scale and it can be carried out to investigate realistic materials.

In addition to the rheological investigations, a concept of large scale testing for simulating the mixing processes is prepared in the excavation chamber.

In line with WP4, realistic studies under pressurized conditions in the large scale test stand COSMA (Fig. 3) as well as in a pressure cell of the rheometer are planned. Furthermore, first tests to estimate the abrasiveness in the large scale test are planned to be conducted.

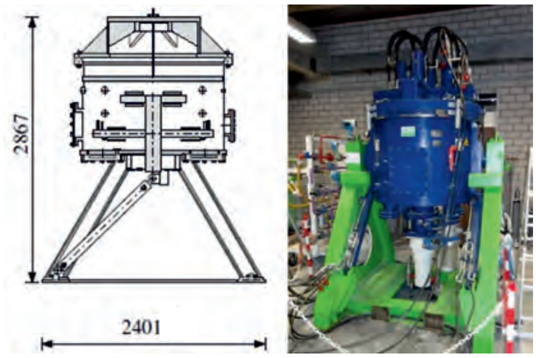

Fig. 3: Large scale test COSMA

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ADAPTIVE CONSTITUTIVE MODELING OF SOIL WITH SPECIAL CONSIDERATION OF DESTRUCTURATION

A5

T. Barciaga, A.A. Lavasan, C. Zhao, T. Schanz

INTRODUCTION

Mechanized tunneling with tunnel boring machine (TBM) is a widely applied method to conduct subsurface infrastructural projects, especially in urban areas. Reliable predictions of ground settlements induced by mechanized tunneling processes require complex numerical interaction models. An advanced 3D numerical model for simulation of the physical aspects which occur in reality has to consider the most decisive sub-models (sequential advance, face support, grouting of the annular gap, lining) and the soil-structure interaction. The complex non-linear soil behavior is modeled using adequate constitutive models.

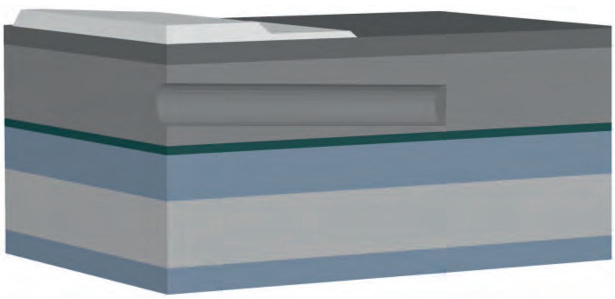

Fig. 1: 3D simulation model for mechanized tunneling: The Western Scheldt case

AUTOMATIC ADAPTION OF CONSTITUTIVE RELATIONS

Due to the complexities of numerical modeling, the identification of realistic model parameters gets more expensive. By employing sophisticated constitutive soil models, the numerical analysis becomes time-consuming and cost-intensive, regarding the computation time and the experimental determination of model parameters. Furthermore, the model responses (e.g. ground settlements, pore water pressures or lining forces) are strongly influenced by the uncertainty of the model parameters.

An adaptive constitutive modeling approach is being developed for reduction of the model complexity. Adaption is defined as allocation of sophisticated constitutive soil models to subdomains which have significant influence on the model response in the nearfield around the TBM.

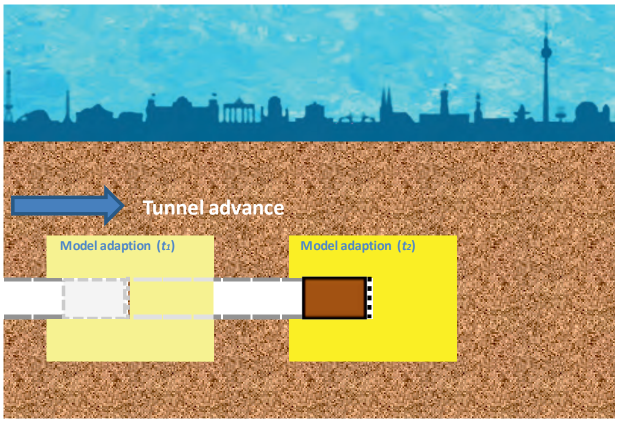

Fig. 2: Concept: Adaption of constitutive relations

Therefore, the criteria for the automatic identification of subdomains are determined by evaluation of temporal evolution of local and global strain energies and the direction of stress paths.

HM-MODEL IN THE NEARFIELD AROUND THE TBM AND AUTOMATIC ADAPTION OF CONSTITUTIVE PARAMETERS

The nonsteady fluid flow in the nearfield around the TBM is a very complex phenomenon, where the flow is induced by cyclic consolidation of the soil or by infiltration of grouting suspension in the annular gap or bentonite slurry at the tunnel face.

The analysis of pore water dissipation and effective stress paths is of main importance for stability and deformation analyses and for the tunnel structural design. Hence, the transient constitutive parameters of the soil model are automatically adopted considering the evolution of state parameters (stress state and void ratio) and temporal progress of consolidation.

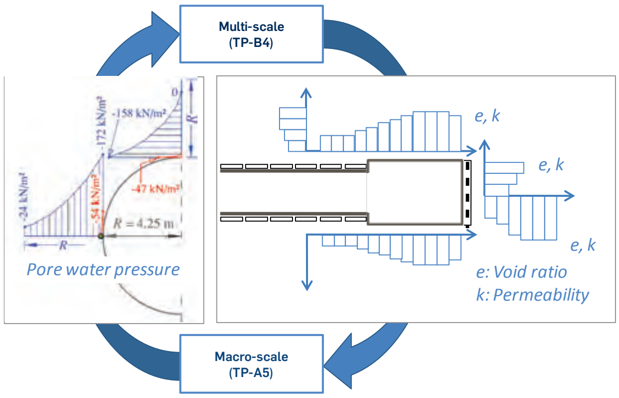

Fig. 3: Concept: Adaption of hydro-mechanical model parameters in the nearfield around the TBM

In order to adequately simulate the interaction between the support media and the surrounding soil, the numerical tunnel simulation model is coupled with a hydro-mechanical model. The coupling approach is based on the automatic exchange of model parameters between a physical model (time and space dependent hydro-mechanical boundaries) and an HM-model (evolution of void ratio, stiffness and permeability).

CONSTITUTIVE MODEL FOR NATURAL STRUCTURED SOILS

Excavating tunnel in natural structured soil deposits is challenging because this type of soil exhibits a complex micro-mechanical and time-dependent constitutive behavior.

Special focus is set on the analysis of the influence of anisotropic fabric and destructuration on the system response in mechanized tunneling. The destructuration is associated with the stress-induced damage of the microstructure (bonding between the particles).

Therefore, adequate simulation of the behavior of natural soils demands an appropriate constitutive soil model in a way that the complex micromechanical behavior of natural soils is sufficiently approximated. Based on the Bounding Surface Plasticity (BSP) concept, a series of hierarchical constitutive models will be formulated, validated and implemented. The BSP concept offers the opportunity of modeling complex stress paths and cyclic consolidation.

Experimental investigations (innovative soft-oedometer) on structured and reconstituted soil samples under isotropic and anisotropic boundary conditions and stress paths are being conducted for parameter calibration and model validation.

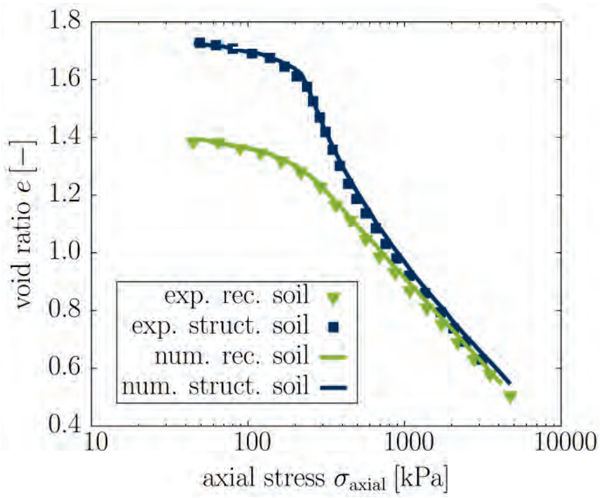

Fig. 4: Compression behavior of structured and reconstituted soil in oedometer tests. Comparison of experimental (symbols) and numerical (lines) results

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1. LAVASAN, A.A. ; BARCIAGA, T. ; ZHAO, C. ; DATCHEVA, M ; SCHANZ, T. : Adaptive constitutive soil modeling concept in mechanized tunneling simulation. (Preprint submitted to Computers and Geotechnics)

2. ZHAO, C. ; LAVASAN, A.A. ; BARCIAGA, T. ; DATCHEVA, M ; SCHANZ, T. : Model Calibration and Validation for Mechanized Tunnel Simulations – The Western Scheldt Case. Preprint submitted to Computers and Geotechnics.

3. SCHINDLER, S. ; HEGEMANN, F. ; ALSAHLY, A. ; BARCIAGA, T. ; GALLI, M. ; KOCH, C. ; LEHNER, K.: An interaction platform for mechanized tunnelling. Application on the Wehrhahn-Line in Düsseldorf (Germany). DOI: 10.1002/geot.201310015, 2014.

LOCAL TRANSIENT FACE SUPPORT WITHIN HYDRO-SHIELDS

I. Popovic, Z. Zizka, T. Schanz, B. Schößer

FOCUS

The excavation chamber is filled with a bentonite suspension (slurry) during hydro shield tunneling. The slurry support pressure is regulated by an air-cushion located behind the submerged wall. The slurry penetrates into the soil skeleton up to a certain distance due to its excess pressure. In this penetration zone, the slurry excess pressure is transferred to the soil skeleton.

Slurry penetration and soil excavation, however, are acting in the same direction (Fig. 1). The excavation is carried out by means of cutting tools fixed on a rotating cutter head of the machine. Thus, the cutting tools are continuously excavating soil from the tunnel front. During the excavation process, the zone at the tunnel face, where the pressure transfer mechanism acts, is periodically damaged by the cutting tools.

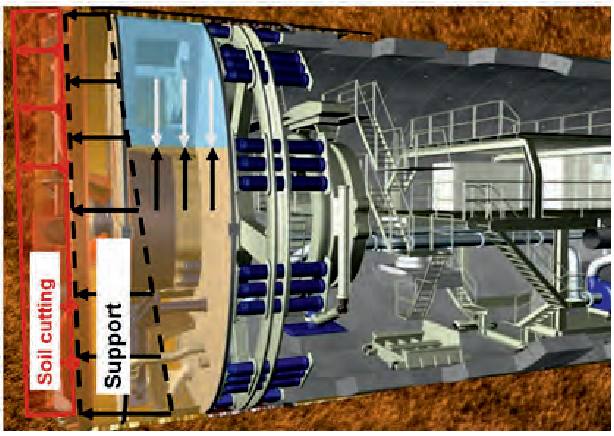

Fig. 1: Hydro shield (Source: Herrenknecht AG)

The chronological superposition of the penetration process of the suspension and the soil excavation results in a local transient process at a particular point on the tunnel face (Fig.2). By periodical passing of a cutting tool through the particular point, the pressure transfer mechanism is herein partially or even completely damaged. The slurry may penetrate again into the soil between the subsequent passings of a cutting tool, and thereby the pressure transfer mechanism may form again.

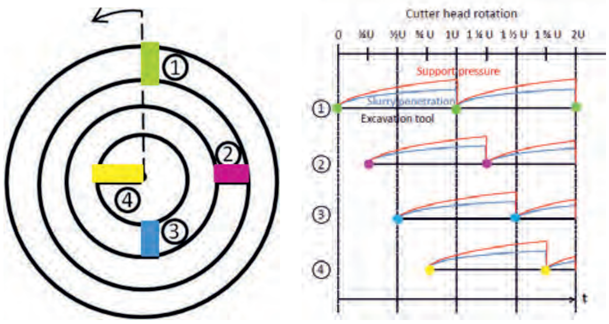

Fig. 2: Arrangement of the cutting tools on the cutter head (left), Superposition of the processes: slurry penetration and soil excavation (right)

The experimental investigations performed within this project aim at a time-dependent description of the possibly occurring soil-mechanical, hydro-mechanical and rheological changes, and furthermore, at visualizing and understanding the simultaneous happening penetration and excavation processes.

