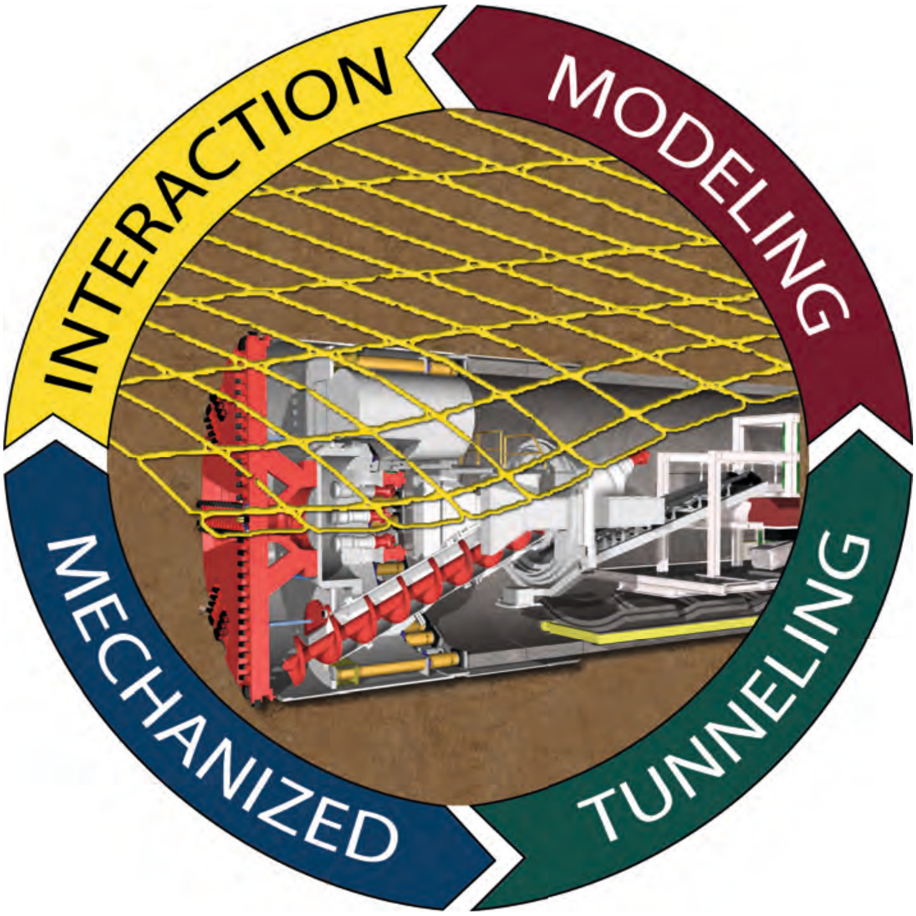
Collaborative Research Center 837

Interaction Modeling in Mechanized Tunneling



SFB 837 Brochure 2016

RUHR UNIVERSITY BOCHUM

CONTACT

COLLABORATIVE RESEARCH CENTER 837

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SFB 837

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 Earth Pressure Balanced (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,

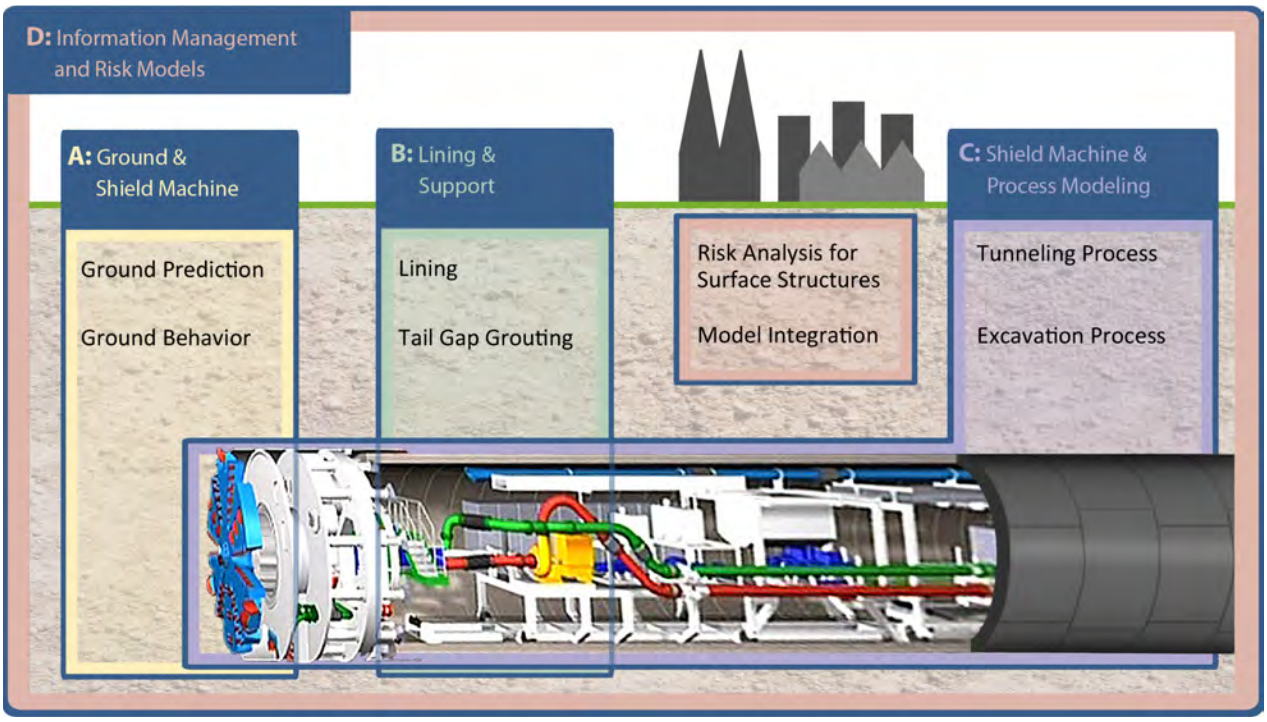


Fig. 1: Components and processes involved in mechanized tunneling and their representation within 4 project areas in the SFB 837.

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. 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 Deutsche Bahn (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 further expand this international presence in the current research period.

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, an associate member of the Austrian Academy of Sciences and a member of the Austrian Science Board. He is the author of over 280 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 studied 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 is a 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. Markus KÖNIG

Computing in Engineering

Leader of subprojects:
C2, C3, D1, D3

Prof. Dr.-Ing. Markus König is the head of the Chair of Computing in Engineering at the Ruhr University Bochum. His research focuses on process modelling, building information modelling, heuristic optimization methods, simulation of construction and logistics processes, as well as uncertainty, risk and knowledge management in construction. He is the coordinator of the scientific evaluation of the pilot projects of the Federal Ministry of Transport and Digital Infrastructure for the application of building information modelling.

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 for Theoretical Methods of Project Management at the Bauhaus University 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) and also of the national VDI-committee 2552-5 "Building Information Modelling – Data Management". He is the author of over 120 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

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 PhD (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.

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".

PROJECT LEADERS

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 PhD. in 2005 at the Otto-von-Guericke University in Magdeburg, Germany (awarded by the Association of German Engineers VDI as best PhD. 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.

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.

PROJECT LEADERS

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 the research group. Based on its research experience the group is able to measure and control state parameters for both saturated and partially saturated multiphase materials. An additional focus of the work is the design of smart materials which are adopted 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 the mechanised tunnelling is understood as a transient multi field process to be modelled on different scales with adequate complexity considering inherent uncertainty and heterogeneities typical for geomechanical problems.

Dr.-Ing. Britta SCHÖßER

Tunnelling and
Construction Management

Leader of subproject:
A6

Dr. Schößer is a Group Leader and Head of the bentonite laboratory at the Institute for Tunnelling, Pipeline Construction and Construction Management. Her research topics include the application of bentonite suspensions as a 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 also part of her research scope.

In 1997, Dr. Schößer was working as project engineer at the engineering office of Prof. Maidl, Bochum, and at the Deutsche Montan Technologie (DMT), Essen. Since 1998, she was a research assistant at the Working Group Pipeline Construction and Construction Management of Prof. Stein and received her PhD. in 2004. In the time period 2005–2007, Dr. Schößer worked as project manager at the Joint Venture “ARGE emscher:kanal”. Since 2008, she is Senior Researcher at the Institute for Tunneling. 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.

PROJECT LEADERS

Prof. Dr.-Ing. Holger STEEB

Continuum Mechanics (University of Stuttgart)

Leader of subprojects: A4, B4

Prof. Dr.-Ing. Holger Steeb is Professor for Computational Continuum Mechanics at the University of Stuttgart. His research focuses on characterization methods and modeling techniques 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 (e.g. finite elements or Smoothed Particle Hydrodynamics (SPH). Prof. Steeb's lab offers experimental tools like X-ray microtomography, opto-rheometry and dynamical testing devices from sub-Hz to the MHz-regime.
Holger Steeb studied Civil Engineering at the University of Stuttgart, where he received his doctorate in 2002. 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. From 2009-2015 he was Professor for Continuum Mechanics at Ruhr-University Bochum. Since 2015 he is Professor for Computational Continuum Mechanics at the University of Stuttgart and Fellow of the SC SimTech-Stuttgart Centre for Simulation Sciences. 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. 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 on Ni- and Co-based 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. Wiebke BAILLE

Foundation Engineering, Soil & Rock Mechanics

Subprojects: A6

Dr. Baille is a Group Leader and Head of the Clay Lab at the Chair of Foundation Engineering, Soil and Rock Mechanics. Her research topics contain the influence of mineralogy, physico-chemical properties and fabric of clays on their hydro-mechanical behavior. This includes the effects of microscopic properties on the macroscopic behavior of clays. Further research focus is on concepts for effective stress in unsaturated soils, so-called soil liquefaction.
After receiving her Diploma in Civil Engineering in 2002 at Bauhaus-Universität Weimar, Dr. Baille worked from 2002-2005 as project engineer at the engineering consulting office Aquasoil GmbH, Westheim. Since 2005, she was a research assistant at the Chair of Soil Mechanics, Bauhaus-Universität Weimar, of Prof. Schanz. In 2005 she was at the École Nationale des Ponts et Chaussée (ENPC), Paris, for a research stay. From 2009 on, she continued her research work at the Chair of Foundation Engineering, Soil and Rock Mechanics, at Ruhr University Bochum of Prof. Tom Schanz. She received her Ph.D. in 2014, and received the Gert-Massenberg Preis for her Ph.D in 2015. She is member of the 4th Global Young Faculty, funded by the Stiftung Mercator in cooperation with the University Alliance Metropolis Ruhr.

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 has been working in the Institute for Structural Mechanics at the Ruhr University Bochum within different projects of basic and applied research in numerical structural mechanics.

Dr.-Ing. Ralf JÄNICKE

Continuum Mechanics

Subprojects: A4, B4

Dr. Ralf Jänicke is a research associate and leads the Chair of Mechanics - Continuum Mechanics. His research interests cover the mechanical modeling and computational simulation of non-standard multi-scale and multi-phase materials. In particular, he addresses the physical understanding and the mechanical description of transport processes in fluid-saturated and fractured porous media. He develops numerically efficient computational homogenization concepts based on order reduction techniques. Dr. Jänicke's research interests moreover include the numerical simulation based on real 3D data generated, for example, using X-Ray Computer Tomography.
Dr. Jänicke completed his Diploma in Materials Science (Dipl.-Ing.) 2006 at the Saarland University, Saarbrücken, Germany. From 2006 to 2010 he was a PhD student at the chair of Applied Mechanics at the Saarland University under the guidance of Prof. Stefan Diebels. He completed his doctorate 2010 and came to the Ruhr University Bochum. Here, he is active as research associate (Akademischer Rat). Since April 2016, Dr. Jänicke leads the Chair of Mechanics - Continuum Mechanics (Vertretungsprofessur). Dr. Jänicke completed several research stays at the École des Mines (Prof. Samuel Forest, Mines ParisTech, France) and at the Chalmers University of Technology (Prof. Kenneth Runesson, Prof. Fredrik Larsson, Göteborg, Sweden). He is member in the scientific network (DFG) CoSIMOR and in the Research Department Subsurface Modeling and Engineering (RUB). Since 2015, Dr. Jänicke is junior fellow at the North Rhine-Westphalian Academy of Science, Humanities and the Arts.

POST-DOCTORAL RESEARCHERS

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

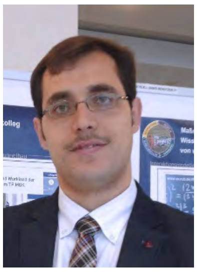
Computing in Engineering

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.

