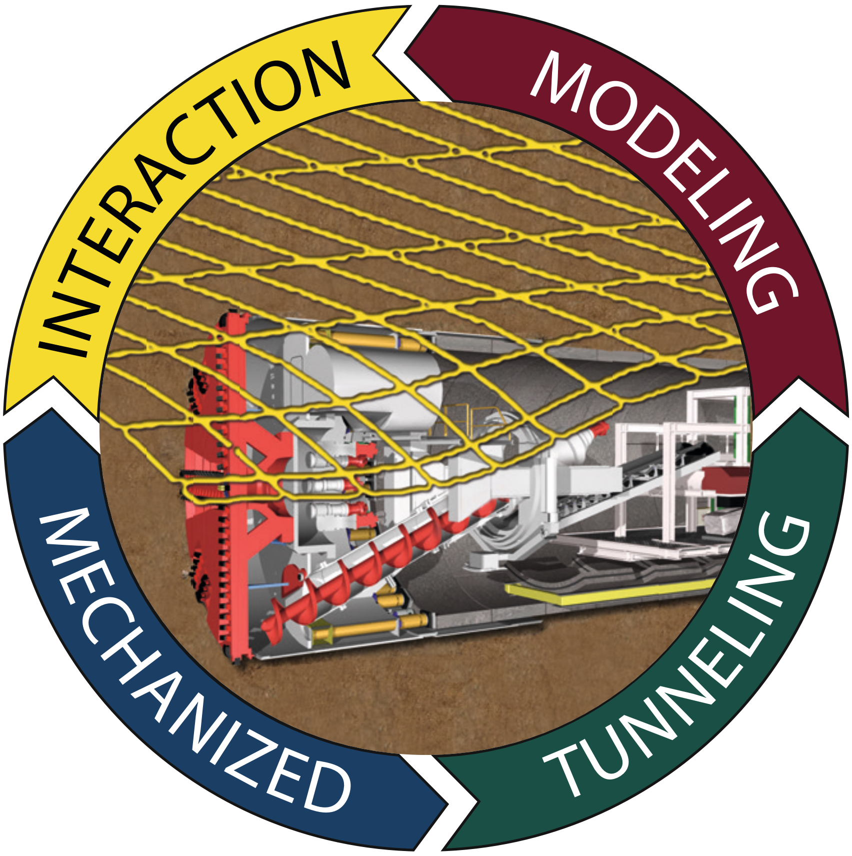
Collaborative Research Center 837

Interaction Modeling in Mechanized Tunneling



SFB 837 Brochure 2019

RUHR UNIVERSITY BOCHUM

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COLLABORATIVE RESEARCH CENTER 837

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Collaborative Research Center 837

INTERACTION MODELING IN MECHANIZED TUNNELING

SFB
837

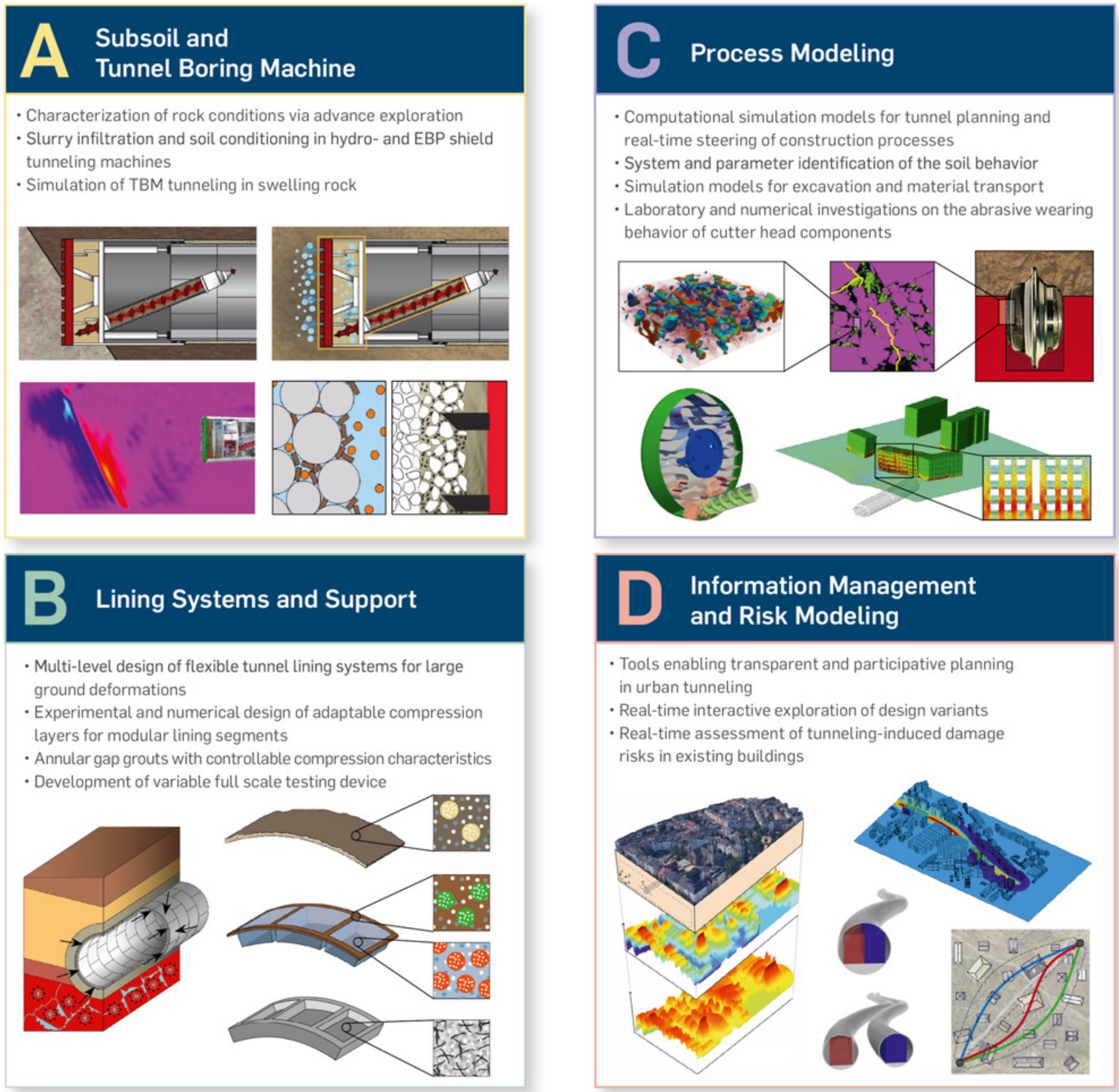
THE SFB 837: INTERDISCIPLINARY FUNDAMENTAL RESEARCH IN MECHANIZED TUNNELING

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 extended to an ever increasing variety of geotechnical conditions.

However, problems inherent in the mechanized tunneling process, such as its lack of adaptability to unexpected changes in geological conditions, uncertainties in a priori soil information and the complexity of machine-soil interactions, present significant challenges in both the planning and the construction of tunnels. As a result, tunnel boring machines only reach a fraction of their theoretical production capacity during typical tunnel drives.