CHALLENGE

The penetration of the bentonite slurry into the soil skeleton thereby induces reactions (Fig. 3): (a) flow force is acting in the pore space, (b) the shear stresses are transferred simultaneously on the surface of soil grains due to the yield point owned by the slurry suspension, (c) the bentonite particles are filtered out from the suspension directly on the soil boundary, so that a thin membrane (called filter cake) secures a uniform transfer of suspension pressure on the soil grains, (d) the permeability of the soil is successively reduced by the increasing disposal of bentonite particles within the skeleton. The sum of the all reactions corresponds to the support pressure.

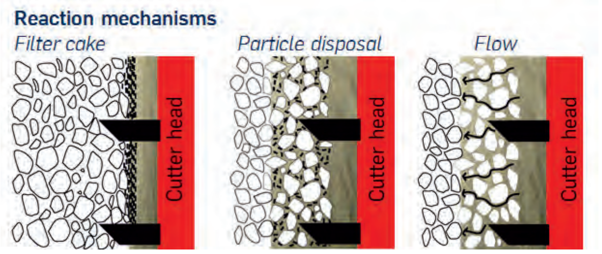

Fig. 3: Reaction mechanisms in the soil

The contribution of the every single reaction is changing successively during excavation, and depends strongly on the observed instant. In this project, the time-dependent processes on the tunnel face during excavation are identified in order to achieve a better understanding of them. Additionally, investigations on the evolution of the soil-system (Fig. 4) and on changes in the slurry rheology during the penetration process are performed. At first, the experiments are carried out separately from each other.

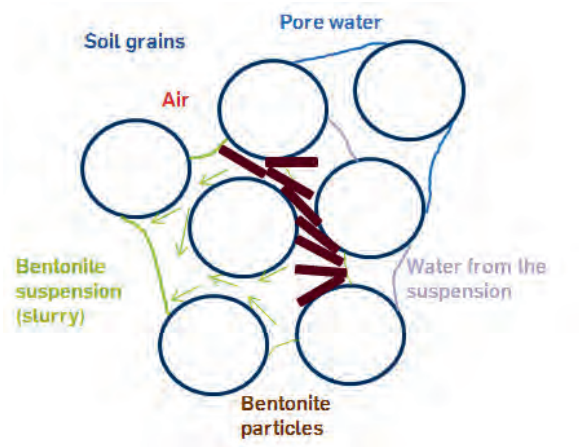

Fig. 4: Changes in soil-system composition

Consequently, all effects are combined in a multiple-scale experimental set-up considering real overburden stresses within the soil. In the multi-scale experimental set-up, the slurry penetrates the soil simultaneously with the soil excavation. Emphasis is given here to the interaction of the slurry suspension and the soil, and to the influence on the variation of reaction mechanisms within the soil.

GOAL

Suitable theoretical and numerical models are to be developed within this project in order to describe the influence of soil-meachnical, hydro-mechanical and rheological changes on the support pressure transfer during excavation.

The models shall enable a description of the local transient processes during the slurry penetration and an assessment of their influence on the global stability of the tunnel face (Fig. 5).

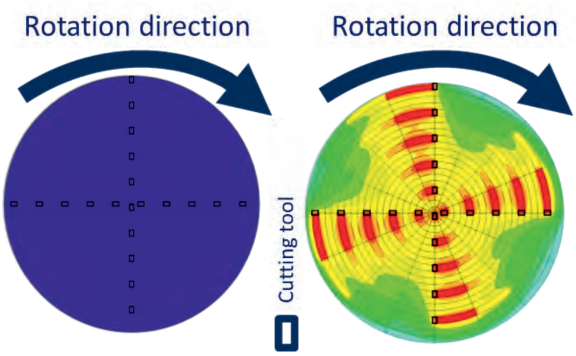

Fig. 5: Model of the homogeneous support pressure transfer (left) and of the transient support pressure transfer (right)

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OPTIMIZED STRUCTURAL SEGMENTS FOR DURABLE AND ROBUST TUNNEL LINING SYSTEMS

B1

T. Putke, F. Song, R. Breitenbücher, P. Mark

INTRODUCTION

Following two complementary approaches the subproject intends to develop hybrid concrete lining segments regarding aspects of safety, durability and robustness. Small-sized and tailor-cut built-in components acc. to the concept "fresh on solid" for specific loading scenarios and a "fresh in fresh" concreting concept for a monolithic production process of segments with two different concrete types are to be investigated and experimentally tested. The global challenge is to integrate the entire chain of production and lifetime, especially focused on damage-relevant construction stages, early into the design process. The proposed concept covers different levels, from detailed analyses on material-level (steel fiber reinforced concrete: SFRC) to individual segments on component-level and finally to tunnel linings on building-level. Particularly of interest are: a) a multi-level optimization-based design concept, subsequent robustness analyses and subsidiary experiments as well as b) the manufacturing process and the development of suitable precast systems with applicable joint and material concepts.

MATERIAL LEVEL

In order to utilize the enhanced ductility of SFRC for the application in segmental tunnel linings, a comprehensive experimental study on its material behavior was conducted. The main objective was to investigate the load bearing and fracture behavior of SFRC particularly under partial-area loading and shear loading.

The partial-area loading tests were designed to simulate the segments subjected to local forces, e. g. jack forces or edge contact pressure on a small-scale. Hereby, the effects of the influential variables on the bearing capacity and fracture behavior of plain and fiber concrete were systemically and intensively studied. As an example, Figure 1 demonstrates the distinctly different bearing behavior between plain concrete and concretes reinforced with various fiber combinations. The SFRCs exhibit a considerable higher bearing strength and an even more ductile post-cracking behavior, particularly in the case of concretes strengthened with fiber-cocktails (e. g. SFRC_L60S60_50). Moreover, with the presence of steel fibers, the fracture mode of concrete changed from a brittle to a ductile one.

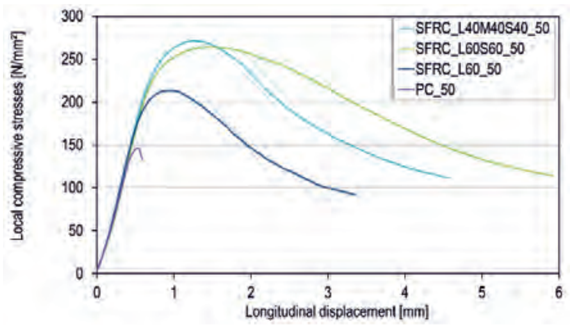

Fig. 1: Stress-displacement behavior of PC and SFRCs under partial-area loading

The behavior of the shear load transfer in circumferential joints of the tunnel linings was then investigated on small-sized prismatic specimens having a cam profile. As illustrated in Figure 2, no difference was observed for the ultimate bearing strength of fiber concrete prisms cast in lying molds compared with plain concrete samples. By contrast, specimens cast in standing forms, in which the steel fibers orientated preferentially perpendicular to the shear plane, showed a drastic increase in the ultimate bearing strength ranging approximately from 50 % up to 150 %. This implies a significant effect of the concreting direction or the fiber orientation on the behavior of fiber concrete under shearing.

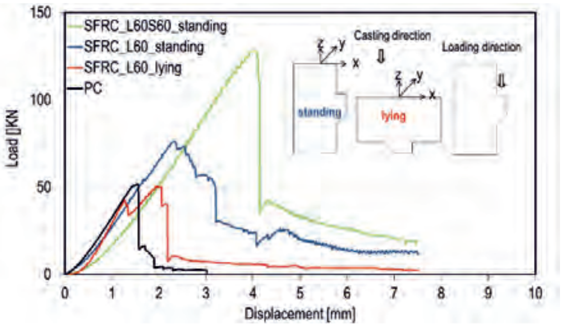

Fig. 2: Load-displacement behavior of PC and SFRCs under shearing

COMPONENT AND BUILDING LEVEL

A design concept based on optimization results was developed at the example of shear load transfer mechanisms in circumferential joints:

In the first step parameterized, numerical 3D models based on finite elements of beam and shell types were used to identify potential damages evaluating the kinematics of the tunnel shell. Thereby, the tunnel lining was modeled as a holistic system with individual segments coupled by nonlinear springs in longitudinal and circumferential joints. Typical loading scenarios representing the final state, e.g. earth pressure and buoyancy induced by ground water, as well as various intermediate construction stages, for instance jack forces (also unsymmetrically applied), grouting pressure or insufficient bedding conditions, are implemented (Fig. 3).

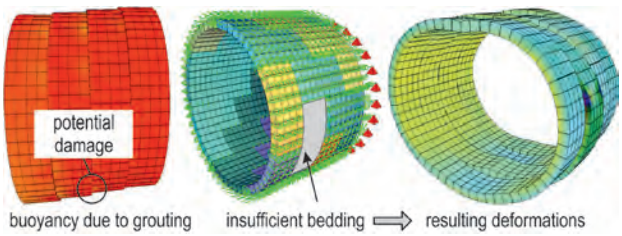

Fig 3: Numerical deformations and Mises stresses for exemplified load case scenario (buoyancy in grouting, insufficient bedding conditions)

In a next step topological optimization methods were employed. They deliver results that are typically characterized by truss-like density distributions and allow for transformation into strut-and-tie models. From these, structural designs by means of appropriate reinforcement layouts can directly be derived. E. g. to increase the load bearing capacity and to prevent edges from spalling steel plates with welded-on rebars in line of afore identified ties were used to transfer loads from the very edge to the center of the specimens (Fig. 4). Alternatively, locally added steel fibers were implemented.

In the last step, experiments on component level were carried out to assess the efficiency and practical feasibility of the designs obtained so far. In contrast to conventionally reinforced samples without explicitly fixed edges the design featuring steel plates and welded-on rebars led to distinctively increased bearing capacities and a generally more ductile bearing behavior. And both bearing capacity and ductility of samples could be increased adding steel fibers in the local zones.

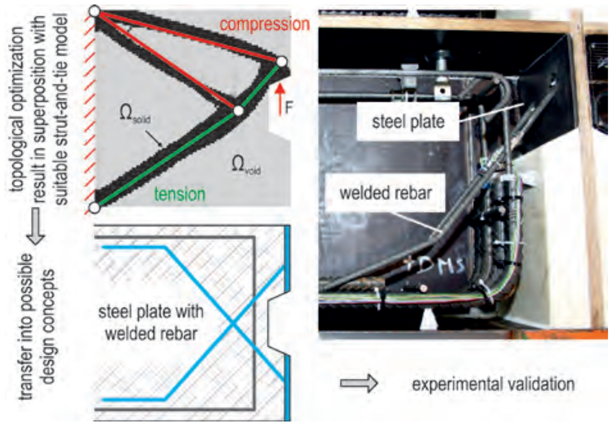

Fig. 4: Steps of the concept for an optimized design at the example of shear coupling

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DAMAGE ANALYSES AND CONCEPTS FOR DAMAGE-TOLERANT TUNNEL LININGS

V.E. Gall, M. Hofmann, J.J. Timothy, Y. Zhan, G. Meschke

GOAL STATEMENT

The goal of the subproject B2 is the development of new tunnel lining designs characterized by an enhanced robustness, especially with respect to construction induced loading conditions (Fig. 1). For this purpose a novel numerical simulation platform is proposed.