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)

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Ba Trung CAO
Subproject: C1

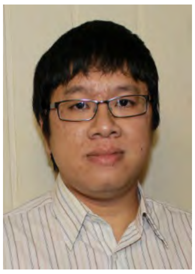
Parameter identification in numerical modeling of tunneling using model reduction techniques

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)

Sascha FREIMANN
Subproject: A4

Investigation of conditioned soil under realistic conditions of EPB-tunneling

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

DOCTORAL RESEARCHERS

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)

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)

Jakob KÜPFERLE
Subproject: C5

Verschleißverhalten und Prognosen von TVM-Werkzeugen im Lockergestein

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

Andre LAMERT
Subproject: A2

Tunnel reconnaissance by seismic full waveform inversion – numerical development and experimental validation

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

DOCTORAL RESEARCHERS

Ahmed MARWAN
Subproject: C1

Computational methods for optimization in mechanized tunneling

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

Hannah MATTERN
Subproject: C3

Integrating BIM in the process simulation of tunneling projects

Supervisor: Prof. Dr. Ing. Markus König (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)

Gerrit NEU
Subproject: B2

Numerical design of fiber reinforced concrete structures

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

DOCTORAL RESEARCHERS

Marcel NEUHAUSEN

Subproject: D3

Detektion von Gebäudemerkmalen zur Rekonstruktion von Gebäuden

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

Luan Thanh NGUYEN

Subproject: A2

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

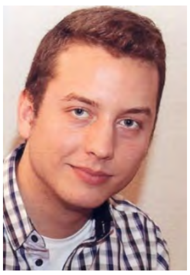
Supervisor: Prof. Dr.-Ing. Tamara Nestorović (Mechanics of Adaptive Systems)

Markus OBEL

Subproject: D3

A risk simulation concept for the evaluation of existing structures during mechanized tunneling

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



Sven PLÜCKELMANN

Subproject: B1

Hybrid concrete segments for durable and robust tunnel lining systems

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

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Sandra ROSE
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System and parameter identification in mechanized tunneling

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

Malte SAUERWEIN
Subproject: B4

Annular gap grouting: Hydro-chemo-mechanical modeling and space-resolved experimental investigations

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

Markus SCHEFFER
Subproject: C3

Simulationsgestützte Verfügbarkeitsanalyse von Tunnelvortriebsmaschinen

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

Christoph SCHULTE-SCHREPPING
Subproject: B3

Development of two-component mortars with innovative or modified binder systems for annular gap grouting in mechanized shield tunneling

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

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Mario SMARSLIK

Subproject: B1

Robustness evaluation of structurally optimized concrete segments

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

Fanbing SONG

Subproject: B1

Verhalten von Stahlfaserbeton unter Teilflächenbelastung

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

Jithender Jaswant TIMOTHY

Subproject: B2

Multilevel micromechanics modeling of materials

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

Andre VONTHRON

Subproject: D1

Konzepte zur interaktiven und visuellen Analyse von Interaktionsketten im maschinellen Tunnelbau

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

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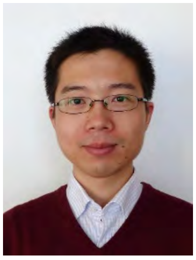
Nicola WESSELS
Subproject: C4

Discrete element simulation of cutting processes in soils

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

Bou-Young YOUN

Subproject: B3

Expected publication 2016

Untersuchungen zum Entwässerungsverhalten und zur Scherfestigkeitsentwicklung von einkomponentigen Ringspaltmörteln im Tunnelbau

Thomas PUTKE

Subproject: B1

Expected publication 2016

Optimierungsgestützter Entwurf von Stahlbetonbauteilen am Beispiel von Tunnelschalen

Veselin ZAREV

Subproject: C2

Expected publication 2016

Model identification for the adaption of numerical simulation models – application to mechanized shield tunneling

Alexander SCHAUFLER

Subproject: B4

2015

Multi-physical simulations: transport and infiltration of suspension in granular porous media

Shorash MIRO

Subproject: C2

2015

Calibration of numerical models considering uncertainties – application to mechanized tunnel simulations

Silvia Payá SILVESTRE

Subproject: A4

2015

Elektrokoagulation zur Trennung von gebrauchten Betonitsuspensionen im Tunnelbau

COMPLETED PhD THESES

Felix HEGEMANN
Subproject: D1
2015
A hybrid ground data management concept for tunneling projects

Jelena NINIĆ
Subproject: C1
2015
Computational strategies for predictions of the soil-structure interaction during mechanized tunneling

Lasse LAMBRECHT
Subproject: A2
2015
Forward and inverse modeling of seismic waves for reconnaissance in mechanized tunneling

Jan DÜLLMANN
Subproject: A1
2014
Ingenieurgeologische Untersuchungen zur Optimierung von Leistungs- und Verschleißprognosen bei Hydroschildvortrieben im Lockergestein

Meng-Meng ZHOU
Subproject: B2
2014
Computational simulation of soil freezing: multiphase modeling and strength upscaling

Steffen SCHINDLER
Subproject: D3
2014
Monitoringbasierte strukturmechanische Schadensanalyse von Bauwerken beim Tunnelbau

COMPLETED PhD THESES

Trung Thanh DANG

Subproject: C3

2014

Analysis of microtunnelling construction operations using process simulation

Sissis KAMARIANAKIS

Subproject: C3

2013

Ein multikriterielles fuzzy- und risikobasiertes Entscheidungsmodell für die Planung unterirdischer Infrastruktur

Christoph BUDACH

Subproject: A4

2012

Untersuchungen zum erweiterten Einsatz von Erddruckschilden in grobkörnigem Lockergestein

SUBPROJECTS OF THE SFB 837

DEVELOPMENT OF EFFECTIVE CONCEPTS FOR TUNNEL RECONNAISSANCE USING ACOUSTIC METHODS

A2

A. Lamert, K. Musayev, L. T. 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 wave field is done with fully numerical approaches that allow prediction of the elastic wave field 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 downscaled 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. Another validation approach is a blind test where project members work in cooperation; synthetic wave fields are calculated by one member whereas inversion is performed by another member who knows nothing about the synthetic model.

FORWARD PROBLEM

For the time domain forward simulations, in case of geologically simple media elastic wave propagation is modeled using the Spectral-Finite-Element-Method (SpecFEM), whereas for complex geological situations a nodal discontinuous Galerkin (NDG) (Fig. 1) approach is applied. Moreover, for the frequency domain forward simulations, a higher-order finite element method with hierarchical shape functions is used.

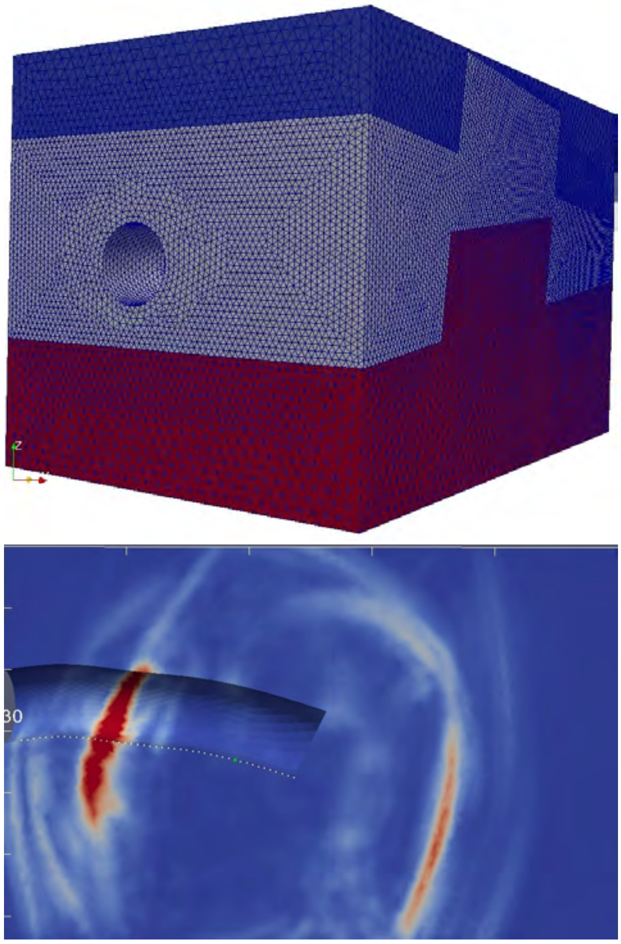


Fig. 1: Top: Tetrahedral mesh with curved tunnel, layer boundaries and steeply dipping faults perpendicular to the tunnel axis. Bottom: Snapshot of the seismic wave field generated by a source at the tunnel face.

INVERSE PROBLEM

The aim is to image the distribution of elastic material properties in front of the tunnel face with the help of full waveform inversion. Up to now, 2D and 3D inverse computations were done in the time domain for the elastic wave equation (Fig. 2). On the other hand, frequency domain inversions of 2D elastic waves and both 2D and 3D acoustic waves were carried out. Apart from this, a blind test was successfully performed based on the 2D acoustic wave equation in the frequency domain (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.

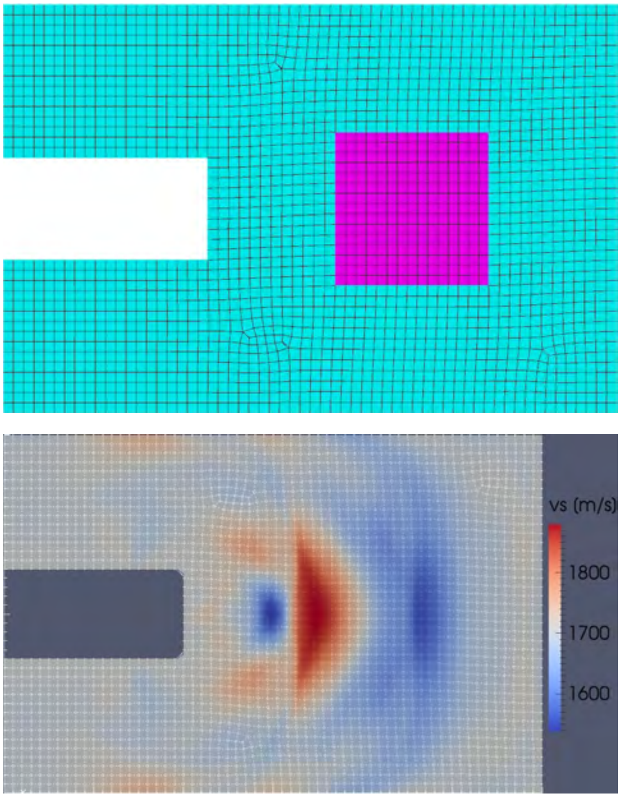


Fig. 2: Simplified test case for the 2D inverse problem in the time domain based on the elastic wave equation. Top: Sketch of the location of a square-shaped structural anomaly in front of the tunnel face. Elastic wave fields were calculated at receivers on the tunnel sidewalls generated by three sources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

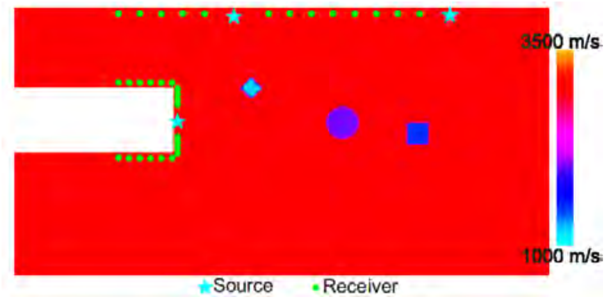


Fig. 3a: Blind test for the 2D inverse problem in the frequency domain based on the acoustic wave equation: Homogeneous test model with embedded structural anomalies.

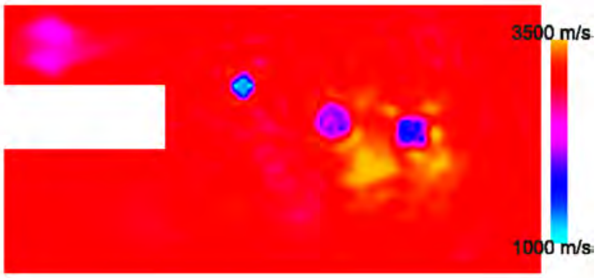


Fig. 3b: Simplified test case for the 2D inverse problem in the frequency domain based on the acoustic wave equation: Reconstruction of the structural anomaly by inversion of spectral amplitudes and phases up to 478 Hz recorded by 33 sensors on the tunnel face and generated by 3 sources.

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MODEL DEVELOPMENT FOR THE CONDITIONED SOIL USED AS FACE SUPPORT MUCK OF EARTH-PRESSURE-BALANCE-SHIELDS

A4

S. Freimann, R. Jänicke, 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

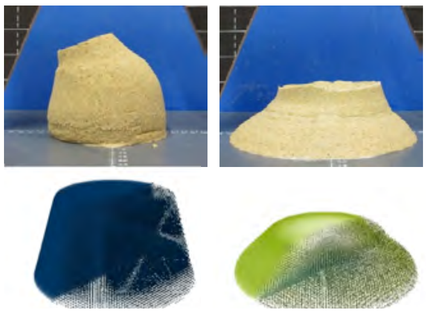

Fig. 1: Slump test – Experiment and simulation.

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.

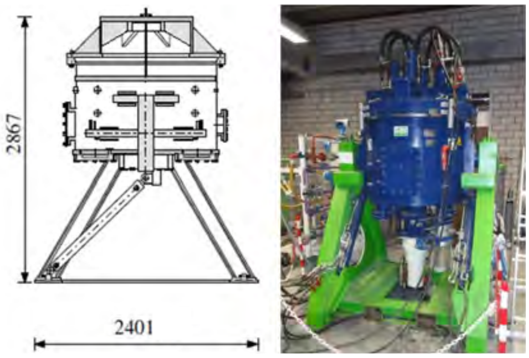

Fig. 3: Large scale test COSMA.