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 pre-existing structures. Heterogeneous geological conditions and often only approximated ground parameters create, in contrast to other engineering projects, special demands. These circumstances and the constant expansion of the range of deployment of shield-supported tunneling as well as the tendency to always larger shield diameters demand the exploration of 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 the 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 Modeling in Mechanized Tunneling” (SFB 837) at Ruhr University Bochum in 2010. Collaborative Research Centers are interdisciplinary scientific research groups in which cooperative research is conducted under the umbrella of a central research topic. With a research budget of app. 12 million euros for the third 4-year funding period, the SFB 837 is currently the largest research group conducting fundamental research in tunneling-related topics worldwide.



A Subsoil and Tunnel Boring Machine

- Characterization of rock conditions via advance exploration
- Slurry infiltration and soil conditioning in hydro- and EBP shield tunneling machines
- Simulation of TBM tunneling in swelling rock

C Process Modeling

- Computational simulation models for tunnel planning and real-time steering of construction processes
- System and parameter identification of the soil behavior
- Simulation models for excavation and material transport
- Laboratory and numerical investigations on the abrasive wearing behavior of cutter head components

B Lining Systems and Support

- Multi-level design of flexible tunnel lining systems for large ground deformations
- Experimental and numerical design of adaptable compression layers for modular lining segments
- Annular gap grouts with controllable compression characteristics
- Development of variable full scale testing device

D Information Management and Risk Modeling

- Tools enabling transparent and participative planning in urban tunneling
- Real-time interactive exploration of design variants
- Real-time assessment of tunneling-induced damage risks in existing buildings

Fig. 1: The four project areas in the SFB 837

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 (cf. Fig. 1). Project area A deals 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. Project area B is focused on 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 topics are each supported by computational models and are all included in an SFB encompassing tunnel information model that was developed within the first funding period. Furthermore, interaction groups were formed in order to integrate and combine the results of different submodels and analyses. These originated partially from prototypical cause-and-effect relationships, and partially from applications to reference tunneling projects.

While research during the first two funding phases was focused on the tunneling in soft ground, the proposed research in the third funding period will additionally concentrate on tunneling in difficult geological conditions which nowadays sets the limits on the application range of mechanized tunneling. Among other topics, research will be concerned with the exploration of significant as yet unexplored factors that control tunneling processes in expansive soils, as well as with the design of novel deformation-tolerant tunnel linings to be used in such situations. From interdisciplinary research between material scientists and geophysicists, essential insights will be gained into the wear of excavation tools and the efficiency of excavation in such difficult geological conditions. Simulation and risk models for the excavation, advancement and logistics processes developed in the SFB 837 will enable improved, environmentally-friendly and low-risk planning and construction processes. These models will be extended to enable real-time prognoses and to provide a platform for the interactive digital design of urban tunneling projects. In doing so, the SFB 837 aims to create new perspectives for innovative participative planning instruments in tunneling. Furthermore, by developing continuously updated real-time models, the SFB 837 will take an important step towards computer-aided steering of the mechanized tunneling process.

The research team constituting the SFB 837 is composed of 19 principle investigators (PIs) supervising 16 sub projects as well as scientific staff with a background in various disciplines in civil engineering, geosciences and mechanical engineering (approximately 40 Ph.D. and Post-Doc researchers). Within 16 subprojects, that are divided into the four project areas, new design concepts, numerical models and excavation technologies for mechanized tunneling are currently being developed. The Coordinator of the SFB 837, along with a four-member Executive Board is responsible for the leadership of the research center. Further administrative support is provided by an assistant coordinator as well as by an administrative assistant responsible for day-to-day organization. All Ph.D. researchers are members of an Integrated Graduate School, where method-oriented competences, tunneling-related knowledge and soft skills are trained in a close-to-practice environment. To support the SFB in strategic planning decisions, especially in the context of the 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 an annual event in which the advisory board discusses the research progress of the SFB. This review process has always resulted in a highly beneficial exchange of ideas for the SFB.

One element of the SFB 837, which has increasingly gained importance in the present 3rd project phase, is the cooperation with companies directly involved in tunnel engineering projects, and the transfer of developed methods and technologies to engineering practice. Through cooperation with the Wehrhahnline 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 established a considerable number of scientific partnerships. In addition, the SFB 837 has been maintaining close cooperations with international scientific institutions. Current academic partnerships include the School of Engineering of Tongji University (China), the Colorado School of Mines (USA), the Universities of Graz, Leoben and Innsbruck (Austria), Brescia University and Politecnico di Torino (Italy), ETH Zürich (Switzerland), Ghent University (Belgium), and the Technical University Delft (The Netherlands). 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 16 subprojects of the SFB 837 as well as a list of per-reviewed journal and book publications. 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 you to contact us.

Günther Meschke,

Coordinator of the SFB 837

EXECUTIVE BOARD

Prof. Dr. techn. Günther MESCHKE

Structural Mechanics

SFB 837 Coordinator,
PI 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". Focus of his research is 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 Member of the German Academy of Science and Engineering (acatech), the North Rhine-Westphalian Academy of Sciences, Humanities and the Arts, the Academia Europaea, an associate member of the Austrian Academy of Sciences and a member of the Austrian Science Board. He is the author of over 370 scientific publications.

Prof. Dr.-Ing. Markus THEWES

Tunnelling and
Construction Management

SFB 837 Vice Coordinator,
PI of subprojects:
A4, C3, D1

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 200 publications in journals and conferences.

EXECUTIVE BOARD

Prof. Dr.-Ing. Rolf BREITENBÜCHER

Building Materials

PI 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" (TC 104/SC1) and also of the national DIN-committee "Beton". Since September 2017, he is the chairman of the board of the German Committee for Reinforced Concrete (DAfStb). Furthermore, he has published more than 140 scientific papers.

Prof. Dr.-Ing. Markus KÖNIG

Computing in Engineering

PI of subprojects:
C2, C3, D1

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 supports the development, implementation and evaluation of the "Road Map for Digital Design and Construction" for the German government.

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. He is the author of over 160 scientific publications.

PRINCIPAL INVESTIGATORS

Dr.-Ing. Wiebke BAILLE

Soil Mechanics, Foundation Engineering & Environmental Geotechnics

PI of subproject:
A6

Dr. Baille is a Group PI and Head of the Clay Lab at the Chair of Soil Mechanics, Foundation Engineering and Environmental Geotechnics. 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, and on 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.

Prof. Dr.-Ing. Daniel BALZANI

Continuum Mechanics

PI of subproject:
C6

Prof. Dr.-Ing. habil. Daniel Balzani is Full-Professor for Continuum Mechanics in the Department of Civil- and Environmental at Ruhr University Bochum since 2017. Research focus in his group is the development of new numerical methods and models to reliably simulate micro-heterogeneous materials at different scales. In this context, aspects as the incorporation of graded properties in single microscopic phases, fracture at the microscale, as well as uncertainties resulting from e.g., microstructure variation are of major importance. The resulting computational models are applied to e.g., metallic materials, soft biological tissues, textile membranes, or reinforced concrete. Before joining RUB, Daniel Balzani was Open-Topic Full-Professor for Mechanics at Technische Universität Dresden since 2014. He received his doctoral degree at TU Darmstadt in 2006 and his habilitation from the University of Duisburg-Essen in 2012. In between he served as substitute professor at Leibniz University Hannover from 2009 to 2010 and from 2010 to 2011 he visited the California Institute of Technology as Visiting Associate. He received a number of awards including the Heinz Maier-Leibnitz Price of the DFG in 2010, the Richard von Mises Award of the GAMM in 2009, the Gottschalk-Diederich-Baedeker Award in 2013, and the M.I.T. Fellowship Award in 2005.