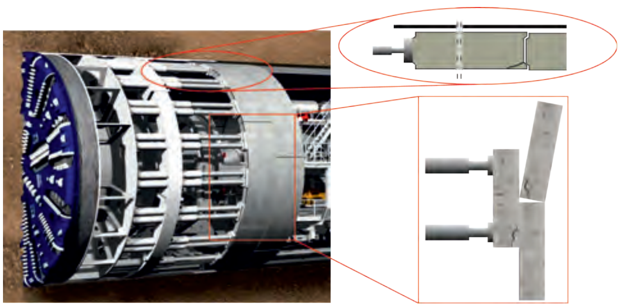

Fig. 1: Possible damage patterns in tunnel lining segments during the excavation process

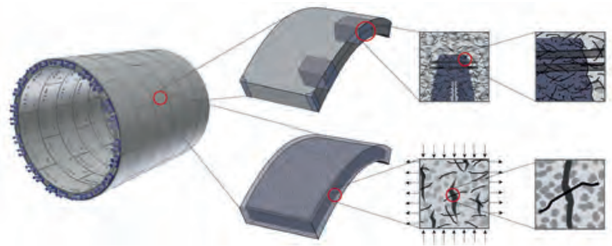

Fig. 2: Prototypes of new robust lining segment design

By means of the integrated utilization of the model components at the material, the segment, and at the lining system level, new prototypes of lining designs are generated. These new lining types are characterized by an enhanced robustness compared to standard linings that is achieved through an optimization of the heterogeneous material compositions (concrete, fiber, steel bar or mesh, etc.) used in the production of lining segments as well as for longitudinal and ring joints. In cooperation with the subproject B1, new prototypes are designed based on proposed techniques (e.g. with combination of precast components and fresh concrete, or with heterogeneous concrete mixture cast at different stages, see Fig. 2).

MULTISCALE MODELING SCHEME OF FIBER REINFORCED CONCRETE

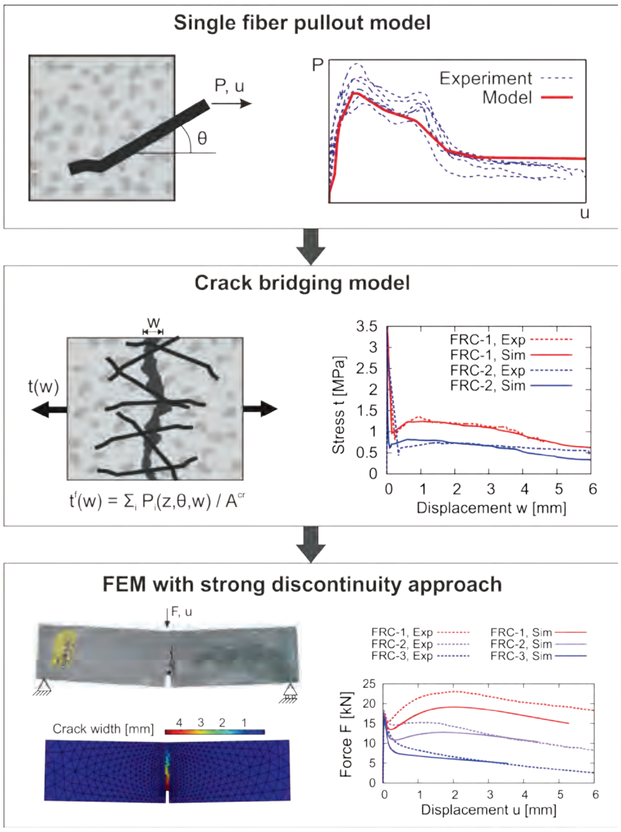

Fig. 3: Modeling of steel fiber reinforced concrete at different length scales

The previous research in the subproject B2 has been oriented towards the development of a multi-level modeling framework, in which the behavior of individual components (concrete, fiber, rebar) and their mutual interactions at different length scales can be captured (Fig. 3). This, in turn, allows the analyses of the influence of various design parameters across multiple scales. At its smallest scale, the multiscale-modeling framework includes an analytical model for the pullout of single steel fibers, with or without hooked-ends, with an arbitrary orientation in respect to a crack. Making use of this model, the crack bridging effect is obtained, from which a traction-separation law is derived and used subsequently in the structural simulation. At the structural level, the finite element method applying advanced modeling techniques for the nonlinear behavior of concrete materials (damage-plasticity model, embedded crack model and interface element) is used to capture the structural strength and the post-peak responses.

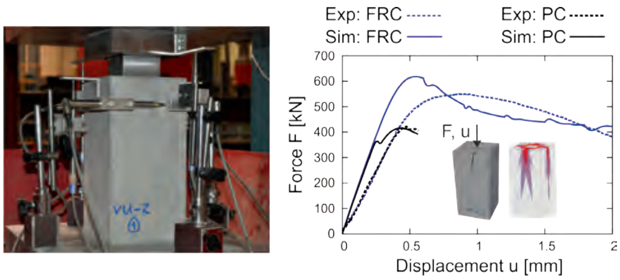

Fig. 4: Partial area loading tests on plain- and fiber reinforced concrete: Left: experimental setup. Right: comparison of the force-displacement curves and crack patterns from experiment and numerical simulation for fiber reinforced concrete (FRC) and plain concrete (PC)

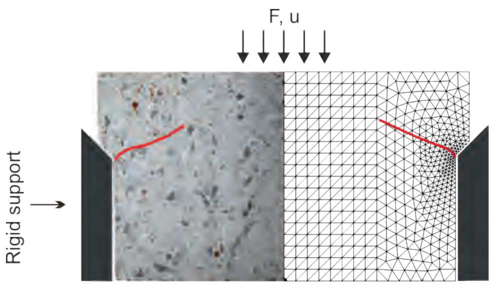

Fig. 5: Experimental and numerical investigation of the shear coupling mechanism in a ring joint: Comparison of crack patterns (left half: experiment, right half: simulation)

Based on this multiscale scheme, the mechanical behavior of lining components in especially vulnerable areas, such as the loading area of hydraulic jacks and the ring joint, can be investigated via numerical simulations. In Figure 4, the numerical results of partial area loading tests on plain- and fiber reinforced concrete specimens are demonstrated. Figure 5 shows the simulation of shear coupling in a ring joint with hybrid reinforcement and a comparison thereof with experimental results.

SUMMARY AND OUTLOOK

In the subproject B2, a multiscale modeling framework for the numerical analyses of fiber-, as well as hybrid reinforced concrete linings has been proposed, which allows the direct tracking of the influence of design parameters from the single fiber to lining structure level. The simulation platform needed in order to investigate improved prototypes of hybrid lining segments characterized by enhanced robustness against construction induced loadings is currently under further development. The research in progress includes a flexible 3D finite element modeling technique using interface solid elements, and an isogeometric finite element model to take into account the imperfections along the joints. Furthermore, the multiscale simulation framework will serve as a submodel for the prognoses of lining utilization and damage as real-time steering indicators during the excavation process.

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ANNULAR GAP GROUTING – DEVELOPMENTS IN CONSIDERATION OF DIVERSE INTERACTIONS WITH BEDROCK AND TUNNEL LINING

B.-Y. Youn, R. Breitenbücher

STATE OF KNOWLEDGE AND OBJECTIVE OF SUBPROJECT B3

In mechanized tunneling during tunnel driving, a gap remains between segment lining and soil with a width of 13 to 20 cm (Fig. 1).

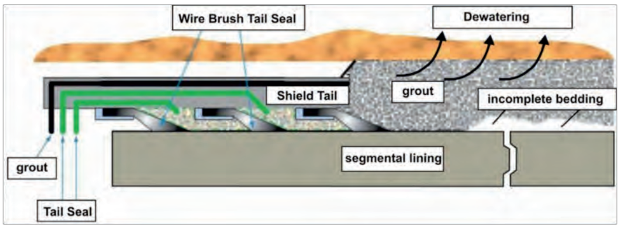

Fig.1: Schematic layout of the annular gap

Instantaneously after mounting of the segment rings, the annular gap must be filled with an adequate grouting mortar to stabilize the tunnel lining and to minimize settlements of the ground surface. The decisive requirements on such annular gap grouts are on the one hand a high flowability lasting several hours as well as a sufficient stability against segregation until grouting, and on the other hand a rapid development of the required shear strength immediately after grouting. The latter is usually achieved by dewatering of the mortar under high pressure into the surrounding soil. Shear strength and stiffness modulus should correspond roughly to the parameters of the respective soil. Thus, two contradictory requirements are demanded on annular gap grouts, which must be fulfilled nearly simultaneously. This requires an appropriate optimization of the component selection and their composition.

Particularly, a flow diameter (tested according to EN 1015-3) of 15 ± 5 cm up to an age of 8 hours of the fresh mortar and a shear strength of at least 2 kPa of the dewatered grout are demanded.

Hitherto, annular gap grouts have been almost exclusively defined on empirical basis. Studies on the grout composition with regard to its dewatering potential and thus shear strength are still missing so far.

METHODOLOGY AND EXPERIMENTAL INVESTIGATIONS

In phase I of the SFB 837, cementitious and cement-free one-component mortars have been investigated systematically under variation of the considerable material-specific and technical parameters with regard to the relevant properties of the mortar (Table 1). Thereby, the significant correlations between the parameters of the components as well as the composition of the grout and therewith-achievable properties have been determined fundamentally. As a basis, grout mixtures were used which already had been applied in practice.

Investigation	Variation parameters
Consistency/workability	i.a. fineness of the fines, type of aggregates, dewatering pressure, thickness of the mortar
Amount of filterable water	
Shear strength	
Infiltration behavior	

Table 1: Testing program

The investigations on the dewatering behavior were performed with a modified filter press, to simulate the conditions in the annular gap with a width of up to 20 cm more realistically (Fig. 2). Thereby, the amount of filterable water, including the temporal effects, was determined under defined conditions (dewatering pressure, filter permeability and dewatering duration). In the course of dewatering/consolidation of the mortar, fine particles are displaced and/or transported to the surrounding soil and lead more or less rapidly to a clogging in the interface between grout and soil, which is called a filter cake. This filter cake influences the further dewatering process of the grout significantly. To evaluate the displacement of the fines, the grain size distributions of individual layers over the height of the dewatered grout specimen were determined by means of wet screening (≤ 0.063 mm).

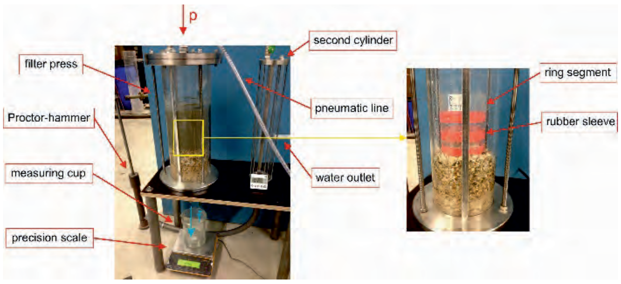

Fig. 2: Modified filter press based on DIN 4127

At additional dewatered grout specimens, the shear strengths were determined with a shear vane according to DIN 4094-4 at different points in time. Before beginning of the filter press test, the shear vanes were pre-installed in different depths of the specimens, to obtain a depth profile of this parameter.

GAIN OF SCIENTIFIC KNOWLEDGE

All investigated grout mixtures exhibited a sufficient workability and flowability (up to 8 h), independent of the amount of the respective additive. However, a significant influence of the granulometry (grain shape, grain size distribution) of the used additives/fines on the consistency as well as on the dewatering behavior could be observed. The expected displacement of fines (D < 4 mm) during dewatering – from the inside to the outside – could also clearly be proven (Fig. 3).

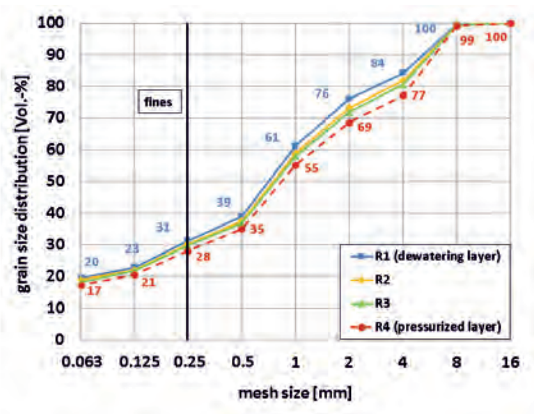

Fig. 3: Grain size distribution of individual layers of a dewatered grout specimen

The amount of coarse aggregates in the pressurized surface (R4) was about 23 %, whereas the dewatered layer (R1) exhibited a relatively small amount of about 16 %.