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ADAPTIVE CONSTITUTIVE MODELING OF SOIL WITH SPECIAL CONSIDERATION OF ANISOTROPY AND DESTRUCTURATION

A5

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

INTRODUCTION

Mechanized tunneling with Tunnel Boring Machines (TBM) is a widely applied method to conduct subsurface infrastructural projects, especially in urban areas. Reliable predictions of tunneling induced ground movement requires complex numerical interaction models. An advanced 3D numerical model for simulating the physical aspects which occur in realistic tunneling processes has to consider the relevant sub-systems (sequential excavation, face support, grouting of the annular gap, lining installation) and the soil-structure interaction. The complex non-linear soil behavior is modeled using adequate constitutive models.

SUBMODELING AND ADAPTIVE CONSTITUTIVE MODELING

Due to the complexities involved in the tunneling process, it is time-consuming and computationally expensive to obtain accurate model responses using a finely meshed Finite Element (FE) model. In order to provide a model that is robust and representative, yet cost-economic, in explaining the complex behavior in the near field around the TBM, a submodeling technique is being developed. A local model (submodel) which is cut from the global model is analyzed using finer mesh discretization. The boundary conditions of the submodel are obtained from the global model. The size of the submodel is time and space dependent with respect to the monitoring section and the current tunnel position.

Additionally, in order to describe realistic system behavior, sophisticated constitutive models are essential. However, the parameter identification and the consequential numerical analysis will be significantly time-consuming and cost-intensive. Therefore, an adaptive constitutive modeling approach has been 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 near field around the TBM.

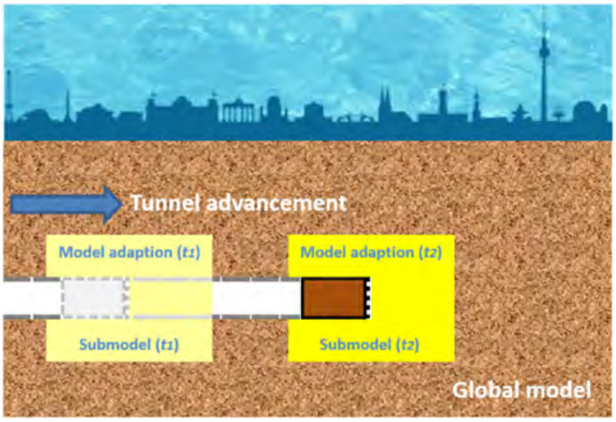

Fig. 1: Concept of submodeling and adaptive constitutive modeling.

HYDRO-MECHANICAL COUPLING IN THE NEAR FIELD AROUND THE TBM

The non-steady fluid flow in the near field 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.

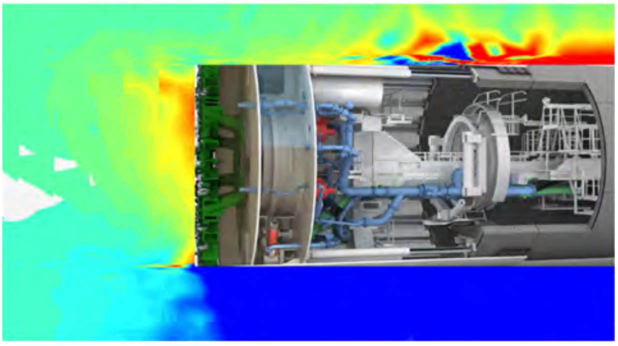

Fig. 2: Excess pore pressure generation around the tunnel.

The analysis of pore water dissipation and effective stress paths is of main importance for the soil stability analysis and the tunnel structural design. Therefore, the influence of tunneling induced evolution of the state variables (stress level, stiffness, void ratio, etc.) and the temporal progress of consolidation on the model system behavior should be evaluated.

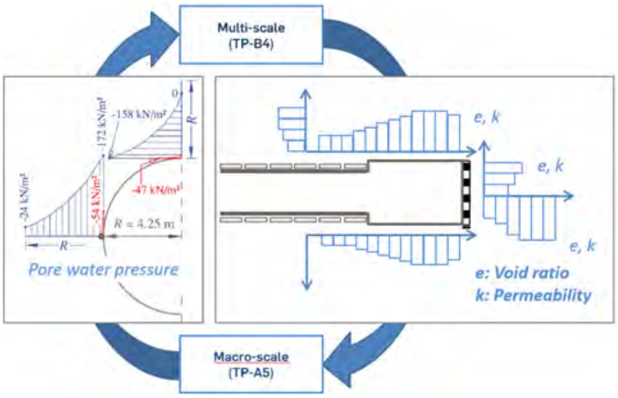

Fig. 3: Concept: Adaption of HM-model parameters.

In order to adequately simulate the interaction between the support media and the surrounding soil, the hydro-mechanical coupling effect is considered in the FE-model. The coupling approach is based on automatic exchange of model parameters between the physical model (time and space dependent hydro-mechanical boundaries) and the HM-model (evolution of void ratio, stiffness and permeability).

CONSTITUTIVE MODEL FOR NATURAL STRUCTURED SOILS

Excavating a 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 of interparticle bonding on the system response in mechanized tunneling. The destructuration is associated with the stress-induced damage of the microstructure. Therefore, an 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. Consequently, a series of hierarchical constitutive models has been formulated, validated and implemented in the Bounding Surface Plasticity (BSP) framework. The BSP concept offers a platform where the fundamental aspects of mechanical behavior of soils under complex stress paths and cyclic consolidation can be captured.

In order to calibrate the parameters and validate the model, a number of experimental investigations (using an innovative soft-oedometer test device) on structured and reconstituted soil samples under isotropic and anisotropic boundary conditions subjected to monotonous and cyclic stress paths are specified.

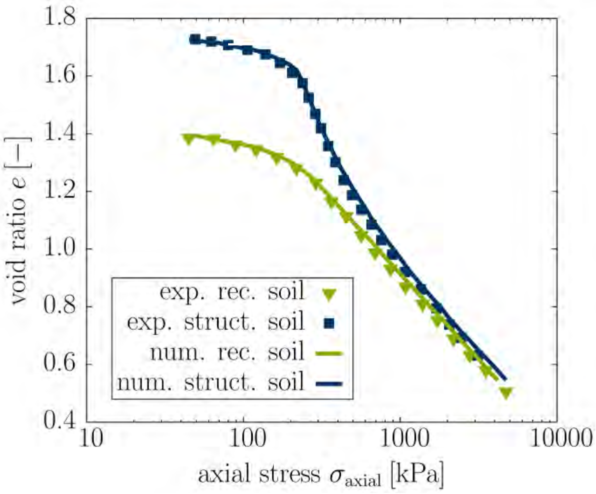

Fig. 4: Compression behavior of structured and reconstituted soil in oedometer tests. Comparison of experimental (symbols) and numerical (lines) results.

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LOCALLY TRANSIENT FACE SUPPORT WITHIN HYDRO-SHIELDS

A6

W. Baille, 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 the 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 which the pressure transfer mechanism acts upon, is periodically damaged by the cutting tools.

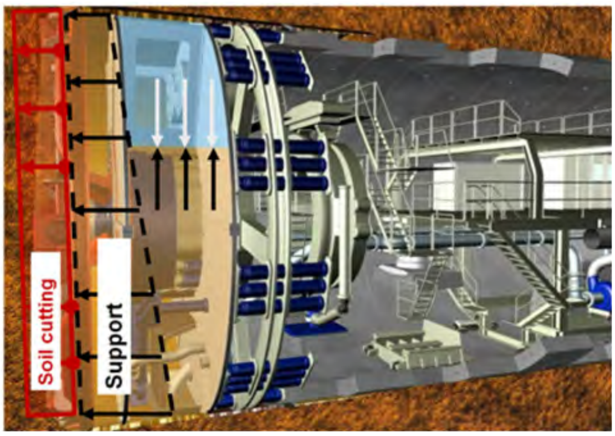

Fig. 1: Hydro shield tunneling (Source: Herrenknecht AG).

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 partially or even completely damaged. The slurry may penetrate into the soil again between the subsequent passings of a cutting tool thus re-forming the pressure transfer mechanism.

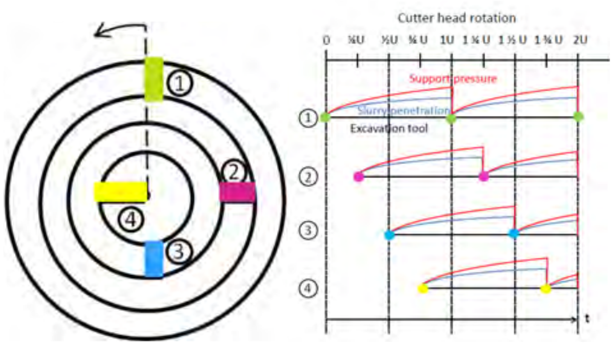

Fig. 2: Arrangement of the cutting tools on the cutter head (left), Superposition of slurry penetration and soil excavation processes (right).

The experimental investigations performed within this project aim to develop time-dependent descriptions of the potentially occurring soil-mechanical, hydro-mechanical and rheological changes, and to visualize and understand the simultaneous penetration and excavation processes.

CHALLENGE

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

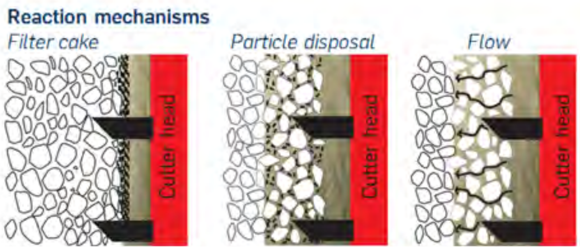

Fig. 3: Reaction mechanisms in the soil.

The contribution of each single reaction is successively changing throughout excavation and strongly depends on the observed instant in time. 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 composition (Fig. 4) and on changes in the slurry rheology during the penetration process are performed.

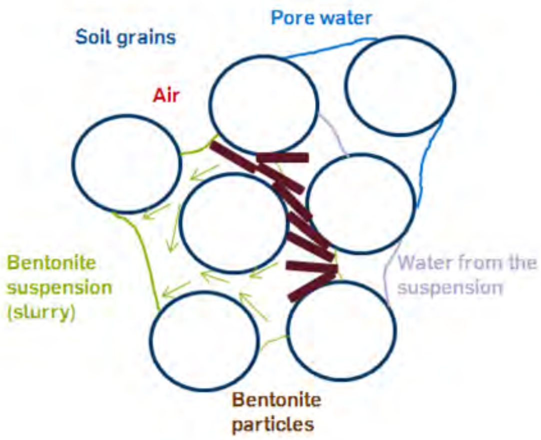

Fig. 4: Changes in soil-system composition.

At first, the experiments are carried out to investigate the processes separately. Consequently, all effects are combined in a multiple-scale experimental set-up considering real overburden stresses within the ground. In the multi-scale experimental set-up, the slurry penetrates the soil simultaneously with the soil excavation. The soil-slurry suspension interactions and the influence of the variation of reaction mechanisms within the soil are emphasized.

GOAL

Suitable theoretical and numerical models are to be developed within this project in order to describe the influence of soil-mechanical, 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).

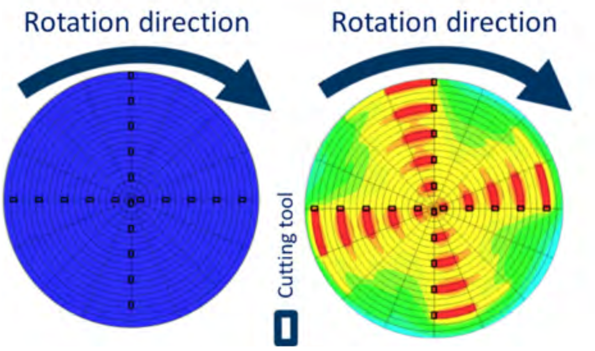

Fig. 5: Model of the homogeneous support pressure transfer (left) and of the transient support pressure transfer (right).

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OPTIMIZED STRUCTURAL SEGMENTS FOR DURABLE AND ROBUST TUNNEL LINING SYSTEMS

B1

S. Plückelmann, M. Smarslik, F. Song, R. Breitenbücher, P. Mark

INTRODUCTION

Following two complementary approaches, the subproject members intend to develop hybrid concrete lining segments regarding aspects of safety, durability and robustness. Small-sized and tailor-cut built-in components as a concept "fresh on solid" for specific loading scenarios as well as 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 at material-level (steel fiber reinforced concrete: SFRC) to individual segments at component-level and finally to tunnel linings at 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 has been conducted. The main objective was to investigate the load bearing and fracture behavior of hybrid concrete elements particularly under partial-area 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 concretes have been systematically and intensively studied. Fig. 1 illustrates the test-setup and the positioning of the specimens for centric and eccentric loading cases. The test results have shown distinctly different bearing behavior between plain concrete and concretes reinforced with various fiber combinations. The SFRCs exhibited a considerably higher bearing strength and a much more ductile post-cracking behavior, especially in the case of concretes strengthened with fiber-cocktails. Moreover, with the presence of steel fibers, the fracture mode of concrete changed from a brittle to a ductile one.