PRINCIPAL INVESTIGATORS

Dr.-Ing. Steffen FREITAG

Structural Mechanics

PI of subproject:
C1

Dr. Steffen Freitag is a Research Group PI 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. He was a visiting scholar (2011–2012) within the Center for Reliable Engineering Computing at Georgia Institute of Technology. From 2015 to 2018, Dr. Freitag was a member of the “Junges Kolleg” at the North Rhine-Westphalian Academy of Sciences, Humanities and Arts, where he also acted as vice spokesman and spokesman. In 2017, the research work of Dr. Freitag has been honored by the Karl-Arnold-Award.

Prof. Dr. rer. nat. Wolfgang FRIEDERICH

Geophysics - Seismology

PI 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".

PRINCIPAL INVESTIGATORS

Prof. Dr. rer. nat. Klaus HACKL

Mechanics of Materials

PI of subproject:
C6

Prof. Dr. rer. nat. Klaus Hackl leads the Chair of Mechanics of Materials at the Ruhr University Bochum. He is director of the international master-program “Computational Engineering” at the Ruhr University Bochum. He is founding member of the GAMM-activity group “Analysis of microstructure”, which he chaired for many years. He is Associate Editor of the "International Journal for Multiscale Computational Engineering" and member of the editorial board of several international journals and author of more than 250 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, dislocation microstructures and damage mechanics.
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.

Dr.-Ing. Arash Alimardani LAVASAN

Soil Mechanics,
Foundation Engineering
& Environmental
Geotechnics

PI of subproject:
A5

Dr. Arash Alimardani Lavasan is research associate and group PI at the chair of Soil Mechanics, Foundation Engineering, and Environmental Geotechnics at the Ruhr University Bochum. His research mainly focuses on assessment of Thermo-Hydro-Mechanical behavior of the geomaterials and numerical simulation of multi-phase systems in Geomechanics including development of advanced constitutive models.
Dr. Lavasan studied civil engineering (Bachelor) from 1998 to 2002 at Shiraz University, Iran. He finished his Master and PhD degrees with special honors in geotechnical engineering respectively in 2005 and 2010 at K. N. Toosi University of Technology in Teheran, Iran. In 2012, Dr. Lavasan received the Alexander von Humboldt Foundation award for Post-doctoral research at Ruhr University Bochum. Since, 2014, his research works at the chair of Soil Mechanics, Foundation Engineering, and Environmental Geotechnics deals with different research topics such as Mechanized tunneling and its coupled interactions in the near-field of TBM, assessment of geohazards in natural slopes due to climate change, and mechanics of geosynthetic reinforced soils.

PRINCIPAL INVESTIGATORS

Dr.-Ing. Elham MAHMOUDI

Computing in Engineering

PI of subproject:
C2

Dr. Elham Mahmoudi is a junior group PI at the Institute for Computing in Engineering at the Ruhr University Bochum. Her research interests include numerical simulation of geotechnical problems considering inherent uncertainty and heterogeneities, sensitivity analysis, optimization concepts, machine learning and probabilistic analysis.

In 2012 Dr. Mahmoudi obtained her master degree in the field of numerical modelling of underground pipelines crossing active faults at IKIU, Iran. Afterwards, in 2014 she awarded a DAAD scholarship for a doctoral program in Germany. She was a research assistant at the chair of Foundation Engineering, Soil and Rock Mechanics under the supervision of Prof. Tom Schanz. Her doctorate thesis focuses on the probabilistic analysis of underground energy repositories was defended with distinction in 2017 at the Ruhr University Bochum. Since 2016, Dr. Mahmoudi joined the chair of Computing in Engineering as research assistance, dealing mainly with system and parameter identification methods in mechanized tunnelling.

Prof. Dr.-Ing. Peter MARK

Concrete Structures

PI of subprojects:
B1, D3

Prof. Dr.-Ing. habil. Peter Mark is professor at the Institute of Concrete Structures and vice-dean at the Faculty of Civil and Environmental Engineering at the Ruhr University Bochum. Main areas of his research are development of optimization based 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 Independent Checking Engineer (ICE). 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 fib TG 10.1 developing MC 2020, the VGB PowerTech Scientific Advisory Board and the German Tunnelling Committee ("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.

PRINCIPAL INVESTIGATORS

Prof. Dr.-Ing. Inka MÜLLER

Structural Health Monitoring

PI of subproject: C7

Prof. Dr.-Ing. Inka Müller (née Büthe) is junior professor for Structural Health Monitoring (SHM) and member of the Institute for Structural Engineering at RUB. Her current research interests are structural health monitoring systems and their reliability, acousto-ultrasonics using piezoelectric transducers as well as intelligent data analysis for monitoring purposes. She has worked in the SHM-field for almost 10 years now with a special focus on reliability of monitoring systems and introduced sensor systems as well as the use of AI-methods for structural monitoring under changing environmental and operational conditions. She studied at University of Siegen and Keio University, Tokyo (Japan) from 2006 till 2011 and worked within the EU-funded project SARISTU and as a subcontractor in the BMBF-funded project CarbonSafe. Her PhD – finished in 2016 at the University of Siegen– was funded by the German Academic Scholarship Foundation. She has presented her work on international conferences and published papers in international journals as well as one technical bulletin. She serves as reviewer for international journals and national funding agencies. Since 2018 she is leading the working group POD in the subcommittee Guided Waves of the technical committee on SHM within the German Association of Non-Destructive Testing.

Prof. Dr.-Ing. Tamara NESTOROVIĆ

Mechanics of Adaptive Systems

PI 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, robust control, inversion methods and reconnaissance in mechanized tunneling, structural health monitoring and nondestructive testing, 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 PI in the field of smart structures and virtual reality. In 2008 she was appointed a full professor at Ruhr University Bochum. Prof. Nestorović is author of over 180 scientific publications.

PRINCIPAL INVESTIGATORS

Prof. Dr.-Ing. Jörg RENNER

Experimental Geophysics

PI of subproject:
C5

After his dissertation at the Ruhr University Bochum (RUB), Jörg Renner held postdoctoral fellowships and appointments at MIT and GFZ before he became Professor for Experimental Geophysics at RUB in 2001. His major research interests are in two strongly linked topics, subsurface fluid transport and rheology of rocks. He addresses problems from groundwater flow near the surface, to oil, gas or geothermal energy production from the upper crust, to melt transport in the Earth's mantle by performing and analyzing laboratory and field experiments. In the laboratory, recent efforts aim at advancements regarding the monitoring of the evolution of the failure of brittle rocks by continuous determination of physical properties, such as permeability and elastic-wave velocities, during triaxial deformation at conditions mimicking those prevailing in engineering applications and earthquake sources. The aim is to derive constitutive relations, often starting from micro-mechanical models that rest on structure analyses performed with optical and electron microscopes, apt for large-scale modeling, e it analytical or numerical. Regarding field applications, the group has focused on developing protocols for pump tests, in particular periodic pump tests, that yield substantial constraints on the architecture of hydraulic conduits and associated flow regimes.