The achieved shear strength was decisively influenced by the granulometry and, thus, the filler-effect of these fines. With increasing specific surface of the fines and advancing age of the grout, the shear strengths were also increasing continuously. At the end of the dewatering tests, layers in different stages of dewatering were observed over the specimen height. Thereby, deeper layers were almost completely dewatered, whereas the pressurized surface still exhibited a relatively high water content and, thus, lower shear strength (Fig. 4).

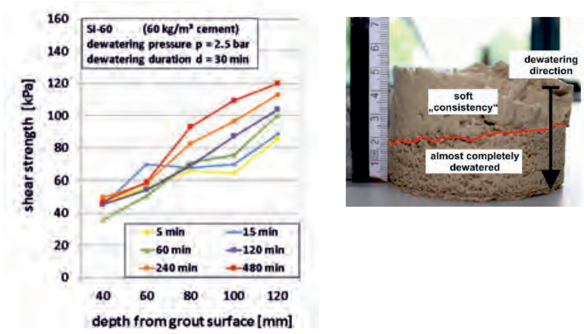

Fig. 4: Shear strengths in different depths (left) and different dewatered layers (right) of a grout specimen

OUTLOOK FOR PHASE II (CURRENTLY)

In phase II the research focus is the development of innovative grouting mortars based on two or more components. Such grouting systems are particularly advantageous for soils with a very low permeability, where the annular gap grout cannot stiffen/consolidate by dewatering. For an alternative development of the required stiffness, additives with physical as well as with chemical properties will be taken into account.

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ANNULAR GAP GROUTING: HYDRO-CHEMO-MECHANICAL MODELING AND SPACE-RESOLVED EXPERIMENTAL INVESTIGATIONS

B4

A. Schaufler, H. Steeb

PRESENTATION OF THE SUB-PROJECT

The sub-project B4 deals with the numerical simulation of annular gap grouting in mechanized tunneling. During the excavation process of the Tunnel Boring Machine (TBM), the diameter of the cutting wheel has to be chosen a couple of centimeters larger than the diameter of the final tunnel construction. Hence, the process results in an annular gap between the tunnel construction and the surrounding soil. During the tunneling process, the surrounding soil is supported by the TBM before the tunnel tube is continued placing the tubbing segments. In order to ensure a continuous support of the surrounding soil, the remaining annular gap is grouted as soon as the particular tubbing segment has been installed. For this purpose, the annular gap has to be thoroughly filled by a suitable mortar for a non-positive connection between the tube and the surrounding soil. This connection is essential to minimize settlements on the surface on the one hand and to prevent the tunnel tube from floating in the annular gap on the other hand.

STATE OF THE ART

State of the art in current technical applications is the continuous grouting of the annular gap using grout supply lines placed in the tailskin of the TBM. This ensures a complete and instantaneous filling of the annular gap in order to minimize surface settlements. An important criterion to measure the quality of the grouting process is the pressure distribution in the annular gap, during and after the grouting process. For this, experimental investigations were performed measuring the pressure distribution in individual tubbing segments during several tunneling projects.

In general, the annular gap grouting mortar needs to fulfill contrary requirements during different steps of the grouting procedure. Before the actual grouting takes place the mortar is pumped through pipes and grout supply lines into the annular gap. This demands a sufficient fluidity of the complex fluid leading to a small shear-viscosity of the mortar. Immediately after the filling, a stable bedding of the tunnel lining is required. Therefore, a rapid evolution of the stiffness of the mortar, i.e. a time-controlled consolidation process has to be ensured. The criterion for a stable bedding is reaching a shear-stiffness of the mortar in the annular gap which corresponds at least to the shear-stiffness of the surrounding soil in its primary stress state. From a technical point of view several possibilities of annular gap grouting mortars can be used.

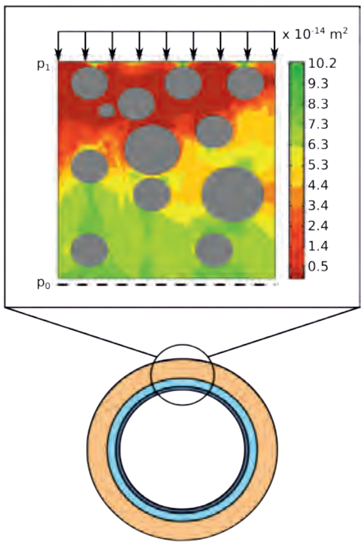

Fig. 1: Permeability distribution in the annular gap and the surrounding soil

In order to overcome the problem of an uncontrolled hydration of the grouting mortar in the supply lines during unwanted disturbances, cement-free annular gap grouting mortars have been lately applied in tunneling projects. Cement-free mortars are characterized by the missing hydration. Thus, the application of cement-free mortars leads to advantages in workability (pumpability), i.e. an adapted fluidity. Due to the missing hydration the required shear-stiffness is achieved by consolidation of the grouting mortar in the annular gap. Therefore, the annular gap is filled by applying a constant grouting pressure. Beyond the filling, the pressure remains constant, leading to consolidation of the grouting mortar.

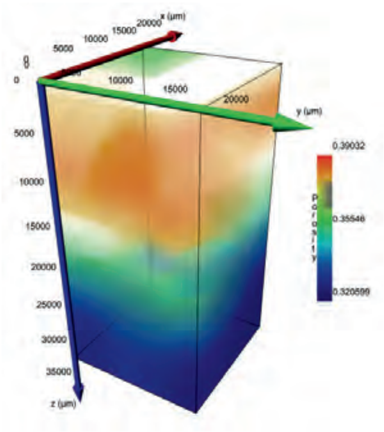

Fig. 2: porosity under as a result of µCT scans a granular mixture weight

The applied pressure induces a convective transport of a suspension resulting in de-watering of the grouting mortar in the annular gap and additional infiltration of fine particles of the suspension to the solid skeleton of the surrounding soil. Due to the reduced porosity of the grouting mortar the contacts between single grains of the grouting mortar are enhanced which causes a significant increase of the shear-stiffness of the grouting mortar and possible evolution of internal or external filter cakes.

OBJECTIVES OF THE PROJECT

The aim of the sub-project is to develop a numerical model for the simulation of the de-watering and infiltration process including the effect of consolidation (hydro-mechanical coupling) within the thermodynamically-consistent framework of the Theory of Porous Media (TPM). Depending on the hydraulic properties of the surrounding soil, the application of classical cement-free mortar or modern two-component mortar leads to particular advantages. A realistic modeling approach for both types of mortars allows an optimization of the grouting process with respect to hydraulic properties of the surrounding soil of a particular tunneling project. Experiments capturing de-watering or infiltration process are a priori heterogeneous. Thus, in this sub-project, advanced spatial discretized experimental methods are developed and performed. Using imaging techniques (X-ray-based micro-tomography and ultrasound-equipped and spatially-resolved triaxial experiment) allows to observe experimentally the evolution of the morphology as well as the evolution of mechanical properties in space and time.

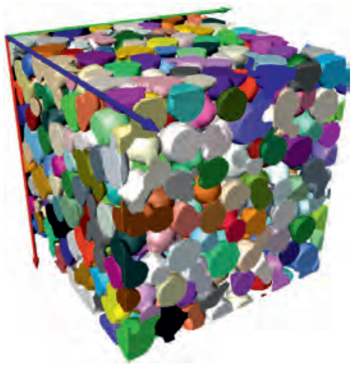

Fig. 3: µCT scan with particle distribution (shown in colour) of a well-graded granular medium

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PROCESS-ORIENTED SIMULATION MODELS FOR MECHANIZED TUNNELING

C1

A. Alsahly, H.G. Bui, B.T. Cao, A. Marwan, J. Ninić, S. Freitag, G. Meschke

GOAL STATEMENT

The subproject C1 is concerned with the holistic process oriented numerical modeling of the mechanized tunneling process in order to predict and to provide recommendations on spatial and time-sensitive steering parameters during the design phase as well as during the construction phase of a TBM drive. The simulation model used for this purpose has been developed within the framework of the Finite Element Method. It enables the realistic simulation of the relevant interactions between the TBM, the surrounding soil, and any on-site above ground structures. This model forms the basis for a simulation and monitoring based support scheme for the mechanized tunneling process that is able to deliver advice on steering decisions in real time.

FINITE ELEMENT SIMULATION MODEL

The simulation platform *ekate* (Fig. 1) has been developed specifically for the numerical simulation of shield driven mechanized tunneling processes. The ground may be modeled as a partially or fully saturated soil within a three-phase framework, and different forms of face support measures can be accounted for. Specifically, the simulation models the advance process of the tunnel boring machine, the deactivation of excavated ground, the application of the face support pressure, the activation of the tunnel lining sections, and the application of jack pressure on the newly installed lining segments. A CAD based automatic model generator as well as parallel computing strategies are being developed in order to insure industry relevance and to minimize modeling and computational time (Fig. 2). In the second phase of the SFB it is planned to incorporate the results of additional sub-models into this simulation model in order to better capture the physics of the TBM advance process.

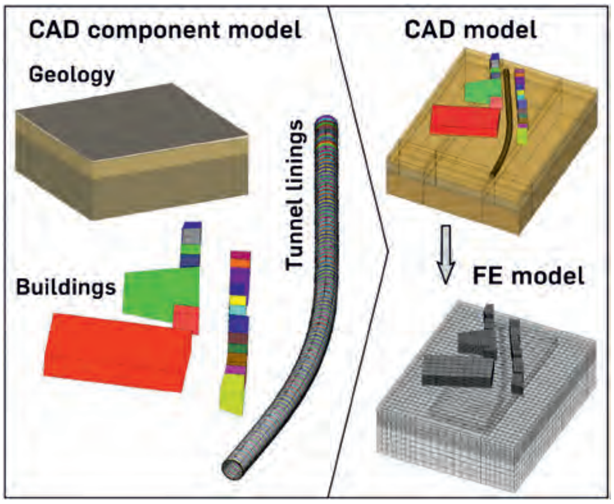

Fig. 2: Automated generation of an FE-Model through combination of CAD based component models

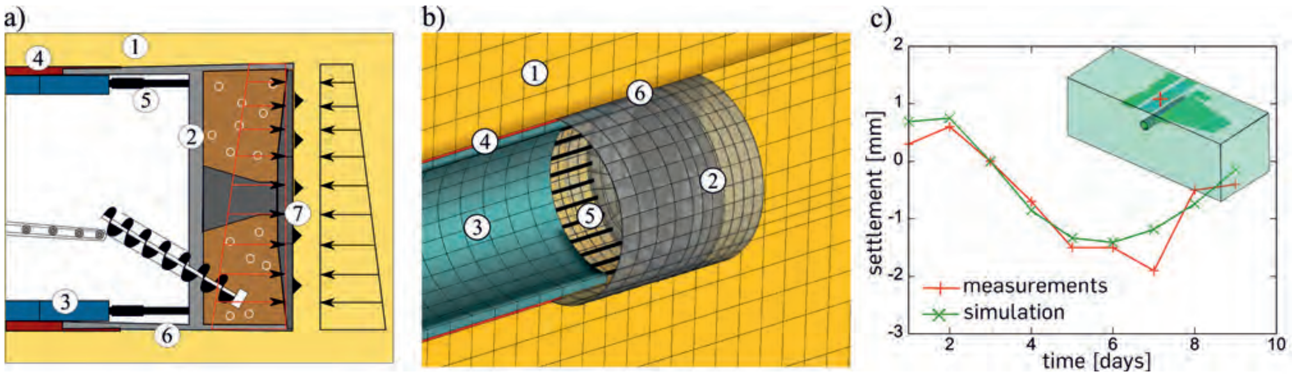

Fig. 1: a) Schematic representation of the components of a TBM drive: (1) soil, (2) shield machine (TBM), (3) tunnel lining, (4) grout, (5) hydraulic jacks, (6) shield skin, (7) cutting wheel und support medium; b) FE simulation model *ekate*; c) Numerical simulation of a section of the Wehrhahn-Linie in Düsseldorf: comparison of the simulation und measurement data