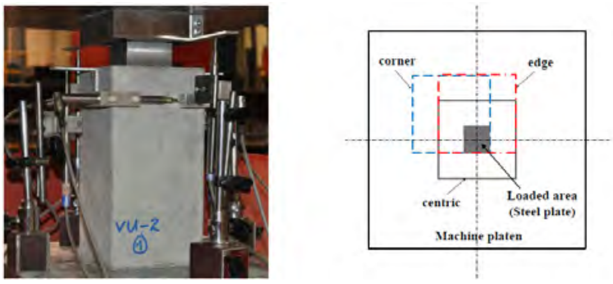

Fig. 1: Test set-up for partial-area loading tests (left) and positioning of the specimen for centric and eccentric loading (right).

In the next step, the research focuses on investigating the load-bearing and bonding behavior of hybrid concrete elements (i.e. hybrid lining segments) under various loading situations (e.g. partial-area loading, tensile loading and shearing). For this purpose, small-sized hybrid concrete specimens (50x30x25 cm) with two different types of concrete have been produced. The upper layer of the specimens with a thickness of 5 cm consisted of SFRC with a high content of steel fibers (up to 120 kg/m^3), whereas the lower layer consisted of a typical tunnel lining concrete (LC) with a modest fiber concentration of about

40 kg/m^3. Before taking drilling cores for the shearing test (Fig. 2), the specimens ought to be preloaded with a certain level of concentrated load to simulate the jack forces.

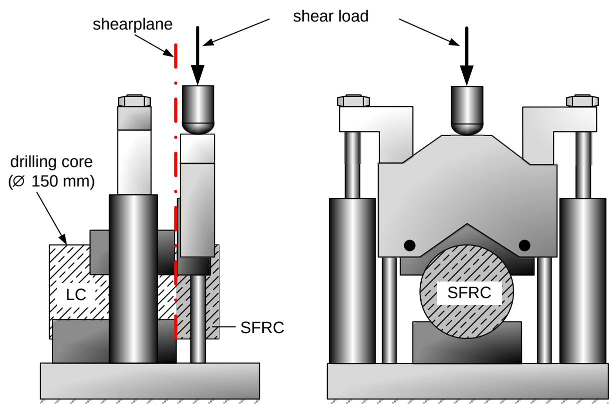

Fig. 2: Test set-up for the shearing test on drilling cores taken from hybrid concrete elements.

COMPONENT AND BUILDING LEVEL

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

In the first step parameterized, numerical 3D models based on finite elements were used to identify potential damages by evaluating the kinematics of the tunnel. Typical loading scenarios, which represent the final state as well as various intermediate construction stages, were implemented and analyzed (Fig. 3). As expected, the critical points were load application as well as circumferential and longitudinal joints.

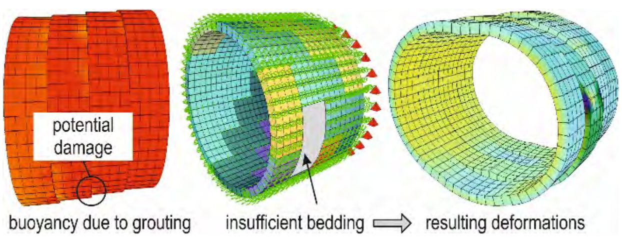

Fig 3: Numerical deformations and Mises stresses for exemplified load case scenario (buoyancy in grouting, insufficient bedding conditions).

Focusing on the shear load transfer mechanism in circumferential joints by cam and pot, topological optimization methods were utilized. Based on the results, optimized reinforcement layouts were derived, which were coupled with locally added steel fibers or prefabricated built-in parts like steel bolts as alternatives to the common cam and pot design. To verify the benefit of the employed methods and to assess the practical feasibility of the optimized designs, experiments were carried out subsequently. The results of the specimens showed increased bearing capacities as well as a more ductile fracture behavior compared to the conventional cam and pot system.

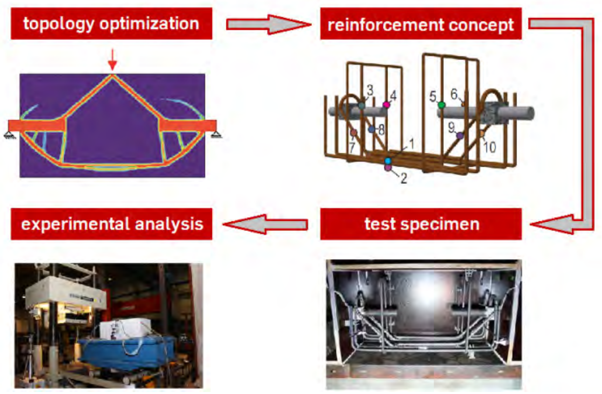

Fig. 4: Steps of the concept for an optimized design for the example of shear coupling.

At the longitudinal joint, which was identified as another critical point, local effects result from partially loaded areas. Local crushing and transversal tensile forces have to be considered in design. Preparations are in progress to conduct a fundamental analysis of beneficial effects on the maximum compressive strength of concrete at partially loaded areas. In particular, the positive effects of a confined compression zone by reinforcement and the use of modified layouts for tensile splitting reinforcement derived from topological optimization are hot topics of current research.

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DAMAGE ANALYSES AND CONCEPTS FOR DAMAGE-TOLERANT TUNNEL LININGS

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

B2

GOAL STATEMENT

The goal of the subproject B2 is the development of new design concepts for tunnel lining segments in order to enhance segment robustness with respect to construction induced loading conditions (Fig. 1).

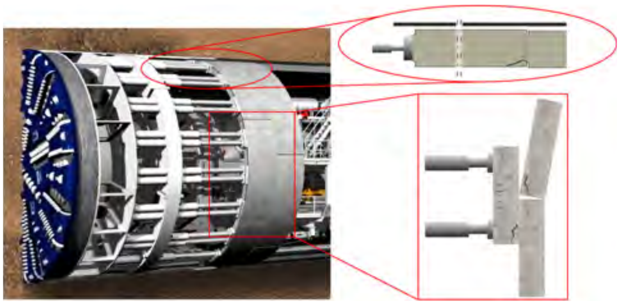

Fig. 1: Possible damage patterns in tunnel lining segments during the excavation process.

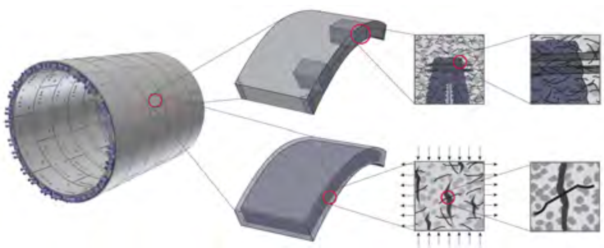

Fig. 2: Prototypes of new robust lining segment design.

This goal is achieved by using novel numerical simulation techniques in order to optimize model components at the material, the segment, and at the lining system level. The enhanced robustness of the proposed lining designs is achieved through a spatial optimization of the placement of the heterogeneous material compositions (concrete, fiber, steel bar or mesh, etc.) used in the production of lining segments. Furthermore, new production techniques are incorporated into the proposed ring designs (e.g. the combination of precast components and fresh concrete, or hetero-geneous concrete mixtures cast at different stages, see Fig. 2) through cooperation with the subproject B1.

MULTISCALE MODELING SCHEME OF FIBER REINFORCED CONCRETE (FRC)

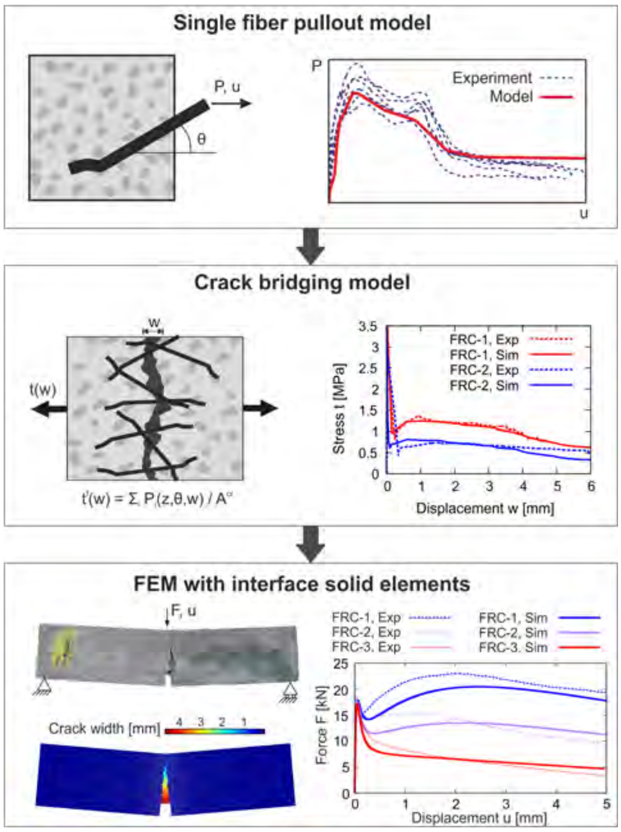

Fig. 3: Modeling of steel fiber reinforced concrete at different length scales.

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 hooked-end or straight single steel fibers with an arbitrary orientation with respect to a crack. Making use of this model, a crack bridging law is obtained from which the traction-separation behavior of the fiber is derived and subsequently used in the structural simulations. At the structural level, advanced simulation techniques available within the framework of the Finite Element Method for modeling the nonlinear behavior of concrete materials (damage-plasticity model, embedded crack model and interface elements) are used to capture the structural strength and the post-peak responses of the segments.

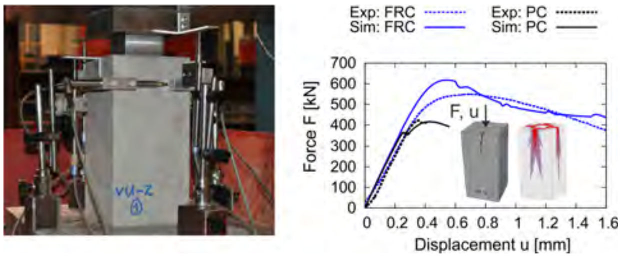

Fig. 4: Partial area loading tests on plain and fiber reinforced concrete. Left: experimental setup. Right: comparison of the force-displacement curves and crack patterns from experiment and numerical simulation for fiber reinforced concrete (FRC) and plain concrete (PC).

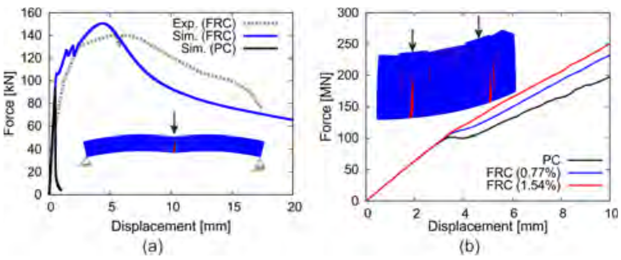

Fig. 5: Numerical simulation of lining segments made of FRC: (a) Ductile behavior under flexural loading; (b) parametric study of the influence of fiber content on the nonlinear responses under thrust forces.

Based on this multiscale scheme, the mechanical behavior of lining components as well as lining segments in critical loading situations can be investigated via numerical simulations. In Fig. 4, the numerical results of partial area loading tests on plain and fiber reinforced concrete specimens are presented. Fig. 5a shows the simulation results of a FRC segment subjected to flexural loads and a comparison thereof with experimental results. Fig. 5b contains the results of a parametric study of the influence of fiber content on the possible inelastic behavior of segments subjected to jack forces.

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 the 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 novel 3D finite element modeling technique for FRC under complex stress states and a finite element model which takes into account the imperfections along the joints. Furthermore, this 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

C. Schulte-Schrepping, R. Breitenbücher

STATE OF KNOWLEDGE AND OBJECTIVE OF SUBPROJECT B3

In mechanized tunneling during tunnel driving, a gap of 13 to 20 cm remains between the segment lining and the soil. Immediately after the 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. In the field of mechanical tunneling two-component-mortar is almost always used for annular gaps in solid rocks, soils with low permeability and water-bearing building grounds. Unlike one-component mortar, the strength development is exclusively based on the hydration of cement.

The stabilizing component A consists of cement, water, bentonite and a retarding agent. Up to 72 hours after production, it has to be workable, sedimentation-stable and suitable for pumping over a long distance. The activating component B is an accelerator, mainly in the form of water glass, and serves the purpose of stimulating the strength development immediately after contact with component A at the end of the shield tail. A typical ratio of component A to B is 9:1.

In the annular gap, the activated mortar needs to gel directly in order to resist erosion in the prevailing soil conditions (standing/running water). Additionally, the mortar needs to ensure an immediate bedding of the tunnel tube by a rapid strength development.

According to this and analogous to one-component mortars, two-component mortars must provide two opposite properties: a long workability and an immediate strength development.

METHODOLOGY AND EXPERIMENTAL INVESTIGATIONS

In Phase II, alternative mixtures of two-component-mortars are being investigated that are based on field-tested mixtures. Further alternatives include geopolymers (alkali-activated granulated blast furnace slag) and the use of superabsorbent polymers (SAP).

Before testing, a suitable, laboratory-scaled production method has been developed in order to ensure a homogeneous mixture of both components (Fig. 1).