Dr.-Ing. Arne RÖTTGER

Materials Technology

PI of subproject:
C5

The research of Dr.-Ing. Arne Röttger focusses on the topics of materials development, hard phase containing materials, additive manufacturing as well as melt and powder metallurgy. The material development take into account aspects of metallurgy as well as technological constraints such as resource efficiency, cost-effectiveness and processability. For the development of new materials computer-based techniques and experimental methods are regarded. In principle, Arne Röttger considers questions of the relationship between the chemical composition and the stability of individual phases, the production-related microstructure formation processes and the associated material properties.

He graduated in 2001 from Mechanical Engineering (Operation Engineering) at the University of applied science South-Westphalia. In 2008 he graduated from Mechanical Engineering (Materials Engineer) at the Ruhr University Bochum. After obtaining his PhD. In 2011 at the Ruhr University Bochum he is working as a group PI at the chair of Materials Technology at the Ruhr University Bochum.

PRINCIPAL INVESTIGATORS

Dr.-Ing. Britta SCHÖßER

Tunnelling and
Construction Management

PI of subproject:
A6

Dr. Schößer is Group PI and Head of the bentonite laboratory at the Institute for Tunnelling and Construction Management. Her research topics include the application of bentonite suspensions as a support, lubrication and transport medium in mechanized 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.

Starting in 1996, Dr. Schößer worked as project engineer in the field of mechanized and conventional tunneling at the engineering office of Prof. Maidl, Bochum, and at the Deutsche Montan Technologie (DMT), Essen. In 1998, she joined the Working Group Pipeline Construction of Prof. Stein and obtained her PhD in 2004. In 2005-2007, Dr. Schößer was project manager in the Joint Venture "Abwasserkanal Emscher", a sewer system with a length of 51 km and the largest pipe jacking project in Europe. In 2008, she joined the Tunneling Institute.

Dr. Schößer is author of internationally recognized technical books and appointed member of the DWA-Working Group ES-5.3 "Trenchless Technologies" working on national standards for pipe jacking and microtunnelling.

Dr.-Ing. Jithender Jaswant TIMOTHY

Structural Mechanics

PI of subproject:
B2

Dr. Jithender J. Timothy is a Research Group PI at the Institute of Structural Mechanics, Ruhr University Bochum. His research interests are model-based characterization and design of materials using scale-bridging computational methods.

He obtained his basic engineering degree in mechanical engineering from Anna University, India in 2006. He received a Master degree and a Ph.D. (Dr.-Ing.) with distinction in Computational Engineering from Ruhr University Bochum in 2010 and 2016 respectively. His doctoral dissertation was awarded the Dr. Heinrich-Kost Prize for developing a new paradigm in the multiscale characterization of disordered porous materials. He currently heads the research group 'Scale-Bridging Modelling of Materials and Structures' at the institute for structural mechanics, Ruhr University Bochum.

PRINCIPAL INVESTIGATORS

Prof. Dr. phil. nat. Andreas VOGEL

High Performance Computing in the Engineering Sciences

PI of subproject: C4

Prof. Dr. phil. nat. Andreas Vogel leads the research group High Performance Computing in the Engineering Sciences at Ruhr University Bochum. His research interests are algorithmic research and software development for high-performance computing applications focused on the usage of largest computer clusters and an efficient scaling of simulation codes.
Prof. Vogel received a Diploma in physics and a Diploma in mathematics from the Ruprecht-Karls-University Heidelberg in 2008. He received a PhD in Informatics (Dr. phil. nat.) in 2014 from the Goethe University Frankfurt. From 2008 to 2017, he was a research fellow at the Goethe-Center for Scientific Computing in Frankfurt am Main and engaged in several high-performance computing projects with a focus on the parallelization of multigrid solvers and their efficient implementation on state-of-the-art computing systems.

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. Abdullah ALSAHLY

Structural Mechanics

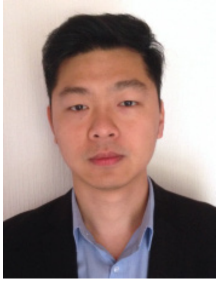
Subproject: C1

Dr. Abdullah Alsahly is a senior research associate and the leader of the “Computational Modeling in Tunneling and Underground Structures” group at the Institute for Structural Mechanics. His research interests lie in the theoretical and applied research in computational structural mechanics, with emphasis on the computational simulations in tunneling and subsurface engineering, multiphase models for geotechnical Materials and associated (multifield) finite element methods and advanced numerical methods for the assessment of stability and failure mechanisms in geotechnical problems.

Dr. Alsahly studied civil engineering (Bachelor) from 1998-2002 at Damascus University, Syria. He finished his master’s degree with distinction in Computational Engineering in 2010 at Ruhr University Bochum. In 2017 he obtained his PhD in civil engineering there in the field of process oriented simulation in mechanized tunneling. Dr. Alsahly has been involved in a wide range of civil engineering activities and has worked on numerous international projects. He is an expert in both analytical and numerically-assisted structural analysis of structures. He has significant expertise in the analysis of the effects of tunneling, specifically in settlement analysis, face stability analysis and evaluation of damage to in-situ structures.

POST-DOCTORAL RESEARCHERS

Dr.-Ing. Ba Trung CAO



Structural Mechanics

Subproject: C1

Dr. Ba Trung Cao is a research associate at the Institute for Structural Mechanics at Ruhr University Bochum (RUB). His research focuses on computational models for mechanized tunneling process, uncertainty quantification, the use of surrogate models for real- time predictions in engineering tasks as well as model reduction techniques.

Dr. Cao received his Bachelor in Civil Engineering from the University of Transport and Communications (Vietnam) in 2007. In 2011, he completed his Master degree in Computational Engineering at Ruhr University Bochum. He then worked at the Institute for Structural Mechanics at RUB where he finished his doctoral thesis “Simulation and Monitoring Assisted Real-time Steering with Uncertainty in Mechanized Tunneling” in 2018. Dr. Cao has been involving in a number of research projects related to mechanized tunneling.

Dr.-Ing. Thai Son DANG

Structural Mechanics

Subproject: C4

Dr. Thai Son Dang is a research associate at the Institute for Structural Mechanics at Ruhr University Bochum. His main research is on tunnel boring machine operation, particle- and mesh-based numerical methods, material flow and mixing process, practical application of numerical models.

Dr. Dang had studied Bachelor of Aeronautical Engineering in Vietnam before he got a master’s degree in Computational Engineering at Ruhr University Bochum. He defended his doctor’s thesis in 2018 with the topic on numerical methods and analyses of muck flow in EPB pressure chambers. He has worked in the Institute of Structural Mechanics and has been the member of the Collaborative Research Center 837 since 2011.

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. Ulrich HOPPE

Mechanics
of Materials

Subproject: C6

Dr. Ulrich Hoppe is a senior research associate at the Institute of Mechanics of Materials at Ruhr University Bochum. His main research interest is the modeling and simulation of mechanical problems, such as finite strain plasticity, shape memory materials, and structural mechanics. In the SFB he has developed an excavation device for tool-soil interaction experiments under laboratory conditions.
After a three year industrial training as a qualified mechanic in compressor and turbine industry, Dr. Hoppe studied Mechanical Engineering at Ruhr University Bochum and obtained his diploma in 1991. In the following years he worked as a research assistant at the Chair of Mechanics II under supervision of Prof. H. Stumpf and got his doctoral degree in 1996 awarded by the Department of Civil and Environmental Engineering for his thesis "Basic concepts of nonlinear continuum mechanics and shell theory". Since 2001 he has been working as PostDoc at the Institute of Mechanics of Materials and has been involved in many research projects.