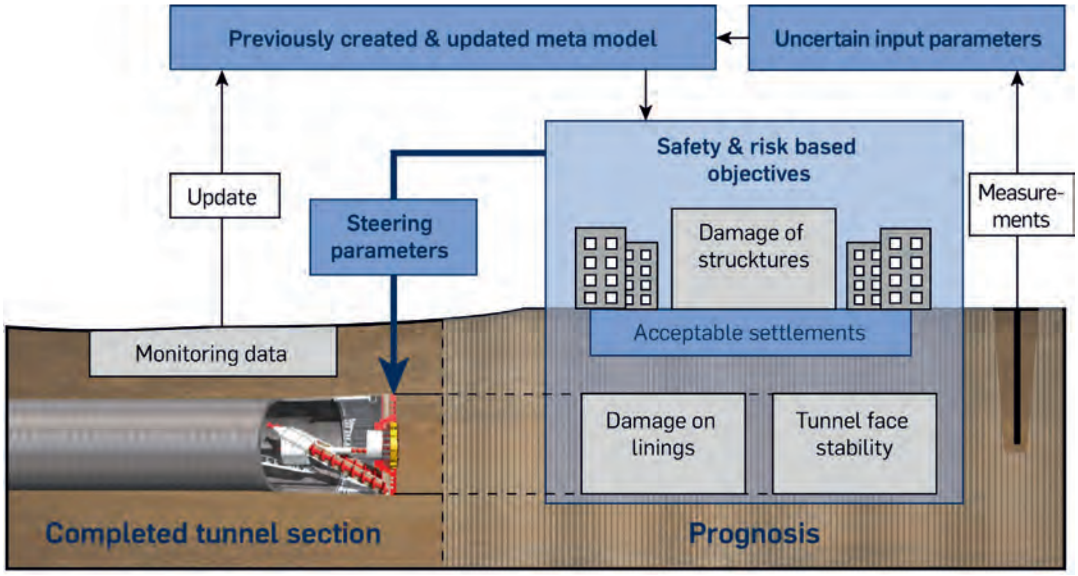

Fig. 3: Concept of the simulation and monitoring based steering scheme for tunnel boring machines

STEERING SUPPORT

The results of FEM simulations and surrogate models form the basis for the development of numerical methods for a real-time simulation and moitoring based TBM steering support scheme that is able to produce results quickly and efficiently during the TBM drive (Fig. 3). These predictions are continuously updated with real time monitoring data and, in turn, use this data to arrive at up-to-date and steering decision advice in real-time. Challenges in the development of this scheme are the consideration of the inherent geotechnical uncertanties of the ground conditions as well as the time varying sensitivty of the steering parameters in respect to the desired outcome of a TBM drive (i.e. the stability of the tunnel face, acceptable settlements and a tolerable level of risk of damage to existing builidings). Figure 4 shows a comparison of settlements arrived at using planned and optimized steering parameters for a representative tunnel section.

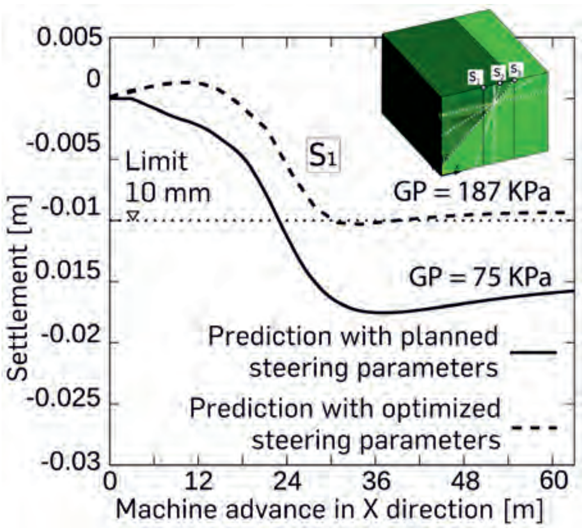

Fig. 4: Calculation of grouting pressure needed to arrive at allowable settlements

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SYSTEM AND PARAMETER IDENTIFICATION METHODS FOR GROUND MODELS IN MECHANIZED TUNNELING

R. Hölter, S. Miro, M. König, T. Schanz

PRESENTATION OF THE SUBPROJECT

The adequate description of subsoil constitutive and geometric properties for numerical simulations of mechanized tunneling is very challenging. This is due to the complex interactions between the subsoil, the TBM, and the surface constructions. However, the more realistic these properties are identified, the more appropriate can be the prediction of the system response (e.g. surface or construction deformations) in the design phase and the execution phase as well. Within the framework of the first phase of this subproject, techniques of identification, validation, and adaptation of adequate soil models for numerical simulations of mechanized tunneling were developed.
Based on the previous results of the subproject, methods of automatic model adaptation based on recorded measurements are being developed. This is being performed in parallel with the development of an optimized measurement design for sensor locations.

PREVIOUS RESULTS

The identification of the model's constitutive and geometric parameters was performed by means of inverse modeling. For this, a numerical model was developed for analyzing the mechanized tunnel driving using slurry-shield machines. In addition to that, due to the time consuming simulation runs that have to be performed in the identification and the sensitivity analysis process, surrogate models were developed to substitute the forward computational model.
The identification techniques for model parameters were verified and validated on the basis of four subsoil scenarios. For this purpose, both deterministic and probabilistic methods were used. In a first step, an adequate numerical model was developed for the sub processes of mechanized tunneling. As there are often several ways of implementing the different submodels, the influences that different concepts may have on the model response were examined.

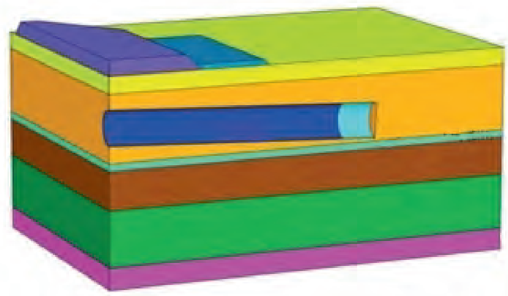

Fig. 1: Numerical Model of the Westerscheldetunnels

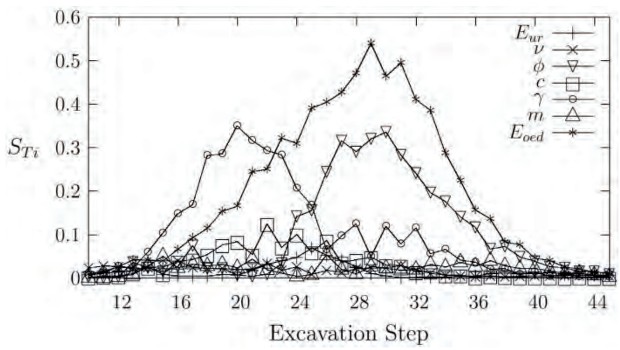

Fig. 2: Sensitivity analysis of decisive subsoil parameters for tunnel driving

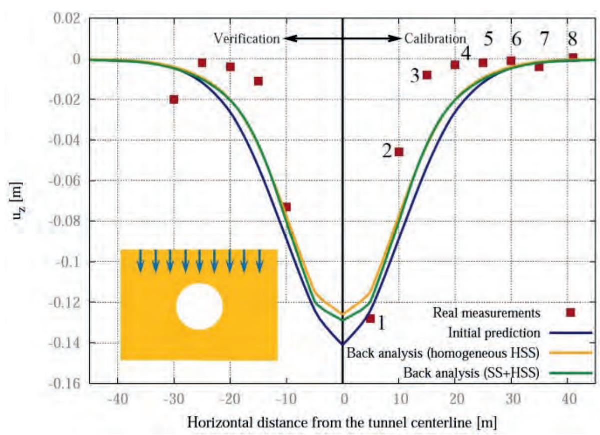

Fig. 3: Validation of the methods by means of real data

OUTLOOK:
OPTIMISED MEASUREMENT PROGRAM

System identification significantly depends on the available measurement data. Here, the quantity, the actuality and the quality of the measurements should be optimally tuned for a successful identification.

Nowadays, due to the ongoing advances in sensor technology, a large amount of measurement data can be recorded. However, the question whether the correct values for a certain problem are available remains often unanswered. Therefore, concepts are being developed, to design a measurement program as optimal as possible, such that relevant measurements can be performed promptly. On the one hand, this reduces the cost and on the other hand it enhances the reliability of system identification. Different technical aspects concerning the task of an optimal measurement setup such as sensor clustering, or displacements of sensors while measuring are relevant in tunneling and will be considered in the context of this subproject.

In mechanised tunneling problems, the relevant boundary conditions must be classified and adequately described. Additionally, appropriate assignments of subsoil properties should be enabled through a parameter identification process. For that, better sensor locations could possibly be achieved in future based on these studies.

Meanwhile, the possible uncertainties of the model parameters have to be considered explicitly. For identification of an optimized measurement setup based on current subsoil situation, measurement data, and predicted changes, methods of heuristic optimization shall be used. The verification of the surrogate models, the procedure of generating new scenarios, and the alignment of optimized measurement setups is carried out by means of synthetic data. For this, the numerical simulation models created in the first phase are employed.

Furthermore real measurement data shall be used to validate the concepts. Data of two tunneling projects (Wehrhahn-Metroline Düsseldorf and City-Tunnel Leipzig) are at the disposal of the whole SFB.

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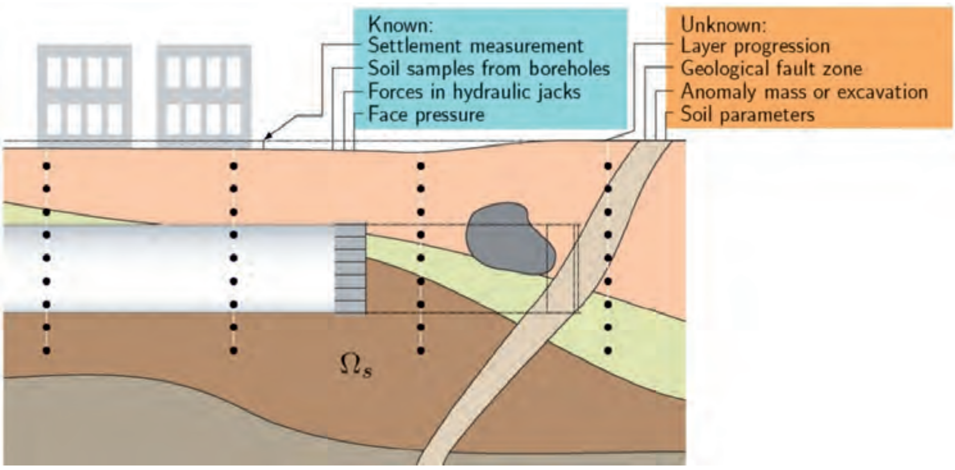

Fig. 4: Identification, validation and adaption of subsoil models based on measurement data

SIMULATION OF PRODUCTION AND LOGISTIC PROCESSES IN MECHANIZED TUNNELING: SIMULATION-BASED MAINTENANCE AND AVAILABILITY ANALYSIS

A. Conrads, R. Duhme, T. Rahm, M. Scheffer, M. König, M. Thewes

PROBLEM AND MOTIVATION

To achieve a good performance in mechanized tunneling, all components of the tunnel boring machine (TBM) have to be adapted to the given boundary conditions. Subsequent modification of TBM setup or supply chain is mostly not possible, or requires much effort. However, accurate planning of the supply chain supports production processes and reduces or avoids times of standstill. For this design, the disturbances of the advance and their effect on the whole system performance has to be taken into account.