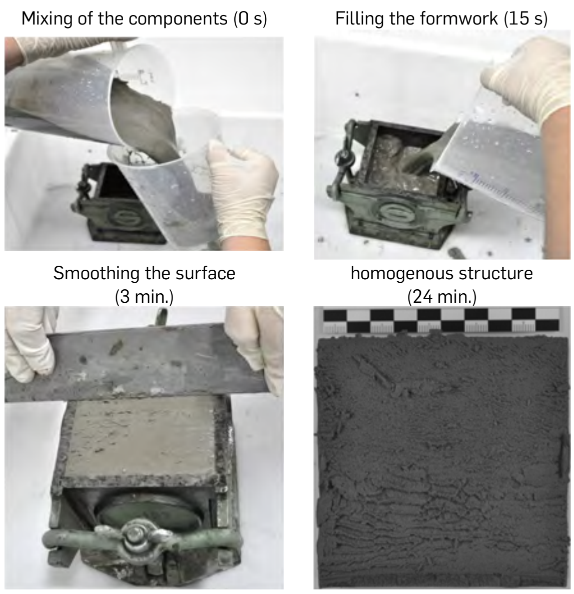

Fig. 1: Sample production of two-component mortar (cube formwork: 100 x 100 x 100 mm³).

GAIN OF SCIENTIFIC KNOWLEDGE

Within first studies, control quantities have been deduced which allow a specific adjustment of the mentioned characteristics concerning workability and early strength development depending on the geological and constructional conditions. Therefore, a stable component A has been initially developed. In order to provide a stable and sufficiently long delayed component A, the concentrations of cement, bentonite as well as the retarding agent have been systematically varied and optimized. As a result, the stated mixture of a two-component-mortar in Table 1 represents a solid basis concerning the required workability (Marsh-time after 48 h < 45 sec). Beside the optimized combination of cement and retarder, the bentonite turned out to be a major control quantity concerning the workability.

Table 1: Design of the two-component mortar

Component A		
Cement (Ordinary Portland Cement OPC)	kg/m³	250
Bentonite (Sodium-activated)	kg/m³	30
Water	kg/m³	830
Retarding agent (Long-term retarding agent LTR)	%/c	2,5
Component B		
Accelerator (Na^+-Water Glass)	kg/m³	70-90

The composition of this mixture lies within the commonly practised upper and lower limits of the respective source materials.

On this basis, two different accelerators and their effect by variation of the dosage have been examined in order to achieve a rapid strength development, considering an early compressive strength of 0.5 MPa after 24 hours (Fig. 2). The results are shown in Fig. 3.

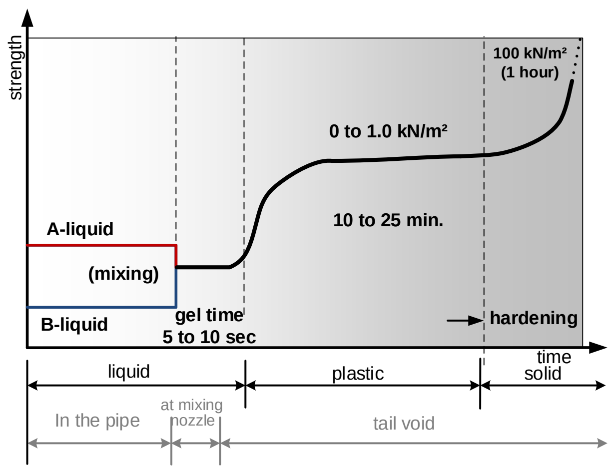

Fig. 2: Strength characteristics of a two-component mortar (TAC Corporation).

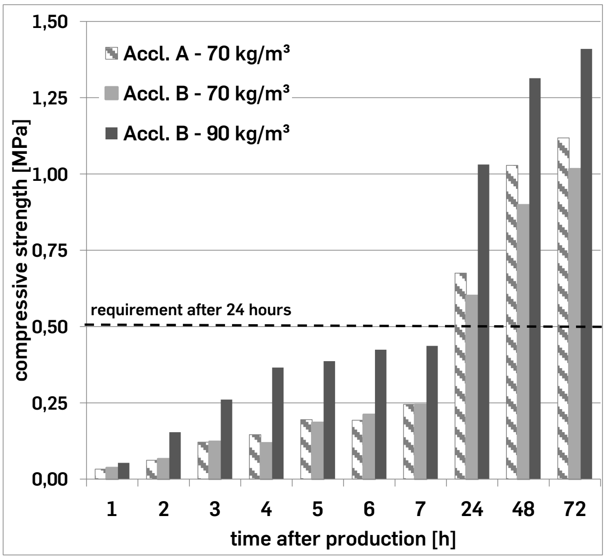

Fig. 3: Compressive strength development up to 72 hours after production with two different accelerators.

In order to ensure a sufficiently rapid strength development with the given amount of cement (250 kg/m³), an accelerator dosage of 70 kg/m³ proved to be adequate.

FURTHER INVESTIGATIONS

In currently ongoing tests, the gelling and the strength development (shear and compressive strength) are being examined by variation of the binder. Based on the defined basic mixture the binder composition is varied with regard to reactivity, fineness and granulometry. Therefore, OPC is substituted by either quartz powder, fly ash or granulated blast furnace slag. Furthermore, depending on first trials, investigations on alkali-activated granulated blast furnace slag and the use of superabsorbent polymers will be performed. Beside the material-technical investigations and optimizations, the suitability of appropriate two-component mortars will be verified concerning a homogeneous grouting of the gap with typical dimensions by a nearly realistic, lab scale test setup.

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

B4

M. Sauerwein, R. Jänicke, H. Steeb

INTRODUCTION

In mechanized tunneling the cutting wheel's diameter of a Tunnel Boring Machine (TBM) is always slightly larger in comparison to the tunnel structure, which results in a cavity between the surrounding soil and the tunnel lining. In literature this gap is referred to by the term annular gap. In order to stabilize the tunnel lining and to prevent settlement of the ground above the tunnel, this gap needs to be filled by suitable mortar. In general, the annular gap grouting mortar needs to fulfill contrary requirements throughout different steps of the grouting procedure. For the process of pumping into the annular gap the mortar requires a sufficient fluidity, meaning the water content in the mixture is high throughout this step. When the gap is filled out completely, a stable bedding of the tunnel lining is required. Therefore, a rapid evolution of the stiffness of the mortar has to be ensured, which is connected to a time-controlled consolidation process. A stable bedding of the tunnel structure is granted if the shear-stiffness of the mortar in the annular gap corresponds at least to the shear-stiffness of the surrounding soil in its primary stress state.

CHALLENGES OF THE GROUTING PROCESS

In state-of-the-art applications the grouting process proceeds continuously by providing the annular gap with mortar through pipes. Hereby a complete and rapid filling can be ensured. The pressure distribution in the annular gap during and after grouting grants information on the quality of the process. Therefore, experimental investigations have been performed, measuring the pressure distribution in individual tubbing segments during several tunneling projects.

In case of unexpected disturbances during the grouting process, the hydration of the mortar in the supply lines might start earlier than planned. In order to overcome this problem of uncontrolled hydration, cement-free mortar mixtures have lately been applied in tunneling projects. Cement-free mortars are characterized by a missing hydration process through which the application of these mixtures leads to advantages in workability (pumpability). The required shear-stiffness is achieved by consolidation of the grouting mortar in the annular gap. Hence, the annular gap is filled by applying a constant grouting pressure which initializes the consolidation process of the grouting mortar. The applied pressure induces a convective transport of a suspension, consisting of mainly water but also fine mortar particles. Thus, drainage of the mortar as well as infiltration of fine particles into the solid skeleton of the surrounding soil are the outcome. Due to the mortar's reduced porosity, the contacts between single grains in the grouting mortar are enhanced which causes a significant increase in the shear-stiffness and a possible evolution of internal or external filter cakes.

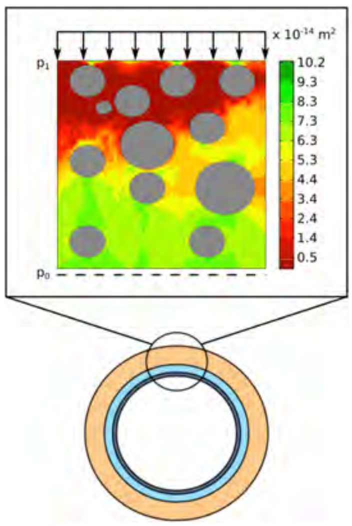

Fig. 1: 1: Permeability distribution in the annular gap and the surrounding soil.

In case of impermeable soils another challenge arises concerning the consolidation process. The surrounding soil restricts the drainage process dramatically so that the mortar cannot develop the necessary shear-stiffness within an appropriate period of time. To this end, water absorbing polymer particles (Super Absorbent Polymers SAP) are currently used as an additive in mortar mixtures. From a chemical point of view, SAPs are cross-linked polyelectrolytes that can, in relation to their own mass, quickly absorb large amounts of water. Due to this, the use of SAP particles seems promising in order to control the amount of free pore water in mortar mixtures and, thereby, allow an instantaneous increase in shear-stiffness when a dehydration process through a convective transport into the surrounding soil cannot be provided.

GOALS OF THE SUBPROJECT

The aim of the subproject is to develop a numerical model for the simulation of the dehydration and infiltration process under suitable boundary conditions (hydro-mechanical coupling) within a thermodynamic consistent framework based on the Theory of Porous Media (TPM). In case of modern two-component mortars, the multiphase model needs to be extended in order to account for the chemo-mechanical coupling between the SAP particles and the overall mortar mixture.

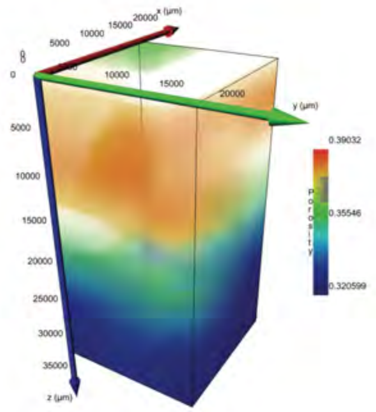

Fig. 2: Porosity distribution as a result of µCT scans of a granular mixture.

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 for a particular tunneling project.

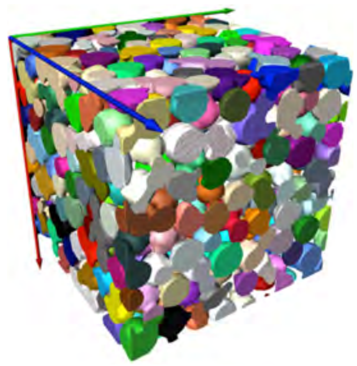

Fig. 3: µCT scan shows a particle distribution of a well-graded granular medium.

Experiments capturing dehydration or infiltration processes are a priori heterogeneous. To this end, advanced space-resolved experimental methods are developed and performed within this subproject. Using imaging techniques (X-ray-based micro-tomography and ultrasound-equipped and spatially-resolved triaxial tests) allows to observe the evolution of the morphology as well as the evolution of mechanical properties in space and time. Especially the experimental insights concerning the change in morphology will be used to enhance the modeling approach.

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PROCESS-ORIENTED SIMULATION MODELS FOR MECHANIZED TUNNELING

A. Alsahly, H. G. Bui, B. T. Cao, A. Marwan, 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 new approach based on BIM concepts is proposed, in which the 3D FE-model is automatically generated through a set of compatible geometries of individual components, i.e. the geology, alignment, lining and the TBM. The BIM model also includes all relevant model parameters of the tunneling project that can then be incorporated into subsequent analysis to be performed during the tunnel drive. The setup and the execution of the FE-analysis are performed automatically utilizing all required data from BIM (Fig. 2). It is also 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.

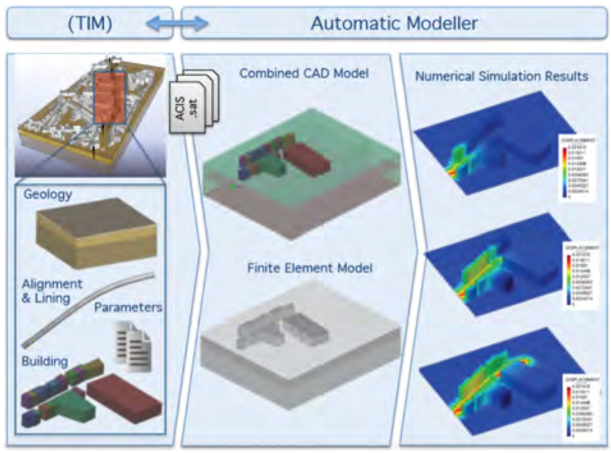

Fig. 2: Automated generation of a FE-Model based on BIM.