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.

Dr.-Ing. Markus OBEL

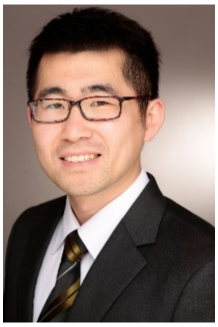
Concrete Structures

Subproject: D3

Dr. Markus Obel is a scientific assistant at the Institute of Concrete Structures at Ruhr University Bochum (RUB). His main areas of research are probabilistic risk analyses, the assessment of tunneling induced damages on existing structures, as well as the efficient evaluation of entire tunnel alignments under consideration of stochastically uncertainties.
Dr. Obel studied civil engineering (Bachelor) from 2008 to 2011 at Hochschule Bochum. He continued his master study at RUB and finished 2013. Afterwards he worked till 2015 as structural engineer at R&P Ruffert Ingenieure in Düsseldorf, Germany. Since then, he joined the collaborative research center 837 and worked on the subproject D3. In 2019 he finished his doctoral thesis “A consecutive probabilistic risk assessment concept for settling-induces structural damages”.

POST-DOCTORAL RESEARCHERS

Dr.-Ing. Hongwei YANG



Experimental Geophysics

Subproject: C5

Dr. Hongwei Yang is a research assistant at the Chair of Experimental Geophysics. His research centers around penetration problems in soils and rocks by means of laboratory experiments, physical and numerical modelling methods. In this project focus is given to the rock fragmentation induced by the indentation of excavation tools.

Hongwei Yang studied geological engineering at the Central South University, Changsha, China from 2006 to 2010. He obtained his Ph.D degree in geotechnical engineering at the University of New South Wales, Sydney, Australia in 2014 with the title “Cone penetration tests in unsaturated silty sand”. During the year from 2015 to 2016 and 2018, he did his postdoctoral research at the University of Hong Kong, Hong Kong, China, focusing on micro-morphology of granular materials.

Dr.-Ing. Bou-Young YOUN-ČALE

Building Materials

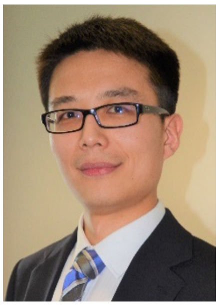
Subproject: B3

Dr. Bou-Young Youn-Čale is a senior research associate at the Chair of Building Materials at Ruhr University Bochum. Her research is focused on concrete and mortar technology in general. Her main area of research is the development of grout mixes and appropriate testing methods of annular gap grouts, particularly with regard to the correlations of the mix designs with the specific grout properties such as the dewatering behavior and, associated therewith, the strength development of the dewatered grout.

Dr. Youn-Čale obtained her diploma in civil engineering at the University of Duisburg-Essen (UDE) in 2008. Since then, she has been working at the Chair of Building Materials at Ruhr University Bochum, where she defended her doctoral thesis “Investigations on the dewatering behavior and development of shear strength of single-component grouts in mechanized tunneling” in 2016. Dr. Youn-Čale is a member of the Collaborative Research Center 837 and Research Department Subsurface Modeling and Engineering.

POST-DOCTORAL RESEARCHERS

Dr.-Ing. Chenyang ZHAO



Soil Mechanics,
Foundation Engineering
& Environmental
Geotechnics

Subproject: C2

Dr. Chenyang Zhao is a research associate at the Chair of Soil Mechanics, Foundation Engineering and Environmental Geotechnics at Ruhr University Bochum. His research interests mainly include soil-structure interaction, numerical simulation of mechanized tunnel excavation, constitutive modeling of soil behavior, computer-aided infrastructure engineering, uncertainty and reliability analyses of the engineering problems.

Dr. Zhao studied civil engineering (Bachelor) from 2006 to 2010 at Hohai University, China. He continued master study at the same university and obtained his Master degree in geotechnical engineering in 2013. After that, he joined the research group of Prof. Tom Schanz at RUB with the PhD topic "A contribution to modeling of mechanized tunnel excavation". Beginning of 2018, he went to Massachusetts Institute of Technology (MIT) as a visiting scholar. In March 2018, he obtained his PhD degree in geotechnical engineering. After that, Dr. Zhao continues working in the SFB 837 group as a postdoctoral research associate.

DOCTORAL RESEARCHERS

Thomas BARCIAGA

Subproject: A5

Constitutive modeling of structured soils with application to mechanized tunneling

Supervisor: Prof. Dr.-Ing. habil. Torsten Wichtmann (Soil Mechanics, Foundation Engineering and Environmental Geotechnics)

Hoang Giang BUI

Subproject: C1

Massive parallel computing in domain coupled problems in computational structural mechanics

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

Sahir Nawaz BUTT

Subproject: C4

Computational modeling of excavation processes in hard rock

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

Florian CHRIST

Subproject: A5

Thermo-hydro-mechanical behavior of clay

Supervisor: Prof. Dr.-Ing. habil. Torsten Wichtmann (Soil Mechanics, Foundation Engineering and Environmental Geotechnics)

DOCTORAL RESEARCHERS

Alena CONRADS

Subproject: C3

Evaluation of maintenance concepts in TBM tunneling using process simulation

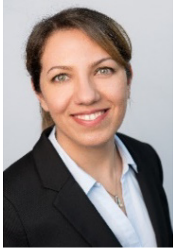
Supervisor: Prof. Dr.-Ing. Markus Thewes (Tunnelling and Construction Management)

Sascha FREIMANN

Subproject: A4

Investigation of conditioned soil under realistic conditions of EPB-tunneling

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



Golnaz HOORMAZDI

Subproject: C6

An investigation of excavation and abrasion processes via the discrete element method

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

Raoul HÖLTER

Subproject: C2

Optimal experimental design in the framework of mechanized tunneling

Supervisor: Prof. Dr.-Ing. habil. Torsten Wichtmann (Soil Mechanics, Foundation Engineering and Environmental Geotechnics)

DOCTORAL RESEARCHERS

Tagir ISKHAKOV
Subproject: B2

Model-based design of compressible cementitious materials for tunnel linings

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

Annika JODEHL
Subprojects: C3, D1

Process simulation in mechanized tunneling: From forecasting to real-time process controlling

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

Sebastian KUBE
Subproject: A6

Local transient face support within Hydro-shields

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

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

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)

Ahmed MARWAN

Subproject: C1

Computational methods for optimization in mechanized tunneling

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

Peyman MIANJI

Subproject: A6

Modelling bentonite suspension infiltration into granular soils in the context of hydroshield tunneling processes

Supervisor: Prof. Dr.-Ing. habil. Torsten Wichtmann (Soil Mechanics, Foundation Engineering and Environmental Geotechnics)

Gerrit NEU

Subproject: B2

Numerical design of fiber reinforced concrete structures

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

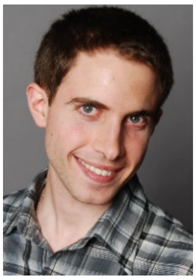
DOCTORAL RESEARCHERS

Marcel NEUHAUSEN

Subproject: D3

Detektion von Gebäudemerkmalen zur Rekonstruktion von Gebäuden

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



Diego Nicolás PETRAROIA

Subproject: B1

Optimisation based design and experimental validation of hybrid concrete segments

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)