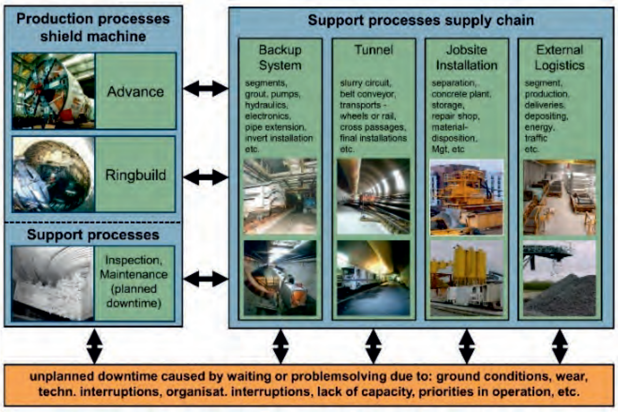

Fig. 1: Interaction of production and support processes in mechanized tunneling

For this purpose, process interaction between the system components as well as the cause of disturbances has to be well examined beforehand. In particular, disturbances of the supply chain as well as technical failures of machine components have to be regarded. Furthermore, the complex interaction of surrounding soil with the cutting tools has to be considered. In addition to the unplanned time of standstill, scheduled stoppages of the production processes for the extension of the supply line as well as for maintenance has to be taken into account.

Simulation of all operational processes, as well as occurring process interaction, provides an opportunity for a detailed and holistic analysis of coupled system 'TBM + supply chain'. Simulation input data is provided based on extensive data analysis of process duration and disturbance frequency of finished projects. Subsequently, occurring disturbances are considered according to their type, rate and duration.

RESULTS OF THE 1ST PHASE

Within the first phase a simulation toolkit for analyzing production and logistical processes was developed. Considering the hierarchical structure of TBM and jobsite, flexible simulation components representing individual process chains and dependencies. Special purpose simulation models can be created using these flexible simulation components without code adaption or generation. The hierarchical structure enables a clear model organization and easy analysis of component dependencies.

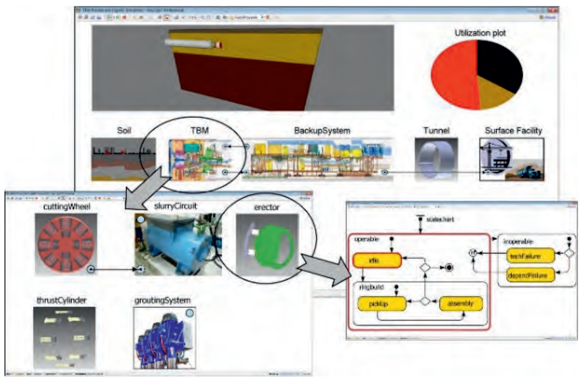

Fig. 2: Simulation model implemented in *AnyLogic* simulation software

Currently we can provide the following features:

- Holistic analysis of production processes and logistical concepts;
- Fast evaluation of different project setups
- Using data fitting methods generating stochastic simulation input data;
- Uncertain boundary conditions based on fuzzy logic formulations;

- Consideration of disturbances and cascading effects (failure propagation) within the process chain.

Formal description of performance influencing elements for jobsites in mechanized tunneling were developed using the System Modeling Language (SysML). Further, in order to evaluate effects of single disturbances on production performance, element dependencies were formulated in SysML graphically as well. Methods of data fitting were applied on a reference project to create a basic concept of typical disturbances and durations. The model components are implemented in the Anylogic multi-method simulation software. First, performance analysis were realized and validated based on the reference project.

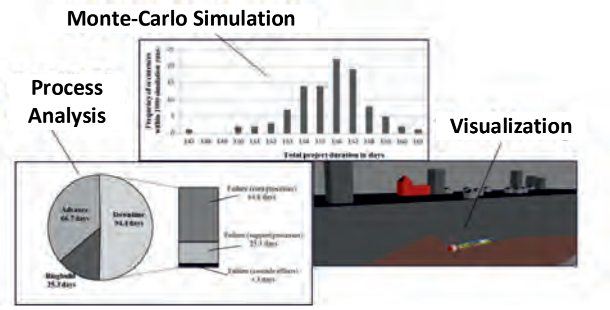

Fig. 3: Simulation results in different

GOAL OF THE 2. PHASE

The 2nd phase focuses on the simulation-based implementation of the maintenance strategies of a TBM, especially for the cutting tools. Different maintenance strategies are going to be analyzed and applied in mechanized tunneling. Particularly entering the pressurized excavation chamber has a lot of restrictions, thus generates long times of standstill. Reaching the wear limit, cutting tools have to be replaced in order to avoid damages at other components of the machine. Determining the state of the cutting tools without entering the excavation chamber is hardly possible. The instant of time when the wear of the cutting tools reaches that limit shall be determined by developing a meta-model including the results of subproject C5. Based on that an optimal scheduling of maintenance processes considering the right point in time as well as convenient boundary conditions can be found. This scheduling is based on several parameters:

- wear of the cutting tools;
- Geology / Hydrology;
- surface development (subproject D3);
- disturbances and planned times of standstill.

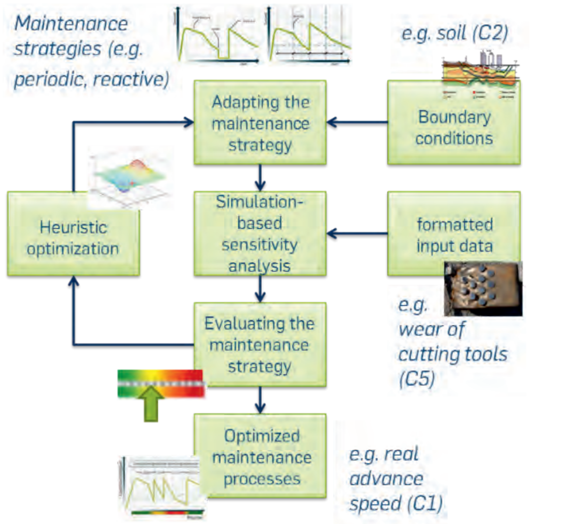

Fig. 4: Simulation-based optimization of maintenance strategy

Introducing maintenance strategies as simulation components enables a flexible evaluation and comparison of different concepts. To conduct simulations under realistic conditions, the model's input parameters are chosen in correspondence with complex and uncertain boundary conditions. Thus, the applied maintenance strategy can be optimized concerning efficiency and resistance to disturbances. At the end of the second project phase, the simulation results shall be validated using data from real construction projects.

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C4

SIMULATION OF THE SOIL-TOOL INTERACTION AND THE TRANSPORT IN THE EXCAVATION CHAMBER

T.S. Dang, N. Wessels, A.R. Leon Bal, K. Hackl, G. Meschke

INTRODUCTION

Topic of research in the subproject C4 is the development of models for the computational analysis of the interaction of the cutting wheel of tunnel boring machines (TBMs) with the soft ground, including the excavation and transport of the excavated material and the abrasion behavior of the cutting tools. The project goal is to more accurately predict the actual face pressure distribution in Earth Pressure Balance (EPB) machines, the transport of the excavated soil and its mixing with the conditioning foam in the pressure chamber and to better understand the influence of the soil-tool interaction on the abrasive behavior of cutting tools.

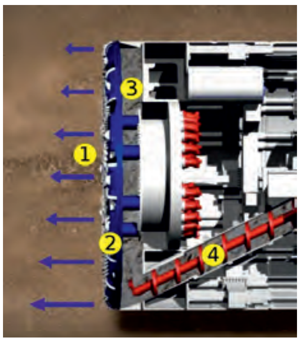

Fig. 1: Aspects of investigation of soil-machine interactions in earth pressure balance tunnel boring machines: (1) Face pressure, (2) excavation process and abrasion of cutting tools, (3,4) material flow inside the pressure chamber

Two project lines have been followed so far: i) numerical modeling of the cutting and abrasion processes of TBMs in soft soil and ii) the numerical simulation of the transport and mixing processes in the excavation chamber. A third project line concerned with laboratory testing will be established to validate the numerical models.

CUTTING AND ABRASION PROCESSES

The Discrete Element Method (DEM) is used to model the excavation process and to investigate the dependence of the excavation process on various parameters, such as cutting speed, penetration depth and cutting angle (Fig. 2). The flux of the excavated soil resulting from the DEM simulation is imposed as an inflow condition for the transport simulation to allow for the analysis of interactions between excavation and transport processes. DEM parameters are identified such that the model represents the material behavior equivalent to a Mohr-Coulomb model.

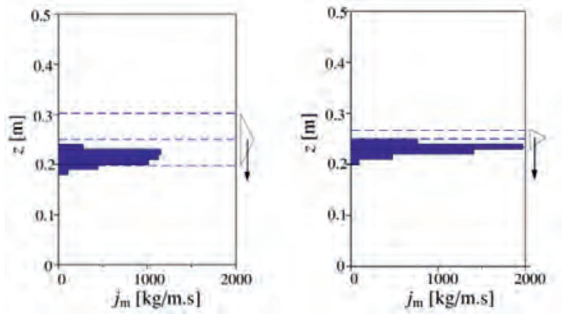

Fig. 2: Simulation of cutting process with a single tool: Profile of the excavated soil flux for 2 cutting tool angles

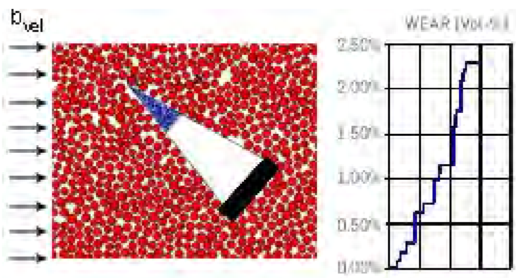

Fig. 3: Simulation of the abrasion process using the DEM

To investigate the abrasion progression, a single cutting tool has been analyzed with the DEM (Fig. 2). The model distinguishes between the top part of the tool, which consists of brittle carbide metal, and the carrier part, which made of a more ductile steel.

TRANSPORT AND MIXING PROCESS IN THE EPB PRESSURE CHAMBER

The soil-foam-water mixture inside the pressure chamber is modeled as a two-phase mixture, in which one phase represents the soil-water and the other one the foam-water mixture. Figure 4 shows results from a 2D analysis of the mixing process of two viscous fluids disturbed by stirrers. The flow of the two-phase mixture is simulated in the framework of the Particle Finite Element Method (PFEM). The viscoplastic parameters of each phase are obtained from experimental data of subproject A4.

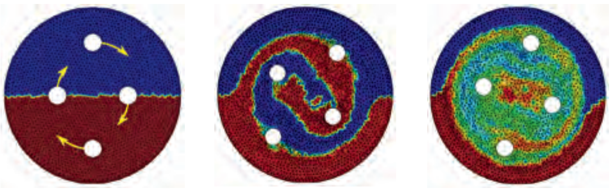

Fig. 4: Simulation of the mixing process of a viscous two-phase mixture: Evolution of volume fraction of one phase

To investigate the transport and mixing process in the pressure chamber of EPB machines, 3D models were developed. Figure 5 shows the results of an analysis of a two-phase mixture flow in the pressure chamber considering the rotating influx at the cutting wheel and the foam injection from the rear wall of the chamber.

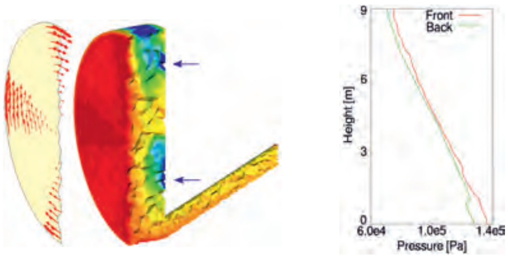

Fig. 5: Simulation of material transport in the pressure chamber: Distribution of one phase (left) and pressure distribution along the front and rear wall (right)

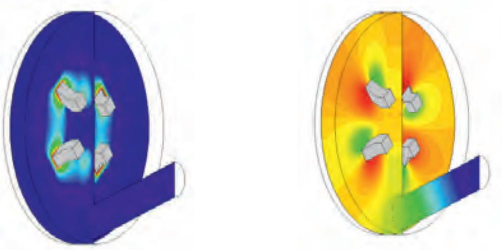

Fig. 6: Simulation of (single-phase) flow in the pressure chamber with moving stirring arms: pressure (left) and velocity distribution (right) in the chamber

In another model, moving mixing arms are considered in the analysis of a one-phase flow in the chamber (Fig. 6). The Immersed Boundary Finite Element Method is employed to allow the description of the moving boundary. The numerical simulations will be further used to analyze the spatio-temporal mixing process as well as the pressure distribution for different configurations. The parameters of the viscous constitutive model for the soil with a pressure dependent yield stress are identified from back analysis of a slump test (Fig. 7), using the Particle Swarm Optimization technique.