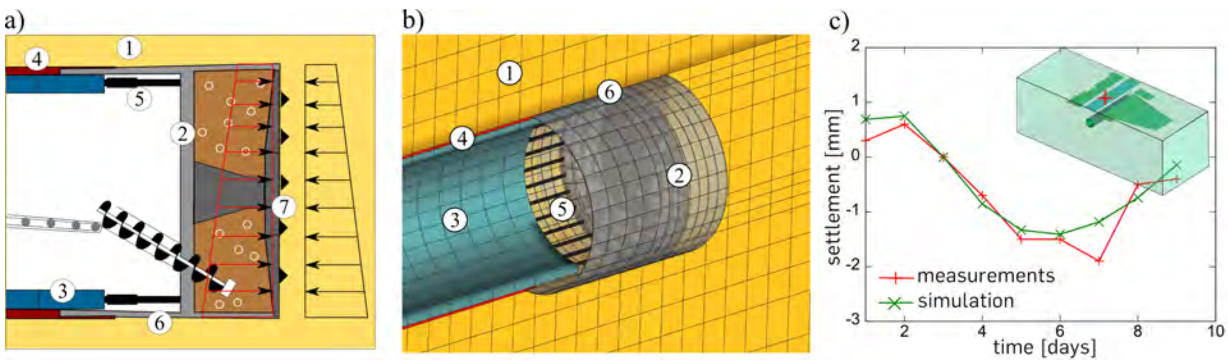

Fig. 1: a) Schematic representation of the components of a TBM drive: (1) soil, (2) shield machine (TBM), (3) tunnel lining, (4) grout, (5) hydraulic jacks, (6) shield skin, (7) cutting wheel und support medium; b) FE simulation model *ekate*; c) Numerical simulation of a section of the Wehrhahn-Linie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

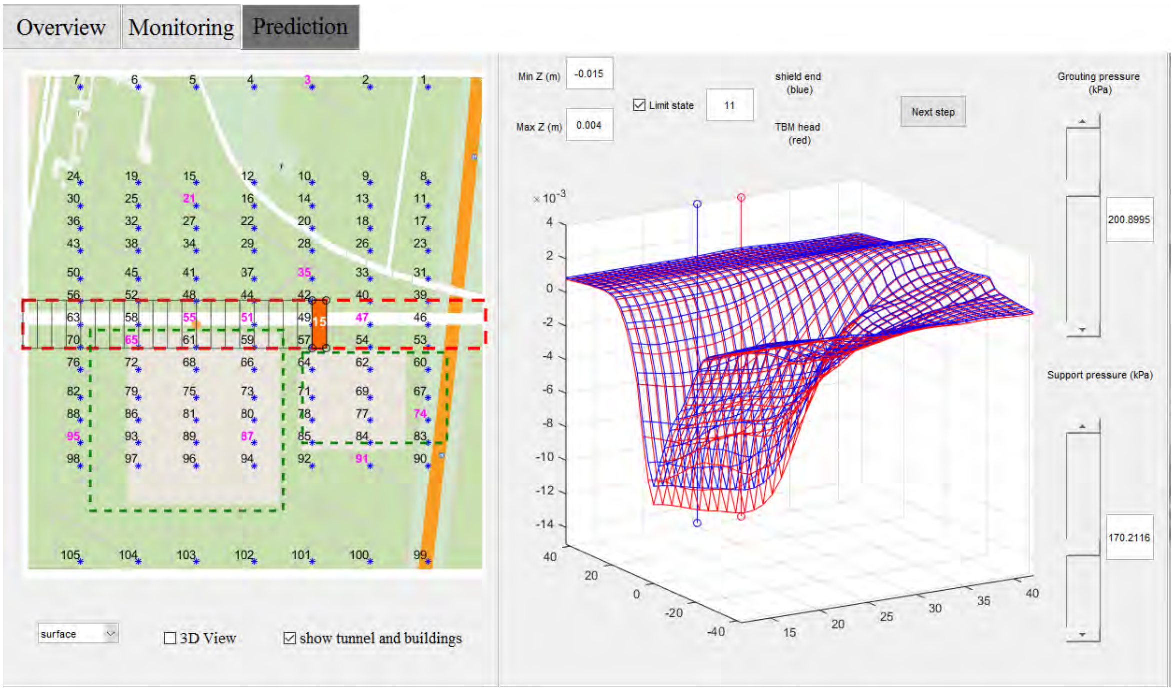

Fig. 3: Simulation and Monitoring-based Assistant for Real-time steering in mechanized Tunneling (SMART).

REAL-TIME STEERING ASSISTANT

The results of the FE simulations form the basis for the development of a Simulation and Monitoring-based Assistant for Real-time steering in mechanized Tunneling (SMART), that is able to produce results quickly and efficiently during the TBM drive (Fig. 3). For real time predictions, the FE simulations are replaced by surrogate models based on Proper Orthogonal Decomposition and Artificial Neural Network approaches. Challenges in the development of this real-time prediction approach are the consideration of the inherent geotechnical uncertanties of the ground conditions.

The uncertainty of the soil parameters can be quantified as intervals using the ranges given in the geotechnical reports. In order to improve the prediction capabilities and to reduce uncertainties, the surrogate models are continuously updated with monitoring data. Figure 3 shows the prediction of time variant interval settlement fields (lower and upper bounds) for user defined face support and grouting pressures in real-time. This allows the user to select suitable values of the steering parameters during the advance of the TBM, such that tolerated settlements are not exceeded.

Further objectives to be incorporated in TBM steering are the tunnel face stability and tolerable risk levels of damage in tunnel linings and existing builidings.

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SYSTEM AND PARAMETER IDENTIFICATION METHODS FOR GROUND MODELS IN MECHANIZED TUNNELING

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

C2

PRESENTATION OF THE SUBPROJECT

The adequate representation of constitutive and geometric properties of the subsoil for numerical simulations in mechanized tunneling is very challenging. This is due to the complex interactions between subsoil, TBM, tunnel and the surface constructions. However, the more realistic these properties are identified, the more accurate the system responses (e.g. surface or construction deformations) are forecast both in the design and in the execution phase. Under the first phase of this subproject, therefore, techniques for the identification, validation, and adaptation of adequate soil models for numerical simulations in mechanized tunneling have been developed. Based on the previous results of the subproject, methods for automatic model adaptation based on measured values will be developed in the next phase. This is done in conjunction with the development of an optimal measurement design for sensor locations.

PREVIOUS RESULTS

The identification of the constitutive and geometric model parameters was performed by means of inverse modeling. For this purpose, a numerical model for the analysis of the mechanized tunneling using slurry shield machines was developed. Because the underlying data were subject to various uncertainties, a number of time consuming simulation runs had to be performed in the identification and the sensitivity analysis process. To improve the response time suitable surrogate models were developed to substitute the forward computational model.

The methods for identifying the model parameters have been 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 for the sub-processes in mechanized tunneling was developed. Since there are often several ways of implementing the various sub-models, the influences of the different concepts on the model response was examined.

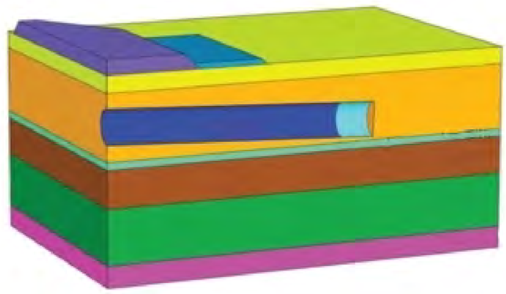

Fig. 1: Numerical Model of the Westerscheldetunnels.

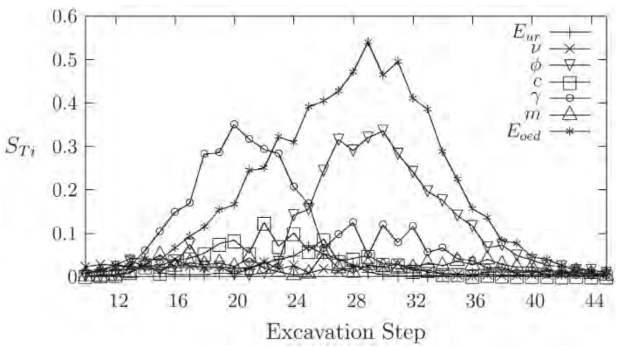

Fig. 2: Sensitivity analysis of decisive subsoil parameters for tunnel driving.

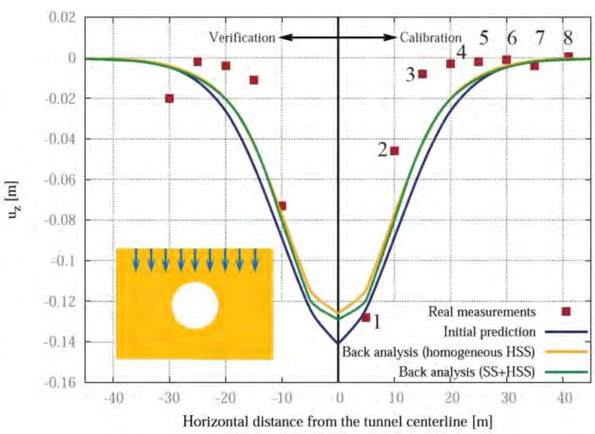

Fig. 3: Validation of the methods by means of real data.

OUTLOOK:
OPTIMISED MEASUREMENT PROGRAM

The system identification depends significantly on the available measurement data. For a successful identification the quantity and quality of the measurements and their being up-to-date should be optimally tuned to the identifiable quantities and prevailing uncertainties.

Nowadays, due to the ongoing advances of sensor technology, a large amount of measurement data can be recorded. However, the question whether the correct values for a certain problem are available often remains unanswered. Therefore, concepts are being developed in order to design an optimal measurement program so relevant measurements can be performed promptly. This reduces costs and also increases the reliability of the system identification. Different technical aspects concerning the task of an optimal measurement setup, such as sensor clustering or sensor displacements during the measurements, are relevant in tunneling and will be considered in the context of this subproject.

In mechanized tunneling problems, the relevant boundary conditions must be classified and adequately described. However, it should also be examined which measurements would be useful to improve the system identification so that on the basis of these studies suitable sensors can be developed in the future.

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

Furthermore, also real measurement data will 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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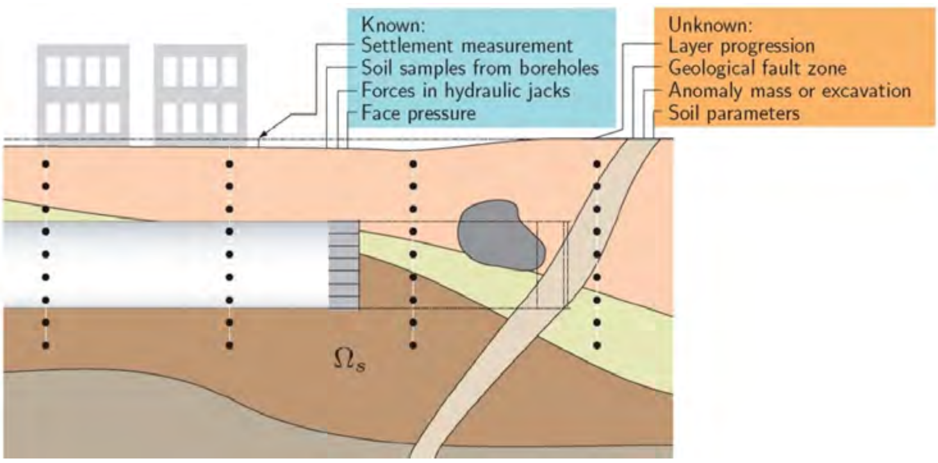

Fig. 4: Identification, validation and adaption of subsoil models based on measurement data.

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

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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 the TBM setup or the supply chain is usually not possible, or it requires too much effort. However, accurate planning of the supply chain supports production processes and reduces or avoids standstill time. For this design, the disturbances of the advance and their effect on the overall system performance has to be taken into account.

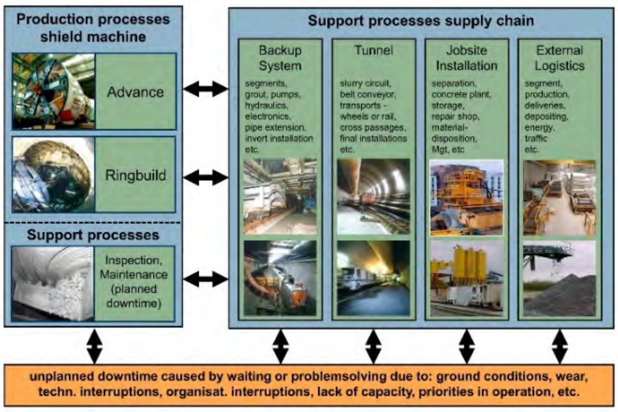

Fig. 1: Interaction of production and support processes in mechanized tunneling.

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

Simulation of all operational processes along with occurring process interaction provides an opportunity for a detailed and holistic analysis of the coupled system "TBM + supply chain." Simulation input data is provided based on an extensive data analysis of the process duration and disturbance frequencies of completed 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 TBMs and jobsites, flexible simulation components representing individual process chains and dependencies were developed. Special purpose simulation models can be created using these flexible simulation components without any code adaption or generation. The hierarchical structure enables a clear model organization and easy analysis of component dependencies.