Christopher RIEDEL

Subproject: A2

Full waveform inversion for seismic reconnaissance in mechanized tunneling - validation via experimental and field data in the frequency domain

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

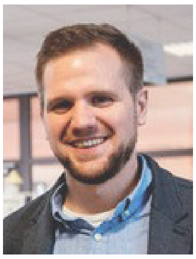
DOCTORAL RESEARCHERS

Poria SABERI

Subproject: C4

High-performance computational models for mixing and transport processes in EPB machines

Supervisor: Prof. Dr. Andreas Vogel (High Performance Computing in Engineering Sciences)



Markus SCHEFFER

Subproject: C3

Simulationsgestützte Verfügbarkeitsanalyse von Tunnelvortriebsmaschinen

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

Maximilian SCHOEN

Subproject: A5

Hydro-mechanical interactions due to mechanized tunneling in swelling clay rocks based on numerical modeling

Supervisor: Prof. Dr.-Ing. habil. Torsten Wichtmann (Soil Mechanics, Foundation Engineering and Environmental Geotechnics)

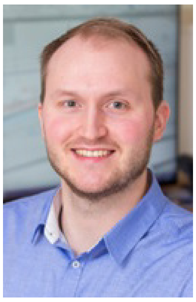
Christoph SCHULTE-SCHREPPING

Subproject: B3

Deformable annular gap grouts for squeezing rock

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

DOCTORAL RESEARCHERS

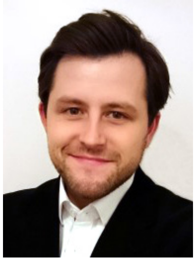


Marius SCHRÖER

Subproject: A4

Investigation of conditioned soil under realistic conditions of EPB-tunneling

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



Mario SMARSLIK

Subproject: B1

Robustness evaluation of structurally optimized concrete segments

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

Maximilian TRAPP

Subproject: A2

Tunnel reconnaissance by seismic full waveform inversion – experimental validation of developed methods

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

Andre VONTHRON

Subproject: D1

Konzepte zur interaktiven und visuellen Analyse von Interaktionsketten im maschinellen Tunnelbau

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

DOCTORAL RESEARCHERS

Rodolfo Javier WILLIAMS MOISES

Subproject: C1

Computational models for ground improvement in subsurface engineering

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

Dennis WINGENDER

Subproject: C6

Numerical simulation of wear resistant metallic materials used for mining tools

Supervisor: Prof. Dr.-Ing. habil. Daniel Balzani (Continuum Mechanics)

COMPLETED PhD THESES

2019

Markus OBEL
Ein konsekutives probabilistisches Risikobewertungskonzept setzungsinduzierter Tragwerksschädigungen

Zdeněk ŽIŽKA
Stability of a Slurry Supported Tunnel Face Considering the Transient Support Mechanism during Excavation in Non-Cohesive Soil

2018

Ba Trung CAO
Simulation and Monitoring Assisted Real-time Steering with Uncertainty in Mechanized Tunneling

Vojtěch Ernst GALL
Numerical Investigation of Hybrid Segmental Lining Response to Mechanized Tunneling Induced Loadings

Thai Son DANG
Computational Methods and Numerical Analyses of Material Transport in EPB Shield Machines

Chenyang ZHAO
A Contribution to Modeling of Mechanized Tunnel Excavation

Jakob KÜPFERLE
Skalenübergreifende materialkundliche Betrachtung des Abbauwerkzeugverschleißes für den maschinellen Tunnelvortrieb in nicht-bindigen Böden

COMPLETED PhD THESES

2017

Abdullah ALSAHLY
Advanced Computational Techniques for Mechanized Tunneling along Aarbitrary Alignments and Tunnel Face Stability Analysis

Ruben DUHME
Deterministic and Simulation Based Planning Approaches for Advance and Logistic Processes in Mechanized Tunneling

Elham MAHMOUDI
Probabilistic Analysis of a Rock Salt Cavern with Application to Energy Storage Systems

Aycan ÖZARMUT
Rheological Characterization of Particle-Foam-Mixtures

Nina Silvia MÜTHING
On the Consolidation Behaviour of Fine-Grained Soils under Cyclic Loading

Thanh Luan NGUYEN
Inference of Ground Condition in Mechanized Tunneling Via Inverse Analysis using Sequential Bayesian Filtering

Fanbing SONG
Steel Fiber Reinforced Concrete Under Concentrated Load

Tobias RAHM
Simulation-Based Quantification of Disturbances of Production and Logistic Processes in Mechanized Tunneling Operations

COMPLETED PhD THESES

2016

Yijian ZHAN
Multilevel Modeling of Fiber-Reinforced Concrete and Application to Numerical Simulations of Tunnel Lining Segments

Nicola WESSELS
Simulation von Abbau- und Verschleißvorgängen mit der Methode der diskreten Elemente

Khayal MUSAYEV
Seismic Reconnaissance in a Tunnel Environment using Full Waveform Inversion

Mario GALLI
Rheological Characterisation of Earth-Pressure-Balance (EPB) Support Medium Composed of Non-Cohesive Soils and Foam

Thomas PUTKE
Optimierungsgestützter Entwurf von Stahlbetonbauteilen am Beispiel von Tunnelschalen

Bou-Young YOUN
Untersuchungen zum Entwässerungsverhalten und zur Scherfestigkeitsentwicklung von einkomponentigen Ringspaltmörteln im Tunnelbau

2015

Shorash MIRO
Calibration of Numerical Models Considering Uncertainties – Application to Mechanized Tunnel Simulations

Alexander SCHAUFLER
Multi-Physical Simulations: Transport and Infiltration of Suspension in Granular Porous Media

Veselin ZAREV
Model Identification for the Adaption of Numerical Simulation Models – Application to Mechanized Shield Tunneling

COMPLETED PhD THESES

Felix HEGEMANN
A Hybrid Ground Data Management Concept for Tunneling Projects

Lasse LAMBRECHT
Forward and Inverse Modeling of Seismic Waves for Reconnaissance in Mechanized Tunneling

Jelena NINIĆ
Computational Strategies for Predictions of the Soil-Structure Interaction During Mechanized Tunneling

2014

Jan DÜLLMANN
Ingenieurgeologische Untersuchungen zur Optimierung von Leistungs- und Verschleißprognosen bei Hydroschildvortrieben im Lockergestein

Steffen SCHINDLER
Monitoringbasierte strukturmechanische Schadensanalyse von Bauwerken beim Tunnelbau

Trung Thanh DANG
Analysis of Microtunnelling Construction Operations using Process Simulation

2012

Christoph BUDACH
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, M. Trapp, C. Riedel, W. Friederich, T. Nestorović, K. Hackl

OUTLINE OF SUBPROJECT

The aim of this project is to develop new effective concepts for reconnaissance in mechanized tunneling using seismic 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 impact on tunnel excavation such as cavities, faults, erratic boulders or cut-off walls should be predictable from the results.

Applied inversion methods make use of the concept of full waveform inversion (FWI) to infer the spatial distribution of elastic material properties based on reflected or refracted waves. FWI is based on the comparison of measured seismic data and synthetic results obtained from forward simulations. 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 FWI methods use gradient-based adjoint approaches and non-deterministic approaches as the unscented hybrid simulated annealing.