To accurately model the soil behavior during the excavation process, in which the soil changes from a solid to a fluid-like state, a constitutive model describing this solid-fluid transition is developed. Figure 8 shows results from an excavation simulation using the Particle Finite Element Method.

Fig. 7: Parameter identification by means of numerical analysis of the slump test: Results from the Particle Finite Element Method (left), and from the DEM (right)

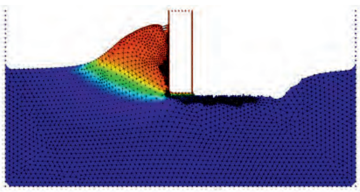

Fig. 8: Numerical simulation of the soil cutting process using a constitutive model able to represent the transition from a solid to a fluid state

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WEAR BEHAVIOR OF TBM-TOOLS IN SOFT GROUND TUNNELING OPERATIONS

M. Alber, J. Küpferle, A. Röttger, W. Theisen

INTRODUCTION INTO THE SUBPROJECT C5 – STRUCTURE OF THE PROJECT

Wear and the associated service life of tools are counteracting the efficiency of tunneling processes. Until today insufficient knowledge about acting wear mechanisms and the interactions between minerals and the tunneling tools in soil is available. Based on this circumstance no reliable predictions about the wear condition and the remaining service time of tunneling tools can be obtained. On this account, the complex tribological system will be briefly described in the subproject C5 by material-related investigations with regard to the wear mechanism and the type of wear. In addition, the determined wear mechanisms will be investigated in a new wear testing device, allowing the estimation of a meaningful wear rate of tunneling tools with regard to more realistic boundary conditions like abrasive size and hardness, load spectrum and material of the base body.

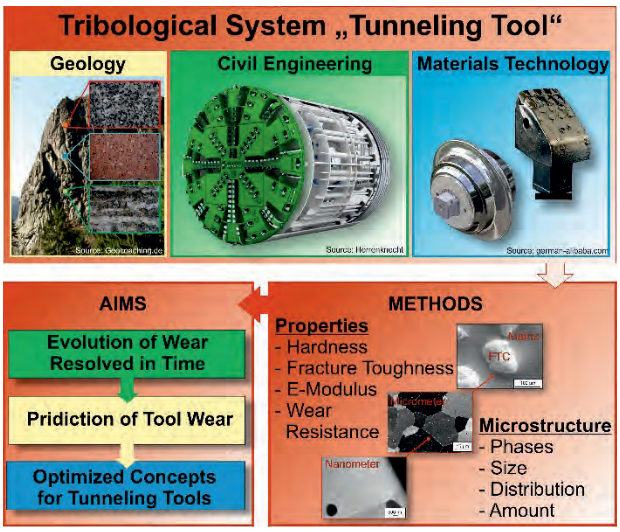

Fig. 1: Mapping of the tribosystem "tunneling tools" and basic aims in the subproject C5

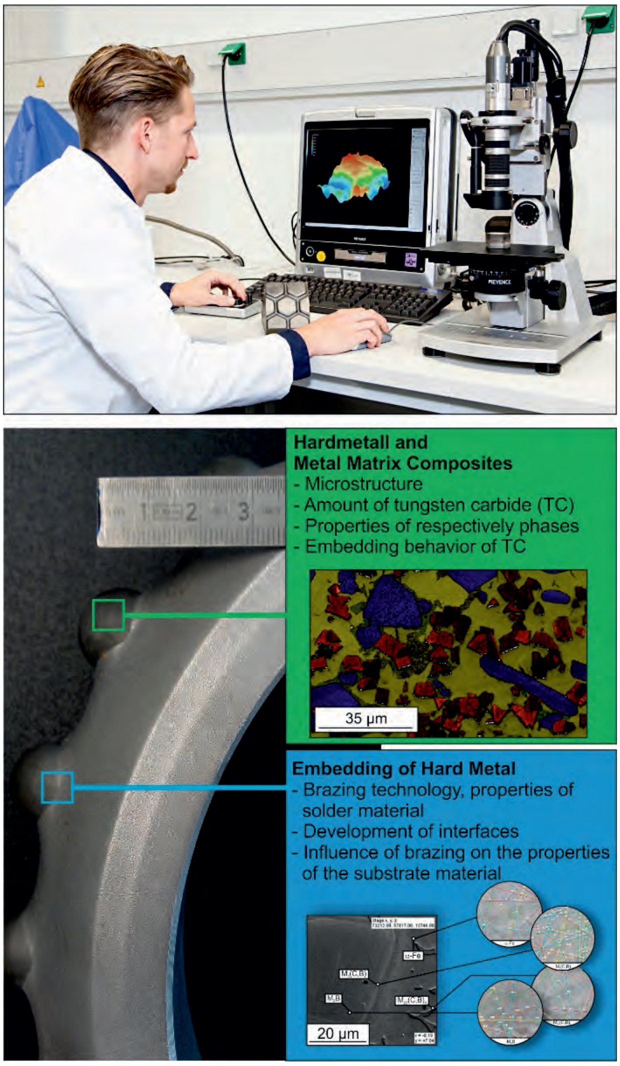

Fig. 2: Investigation of the dominating wear mechanism of worn tunneling tools using optical and scanning electron microscopy

Within the last two decades many tests were developed, allowing a first rough estimate of the abrasivity of soils and hard rock. Hence, a prediction of the service life of tunneling tools could be evaluated. Thereby, the soil or the hard rock is tested against a comparative material, for which reason the real tribological system cannot be mapped by the existing testing methods. As a consequence, the gathered results only provide tendencies of the real tribological behavior. In contrast, real materials which are commonly used for tunneling tools will be considered in the new developed wear testing device. These integral wear tests will be supplemented with single scratch tests using a diamond indenter, giving a deeper understanding about the micro-mechanisms (micro-ploughing, micro-scratching, micro-cracking), acting on submicroscopic scale in the materials microstructure.

AIMS AND SCIENTIFIC-TECHNOLOGICAL QUESTIONS

It is the aim of the subproject C5 to describe the complex tribological system of tunneling tools in soil. Therefore, beside microstructural analysis of worn tunneling tools a new test method should be developed which allows a clear definition of the interactions between the soil and the tunneling tool. At least these investigations should provide a time-resolved description of the wear behavior of tunneling tools during operation. Based on this knowledge it is the main aim to provide a more practical prediction of the wear behavior of tunneling tools. To reach the overall aim, the following scientific-technological questions have to be answered:

A) Which tribological system is present with regard to the geological conditions and to the tunneling-tool concept?
B) How can the interaction between soil and tool material be mapped on laboratory scale?
C) Is it possible to measure in-situ the current state of wear of tunneling tools during operation by the implementation of suitable electronic measuring equipment?
D) Which influences do material properties like fracture toughness of the abrasives and the tool materials possess on the durability of the tunneling tools?
E) How does a change in the geological behavior affect the tribological system? Might these changes in the geological behavior be recognized during tunneling operation by the implementation of suitable measuring equipment?
F) Is it possible to provide a precise prediction of the tunneling wear by the measured tribo-mechanic values from the laboratory test? Which material concepts can be deduced?

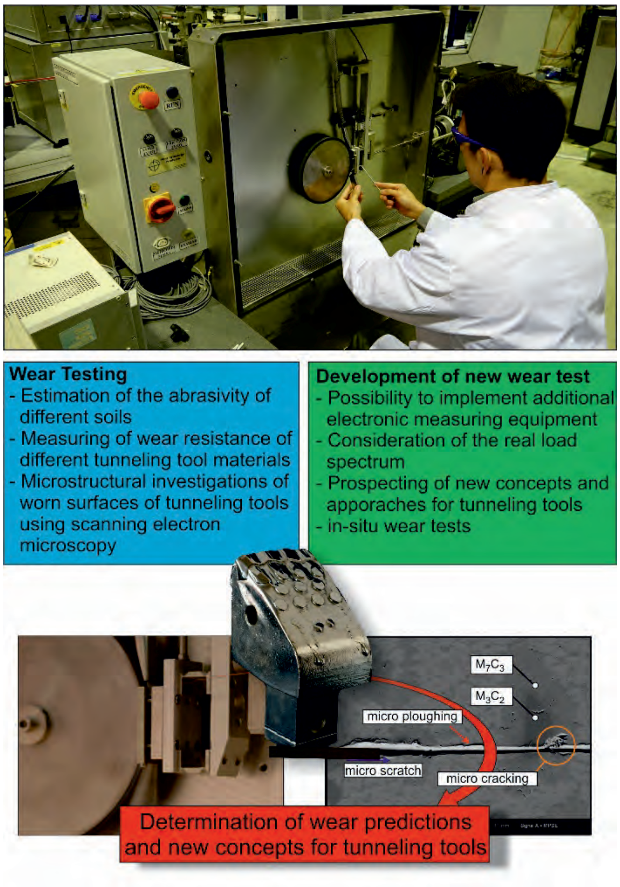

Fig. 3: Performing of tribological tests and the development of a new wear test to evaluate the residual service life of tunneling tools

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ASSESSMENT OF INTERACTION MODELS IN MECHANIZED TUNNELING

K. Lehner, F. Hegemann, P. Manickam, M. König

PROBLEM AND MOTIVATION

The transparent, comprehensive and detailed planning and evaluation of individual systems and processes in the field of mechanized tunneling is essential to keep the risk of tunnel construction at an acceptably low level. The interactions between the soil, the TBM, the tunnel itself, above-ground constructions and the material flow play an important role. In the first phase, basic concepts related to the data modelling of all essential system elements, processes and interactions have been developed. The information related to individual system elements have to be represented in an expandable product model. In particular, information-based concepts are necessary to capture the interrelations of individual system elements and processes when investigating specific issues in mechanized tunneling.

RESULTS OF THE FIRST PHASE

The execution of a single interaction or an entire chain of interactions requires the availability of relevant information. This information is based, on the one hand, on existing product data and, on the other hand, on temporary results that are calculated and directly exchanged between program components. To manage and store such basic data, a 4D information model for mechanized tunneling was developed. Information pertaining to tunneling projects are often available only in a time dependent manner, distributed over various computer systems and coded in a variety of data formats. To enable a coherent and uniform data access, all relevant information needed for the planning and execution of tunneling projects was classified, structured and linked in a holistic, object-oriented Tunnel Information Model (TIM, see Fig. 1), the basis for the implementation of interactions in mechanized tunneling. In the first phase of this project, four main sub-

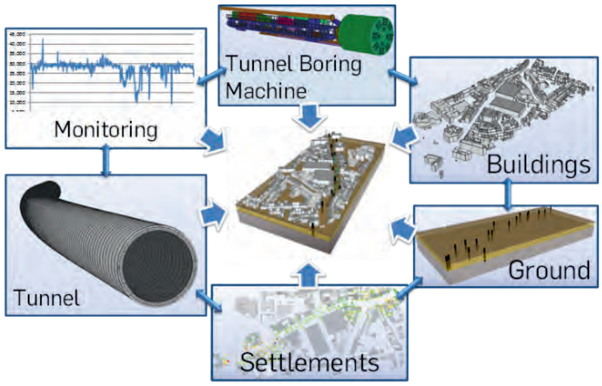

Fig. 1: The tunnel information model consisting of four main sub-models und the time dependent settlement and machine data

models of mechanized tunneling were specified and coupled.