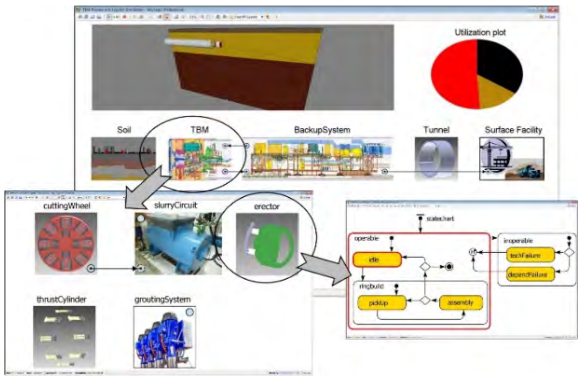

Fig. 2: Simulation model implemented in *AnyLogic* simulation software.

Currently we can provide 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 and

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

A formal description of performance influencing elements for jobsites in mechanized tunneling was developed using the System Modeling Language (SysML). Further, in order to evaluate effects of single disturbances on production performance, element dependencies were also formulated in SysML graphically. 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. Initial performance analyses were realized and validated based on the reference project.

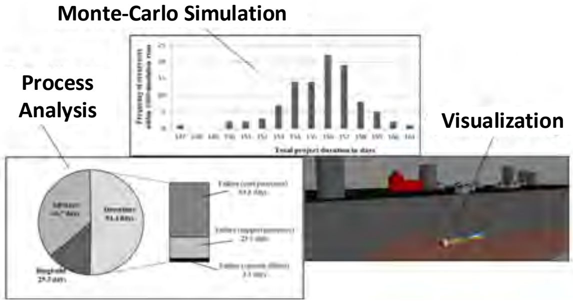

Fig. 3: Graphical analysis of simulation results.

GOAL OF THE 2ND PHASE

The 2nd phase focuses on the simulation-based implementation of maintenance strategies for TBMs, especially for 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 generating long standstill times. When reaching the wear limit, cutting tools have to be replaced on time in order to avoid damages to 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 cutting tools reaches the usability limit will be determined by developing a meta-model including the results of subproject C5. Based on that, the 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,
- existing geology / hydrology,
- surface development (subproject D3),
- disturbances and planned time of standstill.

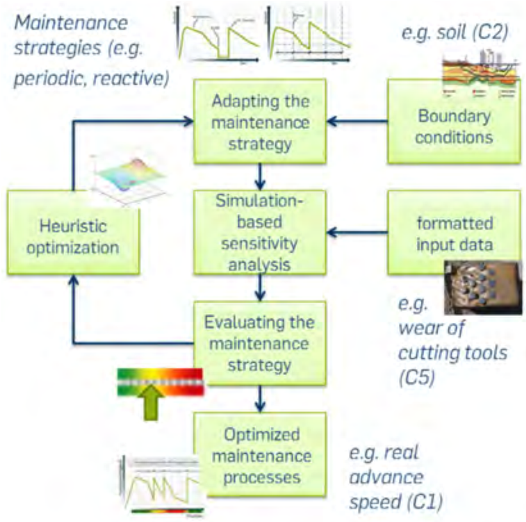

Fig. 4: Simulation-based optimization of maintenance strategies.

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 with respect to efficiency and resistance to disturbances. At the end of the second project phase, the simulation results will be validated using data from real construction projects.

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SIMULATION OF PROCESSES AT THE CUTTING WHEEL AND IN THE EXCAVATION CHAMBER

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

TOPIC OF RESEARCH

Subproject C4 is concerned with the development of computational models for the analysis of the interactions between the cutting wheel of tunnel boring machines (TBMs) and the surrounding soil, including the excavation and transport of the excavated material and the abrasive behavior of the cutting tools. The goal of the project 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.

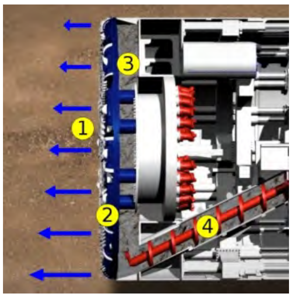

Fig. 1: Aspects of investigation of soil-machine interactions in earth pressure balance tunnel boring machines: (1) face pressure, (2) excavation process and abrasion of cutting tools, (3/4) material flow inside the pressure chamber.

Two project paths 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 path concerned with laboratory testing is currently being established to validate the numerical models.

SIMULATION OF ABRASION PROCESSES

To investigate the abrasion progression of the cutting tool, a single tool with a simplified geometry has been modeled with the Discrete Element Method (DEM). Generally, the cutting tools are made of two different materials. The most stressed components are made of a brittle hard metal and the remaining components are made of standard steel. As such, different failure mechanisms of the different material types must be considered in the simulation. The standard steel components are discretized by a number of small wall elements and for the ductile wear mechanism a material law related to the Archard wear model has been implemented. The resulting behavior is shown in Fig. 2a.

a) b)

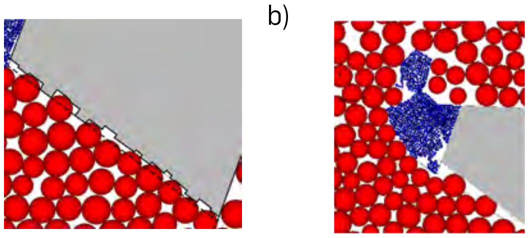

Fig. 2: (a) Failure of the ductile part of the tool (grey), (b) Failure of the brittle tool-part (blue).

The brittle top of the tool is discretized by particles which are connected to each other with bonds, and, as such, this part of the tool fails when the bonds break. As shown in Fig. 2b, there is no wear process as in the ductile part, but rather an abrupt and massive failure. This qualitative behavior is also observed in experiments. In order to validate the results of the wear simulation in cooperation with subproject C5, it is currently being expanded to a three-dimensional version.

SIMULATION OF THE 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 which one phase represents the soil-water and the other one the foam-water mixture. Fig. 3 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.

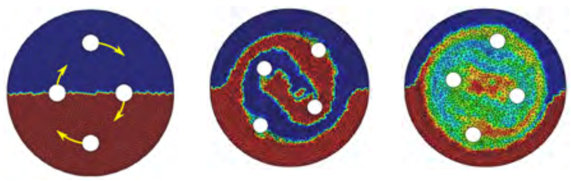

Fig. 3: Mixing process of a viscous two-phase mixture: Evolution of the volume fraction of one phase.

The pressure distribution and the soil transport in the EPB chamber and screw conveyor is simulated by a numerical model with (nearly) realistic geometry including the cutting wheel, the rotating arms and the screw conveyor (Fig. 4a). The Immersed Boundary technique is adapted in the Finite Element Solver to allow the description of moving boundaries. The flow pattern, which depends on the geometry and velocity of the rotating arms, is being investigated to identify the clogging region in the pressure chamber. The efficiency of the foam injection is also assessed by observing the flow field considering the mixing in the pressure chamber. The screw conveyor, which controls the support pressure on the tunnel face, is studied (Fig. 4b) to predict the pressure drop when the soil paste is conveyed through it.

a) b)

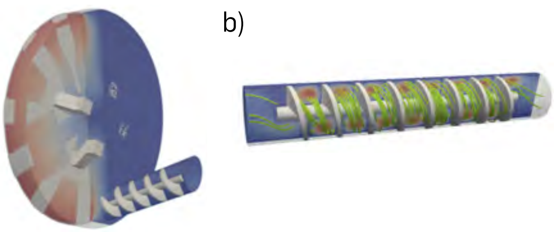

Fig. 4: (a) Simulation of (nearly) realistic EPB geometry with cutting wheel, rotating arms and screw conveyor, (b) Computed streamlines in the crew conveyor.

a) b)

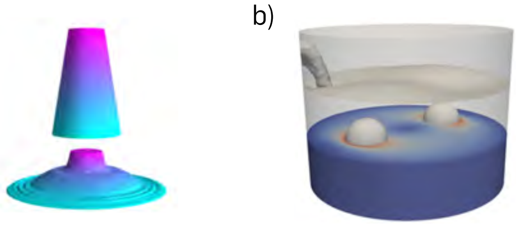

Fig. 5: Numerical simulations for material identification and mixing validation: (a) Slump test, (b) Mixing tank.

The parameters of the viscoplastic constitutive model for the soil are identified from back analysis of slump tests (Fig. 5), using the Particle Swarm Optimization method. The effect of the lifting cone as well as the friction between the slump and floor are taken into account in the slump test simulation. The mixing process is validated by the re-analyses of the mixing tank with immersed stirring balls and material injection (Fig. 5b).

SIMULATION OF THE EXCAVATION PROCESS

To accurately model the soil behavior in the excavation process in which the soil changes from a solid state just before the cutting operation to a fluid-like state when it enters into the pressure chamber, the Particle Finite Element Method (PFEM) is used in conjunction with a non-linear incremental constitutive formulation (hypoplastic model) developed in the project. This model is characterized by a non-linear relation between an objective stress rate and the symmetric gradient of the velocity. Fig. 6a shows the dilatant behavior of sands predicted by the model. Fig. 6b shows the velocity distribution of the soil obtained from the numerical analysis of soil excavation by a single tool.

a) b)

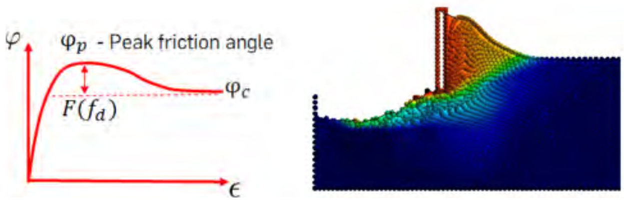

Fig. 6: (a) Control of the peak friction angle value by the model parameter f_d, (b) Particle Finite Element simulation of soil excavated by a moving tool (colors indicate the particle velocity).

The final goal of subproject C4 is to develop a 3D numerical model of the excavation operation with a full scale cutter wheel. This simulation model will be used for the assessment of the soil-TBM interaction.

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WEAR BEHAVIOR OF TBM-TOOLS IN SOFT GROUND TUNNELING OPERATIONS

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

INTRODUCTION – STRUCTURE OF THE PROJECT

Wear and the associated reduced service life of tools counteract the efficiency of tunneling processes. Up to now, the knowledge about the acting wear mechanisms and the interactions between minerals and tunneling tools in soil is insufficient. Based on this circumstance, no reliable predictions about the wear condition and the remaining service time of tunneling tools can be given. On this account, the complex tribological system will be briefly described in the sub-project 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 that will allow the estimation of a meaningful wear rate of tunneling tools with regard to more realistic boundary conditions, including abrasive size and hardness, load spectrum and the material of the base body.

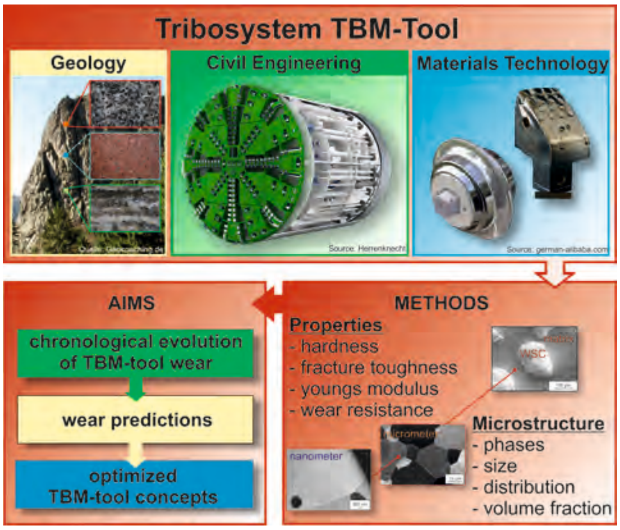

Fig. 1: Mapping of the tribosystem "tunneling tools" to basic aims in the sub-project C5.

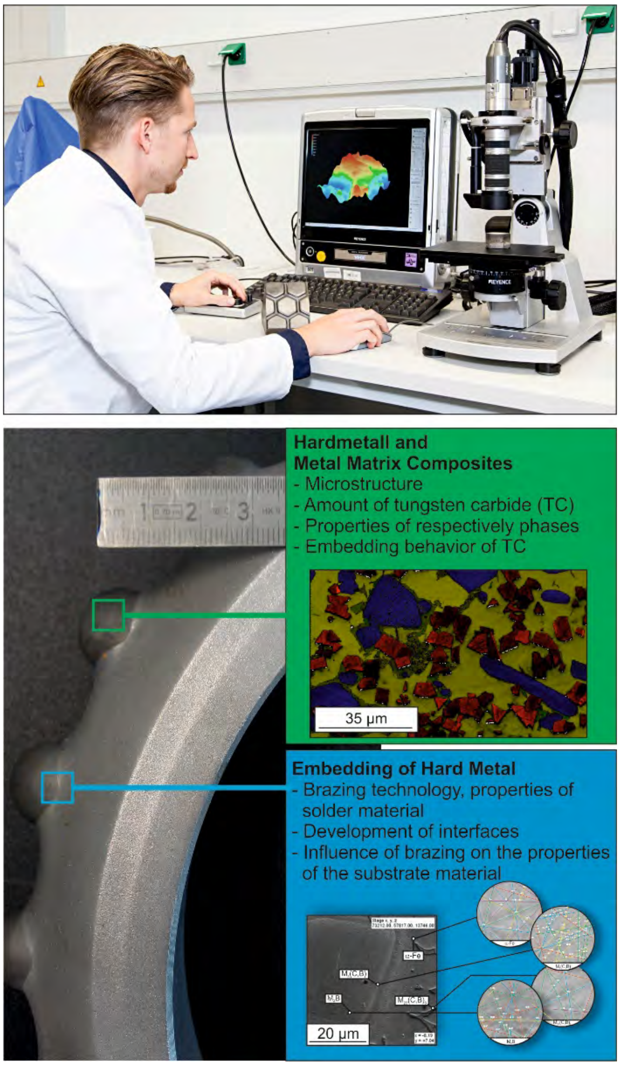

Fig. 2: Investigation of the dominating wear mechanisms of worn tunneling tools using optical and scanning electron microscopy.