For validation of the methods, a laboratory experiment is assembled where a downscaled specimen containing anomalous structures is equipped with emitters and a laser-vibrometer. Scaling in comparison to tunnel environments is in the order of 1:100 to 1:500. Furthermore, in-situ data from tunnel boring projects have been provided to test the developed inversion procedures on real tunnel data, which is the final goal of this subproject.

FORWARD PROBLEM

Wave propagation for the applied non-deterministic approaches is modeled by using the Spectral-Finite-Element-Method (SpecFEM). On the other hand, a nodal discontinuous Galerkin (NDG) approach is applied for the inversion with the adjoint gradient method in the time domain whereas a higher-order finite element method with hierarchical shape functions is used for the adjoint gradient method in the frequency domain.

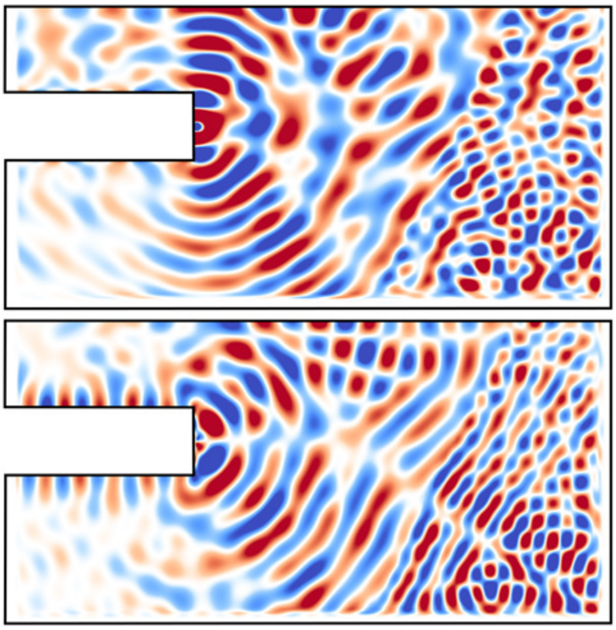


Fig. 1: Wave field in the frequency domain of a 2D elastic tunnel environment with an inclining fault in front of the tunnel for a single frequency (above: horizontal displacements; below: vertical displacements)

INVERSE PROBLEM

A prediction of the elastic material properties in front of the tunnel face should be achieved using the concept of FWI, which directly depends on the employed source and receiver configuration. The inversion in the time domain is more intuitive whereas performing the inversion successively for single frequencies in the frequency domain decreases the nonlinearity of the inverse problem.

Inversions using the 2D and 3D acoustic as well as elastic wave equation were carried out successfully for seismic data, which have been produced by different numerical tools. To imitate more realistic scenarios, several blind tests have successfully been performed.

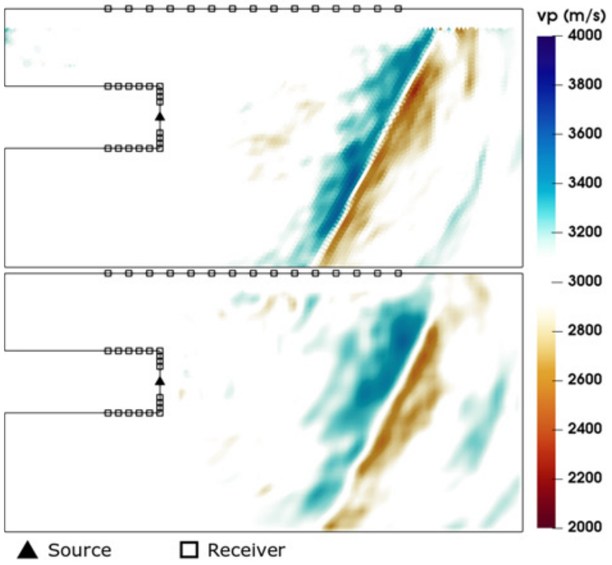


Fig. 2: Reconstructed p-wave velocity field for the inversion of an inclining fault based on the 2D elastic wave equation using the time domain (above) and the frequency domain (below) approach

EXPERIMENTAL VALIDATION

For validating the FWI methods, a small-scale experimental setup (Figure 3) has been constructed. Individual and well-matching components were selected to assure an optimal measurement process fitting the requirements of the project. Piezoelectric transducers trigger ultrasonic waves in a frequency range between 50 kHz and 2 MHz. Waveforms are acquired with a laser interferometer. Laser navigation is performed by a positioning system controlled by a self-programmed software. An optical table reduces noise and uncertainties due to influences from environment.

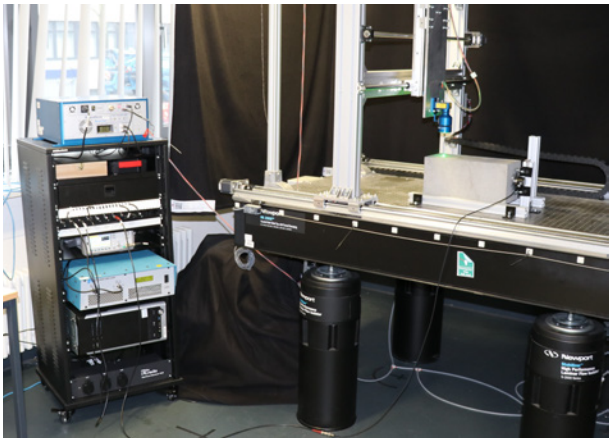


Fig. 3: Picture of the small-scale experiment

Successful inversions have been achieved in localization scenarios of hole coordinates in aluminum and concrete specimen with unscented hybrid simulated annealing. Figure 4 illustrates the inversion scenario on a concrete plate. Ultrasonic measurements are acquired and used for the inversion. The right side of the figure shows the course of the algorithm on the misfit landscape, which is determined beforehand by gridded simulations. The algorithm is able to find the global misfit minimum with a high precision, which is illustrated by the red arrow. Specimen with material inclusions have been recently prepared for investigations.

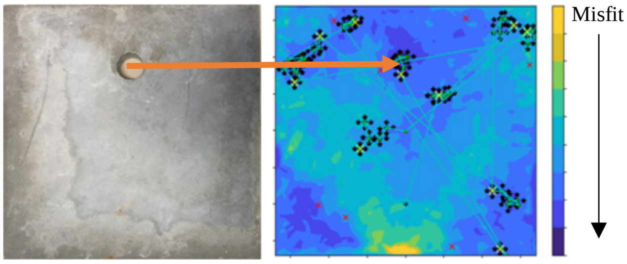


Fig. 4: Unscented hybrid simulated annealing algorithm finding the hole coordinates of the concrete specimen

PUBLICATIONS

1. LAMBRECHT, L.; LAMERT, A.; FRIEDERICH, W.; MÖLLER, T.; BOXBERG, M.S.: A nodal discontinuous Galerkin approach to 3D viscoelastic wave propagation in complex geological media. Geophysical Journal International, Volume: 212(3), pp. 1570 - 1587, 2018
2. LAMERT, A.; FRIEDERICH, W.: Full waveform inversion for advance exploration of ground properties in mechanized tunneling. International Journal of Civil Engineering, Volume: 17(1), pp. 19 - 32, 2019
3. LAMERT, A.; NGUYEN, L.T.; FRIEDERICH, W.; NESTOROVIC, T.: Imaging disturbance zones ahead of a tunnel by elastic full waveform inversion: adjoint gradient based inversion vs. parameter space reduction using a level-set method. Underground Space, Volume: 3(1), pp. 21 - 33, 2018
4. MUSAYEV, K.; LAMERT, A.; HACKL, K.; FRIEDERICH, W.; BAITSCH, M.: Predicting the Geological Structure Ahead of a Tunnel Using Full Waveform Inversion - A Blind Test. 78th EAGE Conference and Exhibition 2016, 2016
5. NGUYEN, L. T.; NESTOROVIC, T.: Unscented hybrid simulated annealing for fast inversion of tunnel seismic waves. Computer Methods in Applied Mechanics and Engineering, Volume: 301, pp. 281 - 299, 2016