The sub-models are: a hybrid model of subsoil data, a machine model, a model of the tunnel construction and a model of the built-up area. These models were chosen due to their significant influence on the construction process. The type of soil influences, for example, the driving speed, the settlement and the annular gap grouting. The modelling of interaction chains are based on the concepts of systems engineering, formally implemented by the Systems Modelling Language (SysML). Here, the basis is defined by a meta-model for defining interaction chains. An interaction chain consists of a collection of product data, analysis methods and interaction elements. An interaction element is based on the exchange of information between two analysis method components. The control of an interaction chain, which consists of several interconnected, individual interactions, occurs by defining interaction workflows. To address individual problems, specific analytical methods and interactions were created. In particular, methods were developed for the numerical simulation of the TBM advancement (DrivSim, TP C1), the annular gap grouting (GroutSim, TP B4) and for the machine logistics and

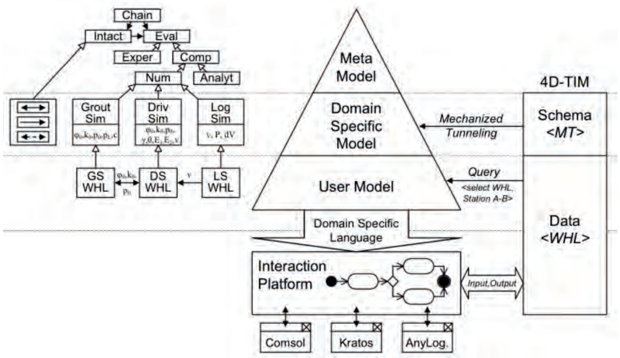

Fig. 2: Definition and execution of interaction chains based on a domain specific modelling language

process chain (LogSim, TP C3). Also, a domain-specific modelling language was developed to specify the identified interaction chains (see Fig. 2).

OBJECTIVES OF THE SECOND PHASE

In the second phase of the D1 sub-project, methods for assessing problem-specific interaction chains in mechanized tunneling are to be developed. Both the fuzzy nature and the transient state of data and models must be considered. Special focus is given to the adequate consideration of machine data and data related to the current soil and settlements. This data must be integrated in a transparent and consistent manner into the interaction chain models by systematically augmenting the interaction platform with corresponding methods. In particular, methods will be developed and verified using concrete problems.

A major scientific objective is the evaluation of the quality of results gained by using interaction chains based on an appropriate context-sensitive metric to quantify such results. However, since a proper evaluation of an interaction chain should not be made based solely on analytical methods, further methods need to be developed to navigate and visualize complex interaction chains (see Fig. 3). Here, navigation and visualization methods are based mainly on the work done in the first phase related to product and interaction models. After a successful evaluation of existing interaction chains, the question often arises whether a higher quality of results can be achieved by certain adjustments. For this purpose, approaches will be developed that can provide information about the cost of possible adjustments and the quality of results thus obtained.

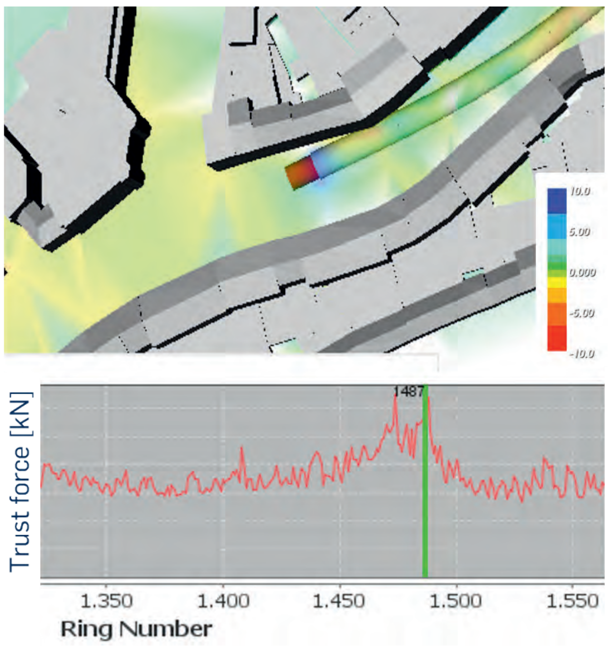

Fig. 3: A visual representation of the connection between settlements and TBM driving forces

Another goal is the development of concepts for storage and reuse of experiences in the context of modelling, use and adaptation of interaction chains in mechanized tunneling. For this purpose, methods are being developed to build a knowledge base.

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MODEL-BASED RISK ANALYSIS FOR HETEROGENEOUS EXISTING STRUCTURES

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PROBLEMS AND AIMS

Surface settlements induced by mechanized tunneling are generally inevitable. At the same time and in particular due to potential damaging effects on existent buildings they naturally are in the focus of owners, construction companies and local residents. Because of a generally high sensitivity to settlements a sound and reliable assessment of potential damage risks is crucial for each tunneling project to be successful.

Hence, the aim of project D3 is to develop an interactive evaluation system to assess damage risks of heterogeneous but standardized structures by means of individual risk profiles already during the planning stage of new tunneling projects. The interactive evaluation system minimizes the efforts to identify and assess the risk of damage and improves the rating score's quality considering fuzzy parameters inherently. That way, individual structural analysis of aboveground buildings is widely rendered unnecessary and limited to very special cases.

DATA ACQUISITION FOR DEFORMATION ANALYSIS OF EXISTING STRUCTURES

In cooperation with the German Aerospace Center (DLR), the Institute of Geodesy and Photogrammetry at TU Braunschweig and the State Capital City of Düsseldorf about 16.000 measurement points, so called Persistent Scatterer (PS), along a one kilometer long shield tunneling project in Düsseldorf have been collected and conditioned (Fig. 1). The accuracy of the Persistent Scatterer Interferometry (PSI) has been rechecked, so that an average standard deviation about ± 1.5 mm compared to terrestrial, but locally-restricted, procedures can be reported. This emphasizes the feasibility of radar interferometric monitoring of ground settlements caused by tunneling in practice.

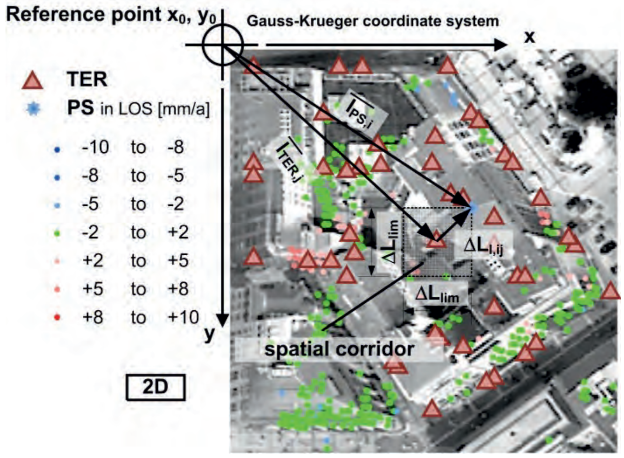

Fig. 1: Accuracy analyses of the Persistent Scatterer Interferometry (PSI)

VULNERABILITY ANALYSES

Applying vulnerability and sensitivity analyses allowed the assessment of individual effects regarding various parameters separately; e. g. the window factor or the building's position above a settlement trough (Fig. 2). The simulation process was systematically enhanced, employing modified interface-elements to account for soil structure interaction and adapting nonlinear material models, e. g. for masonry structures.

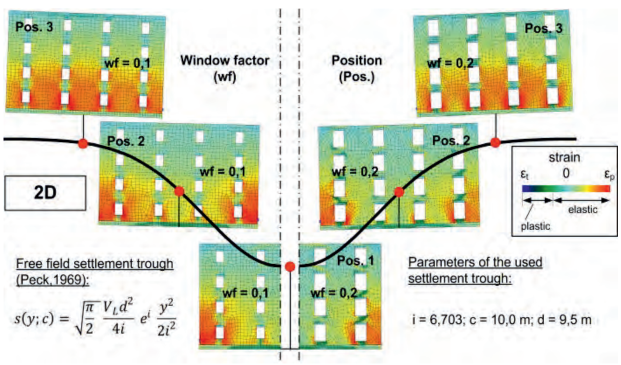

Fig. 2: Results of vulnerability analyses

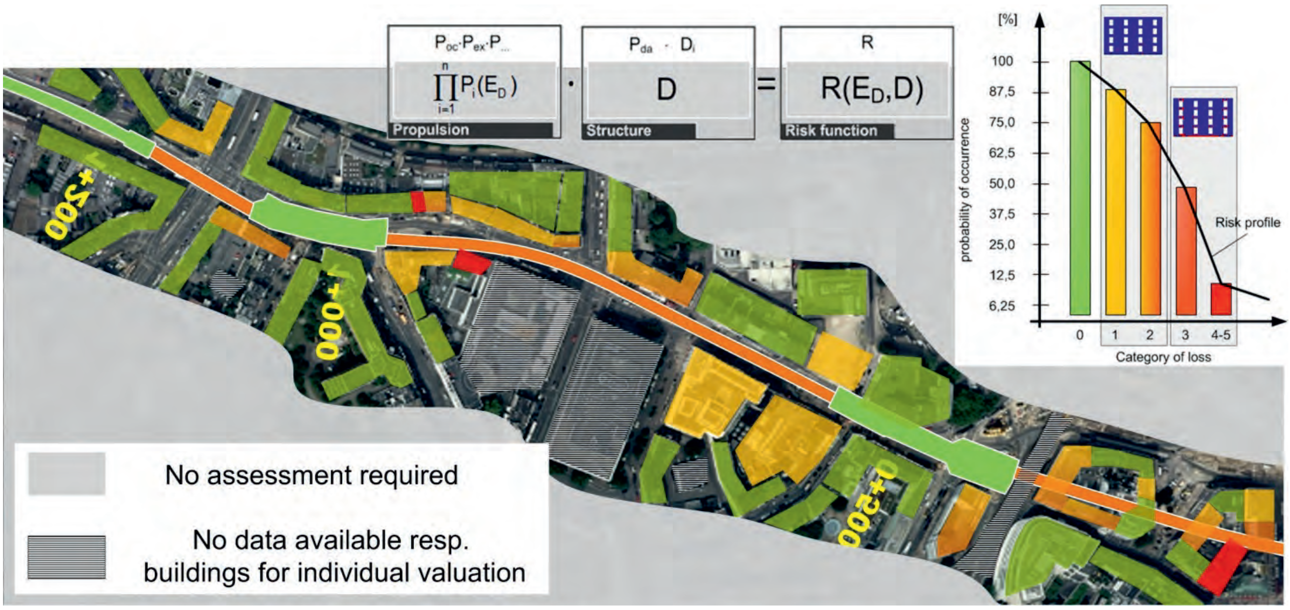

Fig. 3: Interactive visualization and evaluation of the vulnerability by risk profiles

STIFFNESS IDENTIFICATION

Analogue to the principles of system identification three complementary approaches (analytical, numerically-iterative and statistical) have been developed to process physical models of existent infrastructure. Back calculation according to the principle of virtual work extracts and separates decisive building stiffness parameters like bending (EI), shear (GA) or axial (EA) strengths. From these, interaction diagrams have been derived and drawn to graphically determine stiffness and equivalent building masses.

PROSPECTIVE WORK

Starting from the damage-causing event – more precisely the tunneling-induced settlements – and employing stochastic models, risk profiles are to be generated and visualized based on individual restrictions of structural categories. Case studies will be conducted to extract stiffness information and specific vulnerabilities (Fig. 3). The risk profiles will also integrate interactive parameters of partial risks from other sub-projects like shapes and probabilities of settlement troughs to occur as well as probabilities of disturbance in mechanized shield tunneling. Parameterized FE-models with associated stiffness and masses of representative aboveground infrastructure close the chain of interaction inside the collaborative research center. Automatic pattern recognition and vulnerability assessment techniques will be coupled to visually infer from building characteristics to sensitivities to settlements.

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