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. Since the soil or hard rock is tested against a comparative material, 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, we will consider real materials commonly used for tunneling tools in our new wear testing device. These integral wear tests will be supplemented with single scratch tests using a diamond indenter, giving a deeper understanding of the micro-mechanisms (micro ploughing, scratching and cracking) acting at submicroscopic scale in the materials microstructure.

AIMS AND SCIENTIFIC-TECHNOLOGICAL QUESTIONS

It is the aim of the sub-project C5 to describe the complex tribological system of tunneling tools in soil. Therefore, besides the microstructural analysis of worn tunneling tools, new test methods will be developed which will allow a clear definition of the interactions between the soil and tunneling tools regarding different wear mechanisms. 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 a laboratory scale?
C) Which wear mechanisms are dominant in terms of the present tool material? Tunneling tools consist of different components (tool steel, QT steel, cemented carbide, etc.) which feature different microstructures.
D) Which influences do material properties like fracture toughness of the abrasives or 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 the 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?

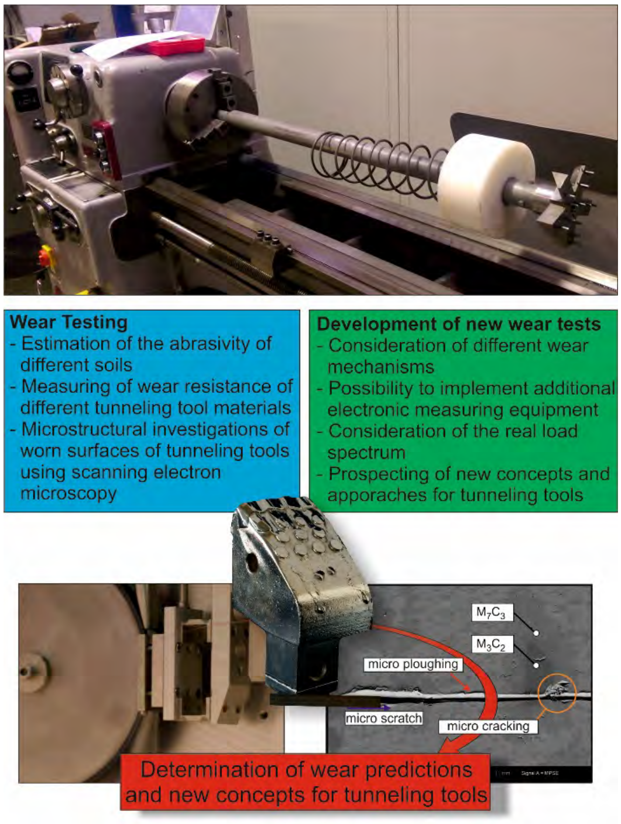

Fig. 3: Performing tribological tests and development of a new wear test to evaluate the residual service life of tunneling tools.

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ASSESSMENT OF INTERACTION MODELS IN MECHANIZED TUNNELING

A. Vonthron, K. Lehner, 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 maintain an acceptably low level of risk during and after tunnel construction. The interactions between the soil, the TBM, the tunnel itself, above-ground constructions and the material flow play an important role in this process. In the first phase, basic concepts related to the data modelling of all essential system elements, processes and interactions have been developed. In order to do so, information related to individual system elements must be represented in an expandable product model. 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 one hand, on existing product data and, on the other, 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 the coherent and uniform access of data, 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. This model forms the basis for modeling the interactions that occur in mechanized tunneling. In the first phase of this project, four main sub-models of mechanized tunneling were specified and coupled.

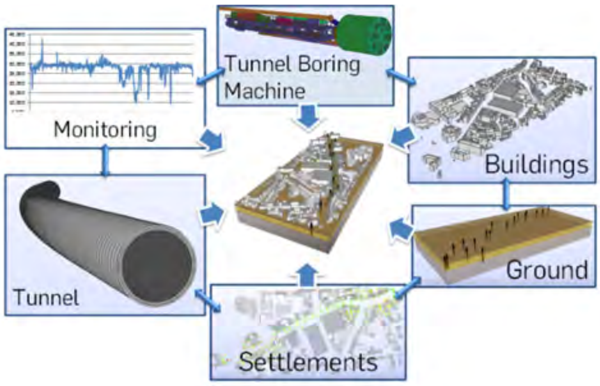

Fig. 1: The tunnel information model consisting of four main sub-models, the time dependent settlements and machine data monitoring.

The sub-models are (see Fig. 1): a hybrid model of subsoil data (Ground), a machine model (TBM), a model of the tunnel construction (Tunnel) and a model of the built-up area (Buildings). These models were chosen due to their significant influence on the construction process. For example, the soil type has an influence on the driving speed, the settlement and the annular gap grouting. The models of interaction chains are based on systems engineering concepts and are formally implemented by the Systems Modelling Language (SysML). Here, the basis is defined by a metamodel 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, is defined by 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 process chain

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

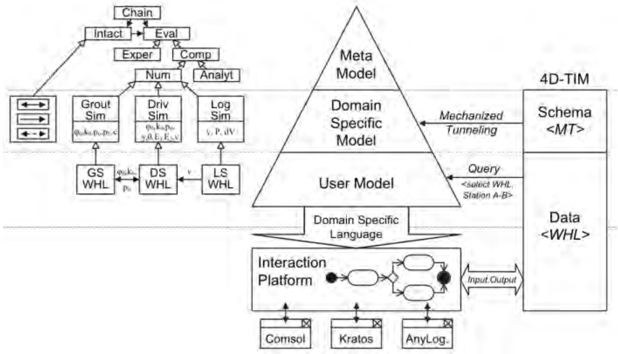

Fig. 2: Definition and execution of interaction chains based on a domain specific modelling language.

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 the proper evaluation of an interaction chain should not be solely based 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.

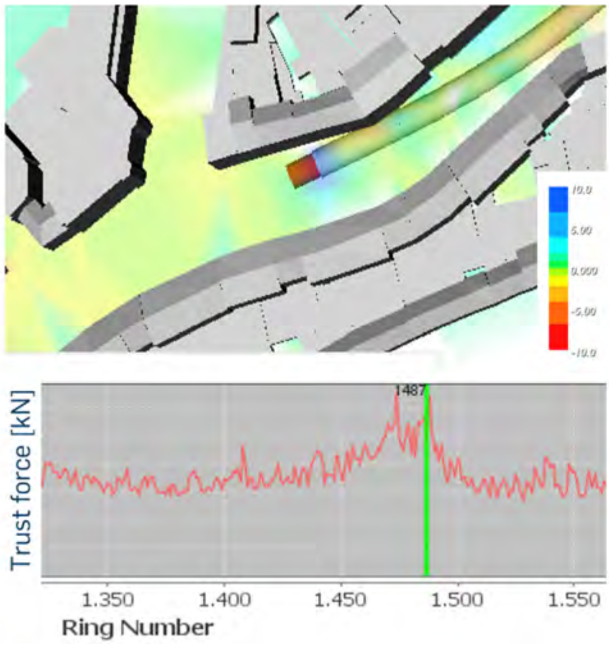

Fig. 3: A visual representation of the connection between settlements and TBM driving forces.

Another goal is the development of concepts for the 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 sufficient knowledge base.

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MODEL-BASED RISK ANALYSIS FOR HETEROGENEOUS EXISTING STRUCTURES

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SCOPE AND CHALLENGES

Settlements at the surface induced by mechanized tunneling are inevitable. Construction companies, owners, and local residents each focus on potential damages to buildings induced by settlements. Due to public sensitivity in dealing with settlements, a solid and reliable assessment of the damage risk is crucial for each tunnel project.

The aim of project D3 is to develop an interactive evaluation system to assess the damage risk of a generally heterogeneous building stock of inner-urban structures. The nearly automated and consequent classification of buildings into representative categories enables the assessment of risk for alternative tracks by profiles even during the planning stage of new tunnels. The inclusion of inherent uncertainties by means of fuzzy parameters helps to increase the rating quality. Thus, the envisaged interactive evaluation system minimizes the required evaluation effort and can make expensive detailed mechanical analyses of individual structures superfluous.

RISK ASSESSMENT

Project planning of new tunnels usually starts with an initial risk assessment of the existing buildings at the surface which delivers an optimal alignment with respect to structural vulnerability. Here, a four step procedure is proposed for pre-assessment. At first, the spatial extent of the expected settlement trough is estimated employing semi-empirical equations. Next, nearby structures are idealized as surrogate beams using the outer dimensions of the building's façade. With these surrogates, bending and shear strains are automatically computed analytically. Third, the damage causing event (settlement) is combined with the idealized structures in a vulnerability analysis. Beam strains are determined with respect to the settlement and compared to limit strains to enable damage classification. That way, all buildings in the tunnel's vicinity are ranked in five categories, ranging from 0 to 4. The lower the category, the lower the induced damage. Category 0 marks the lower limit that indicates negligible damage, such as hair-line cracks. Utmost damage, e.g. structural failure, is associated with category 4. Finally, and once all structures are ranked, individual risk profiles for alternative alignments are computed considering the structures over the tracks. Fig. 1 (top) presents a site map with three alternative alignments (lines) and structures associated with different damage categories (K). The corresponding risk-profiles are shown in Fig. 1 (bottom). They indicate accumulated damage probabilities along the tracks according to the tunneling-induced settlement in mm. In general, the more convex a curve is, the higher the risk of damage. Obviously, line 3 shows the lowest damage potential in the given example.

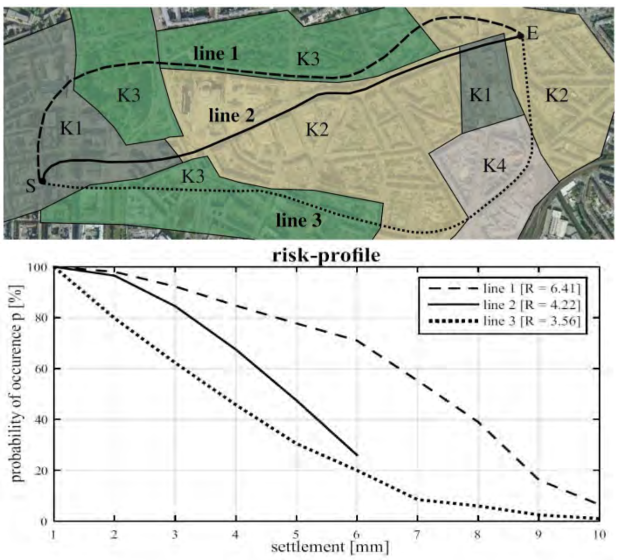

Fig. 1: Site map (top) and corresponding risk-profiles (bottom).

DATA ACQUISITION

Of course, reliable risk assessment requires comprehensive and accurate data acquisition, too. Currently, structural data is gathered based on construction drawings only. However, sometimes no drawings are available at all. Hence, we plan to develop new and automated approaches to determine missing information from other sources, such as façade images or laser scans.

Employing machine learning techniques, wall-openings in façades, which highly influence structural stiffness, can be determined. The detection of windows in Fig. 2 (highlighted in green) and the corresponding stiffness parameters can then be used to refine structural models for an improved risk assessment.

Fig. 2: Detected windows (green) in a façade image.

CONSIDERATION OF UNCERTAINTIES

Until now, the individual vulnerabilities have been computed purely deterministic. However, all input parameters are subject to variations that should be considered in predictions. So far, four alternative approaches–here sorted with respect to computing time demands–are seen as promising: interval arithmetic, random sets, fuzzy sets as well as the probabilistic approach.

In case of interval arithmetic, a pair of values (minimum and maximum) is assigned to every single input parameter. With these upper and lower limits of the expected settlement, the corresponding strains of the surrogate beam are obtained. Random sets generalize this concept. Here, more than one pair of values might be assigned to the input, which is especially useful in case of coexisting data sources or diverging expertise. Fuzzy sets allocate so-called membership functions to uncertain values if data is scarce and distribution functions and their stochastic parameters can be assigned only with doubt. Obviously, the probabilistic approach sets the highest demands. Here, every input parameter has a certain distribution function which must be estimated from the available data or might be known in advance from the physics of the process itself.

By the consequent consideration of inherent uncertainties, more realistic results are to be expected, the precision of the damage risk assessment will increase and, therefore, the quality of prediction will improve greatly.

PROSPECTIVE MILESTONES

The damage categories obtained from vulnerability analyses will be calculated in real-time and are to be visualized in the Virtual Reality Lab to allow remote exploration.

Algorithms at hand that determine the damage causing event and allow risk assessment should be integrated into Web-based applications in a user-friendly manner.

The risk profiles, which currently depend on the damage categories only, should be enhanced by individual weighting factors to gain a more detailed evaluation of the alignments along the very different surface structures.

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