CONDITIONING OF THE SUPPORT MEDIUM AND FACE SUPPORT IN TUNNELING WITH EARTH-PRESSURE-BALANCE-SHIELDS

S. Freimann, M. Schröer, M. Thewes

INTRODUCTION OF THE SUBPROJECT

The construction of tunnels in loose rock often requires the use of shield machines. The earth pressure balance shield (EPB shield) is the machine type predominantly applied worldwide for tunnel driving in soft ground. The excavated soil is used to support the tunnel face. This reduces or prevents subsidence on the surface. Fluctuations of the support pressure during driving demonstrate the influence of the rheological properties of the mostly heterogeneous support medium in the excavation chamber. While clayey and silty soils with a corresponding consistency have sufficient properties as tunnel face support medium, non-cohesive, coarse-grained or very permeable soils cannot be uitilised as support medium without conditioning. If the subsoil does not provide the appropriate properties for optimum support pressure transmission, these properties can be temporarily induced by the use of conditioning agents (e.g. surfactant foams). This process is called soil conditioning.

EXPERIMENTAL RESULTS OF SECOND PHASE

The focus of the work of subproject A4 during the second phase was experimental rheological and hydro-mechanical characterization of surfactant foams. The scientific aim of the investigations was to understand the effective rheological properties of complex particle/soil-foam mixtures and to develop rheological and continuum-based models developed on the experimental knowledge as a function of the composition of the fluid mixture.

A partial aspect of the investigations was the identification of the inherent material parameters of regularized yield stress models proposed for foam-particle mixtures or soil-foam mixtures. Furthermore, numerical results (SPH - Smoothed Particle Hydrodynamics) show a good agreement with the experiments and the analytical solutions.

On the basis of homogeneous rheological experiments, the material parameter regularized Herschel-Bulkley and Bingham fluids were identified in the shear rheometer (Anton Paar, MCR 301).

By means of rheological experiments with the spherical rheometer, the shear stresses of the various soil-foam-mixtures are determined by defining the shear rate. The results show that the soil-foam mixtures investigated exhibit behaviour within a certain range that is almost independent of shear rates. The influence of the amount of foam added or the Foam Injection Ratio (FIR) as well as the water content is clearly visible. In addition to the water content and the FIR, the soil also has an influence on the rheology. The results of the yield point determination show that the yield point decreases with increasing foam injection rate, confirming the results of the slump test.

AIM OF THE THIRD PHASE & STATUS QUO

For the third phase, the subproject was divided into four Work Packages (WP). WP1 intend the complete upscaling of the rheometric experiments and the development of rheological material parameters for different soil types and conditioning agents. In the previous two project phases, the methods of rheometry were implemented on the micro and macro scales. In the third phase it is planned to transfer the rheometric investigations to the real scale with the support of the existing large-scale test device COSMA (Fig. 1).

Fig. 1: Large scale test COSMA

In addition, qualitative and quantitative tests are planned with regard to the wear effect of conditioned loose rocks on the mining tools.

In WP2, a new conditioning agent will be developed to extend the application range for EPB shields. The conditioning agent is based on a two-component, suspension-based and polymer-bound conditioning agent and is to be used as an application for missing fine grain in very coarse soils and rock. The first component can be prepared and mixed with a bentonite suspension. The second component must be fed through a separate feed line into the excavation chamber and reacts there within seconds with the first component to an artificial soil (Fig. 2).

In WP3 the development of a new penetration test is planned to determine the workability of conditioned soils. The workability or flow behaviour of the conditioned soil has an impact on the material flow in the excavation chamber. In the laboratory as well as on the construction site, the Slump Test is an adequate test to investigate the workability of soil-foam mixtures. Since the Slump Test is not suitable for examining coarse-grained gravelly soils or purely cohesive soils, a new penetration test was developed to examine the workability of all kind of soil mixtures and conditioning agents (Fig. 3). With this test device the force-path relationship can be measured force-controlled and path-regulated when the penetration body penetrates the conditioned soil mixture.

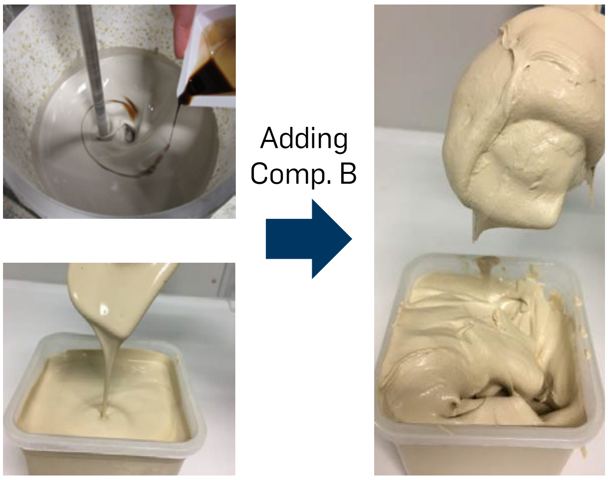


Fig. 2: Two-component conditioning agent (artificial soil)

Fig. 3: New developed Penetration Test

In WP4, experimental tests are planned for realistic simulation of inflows, mixing and flow behavior of the support medium in the excavation chamber. The results will be used for the numerical model, which was developed in the second funding period, for material transport in the excavation chamber of an EPB shield in project C4. The model also includes simplified actual geometries as well as various moving parts.

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HYDRO-MECHANICAL PROCESSES DUE TO MECHANIZED TUNNELING IN SOFT CLAY ROCK

F. Christ, M. Schoen, T. Barciaga, A. A. Lavasan

INTRODUCTION

Reliable prediction of tunneling induced ground movement and structural forces in the tunnel support system requires complex numerical interaction models that can capture the physical aspects which occur in real tunneling (e.g. sequential excavation, face support, grouting of the annular gap, lining installation) and the time dependent coupled hydro-mechanical interactions.

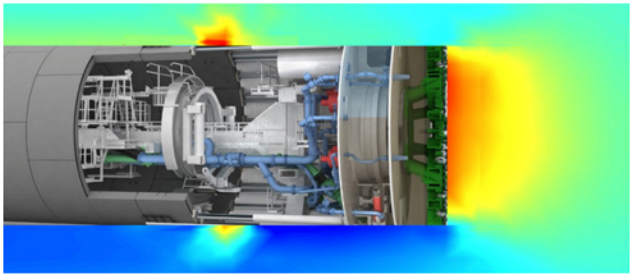

Fig. 1: Pore pressure field around the TBM

In the first and second phases of SFB 837, subproject A5 studied the hydro-mechanical interactions in the vicinity of the TBM in sands and normally consolidated structured clays. In this frame, an advanced bounding surface plasticity constitutive model was developed to address the anisotropy, destructuration and degradation of the stiffness and strength due to tunneling induced cyclic loading in clays. Moreover, the innovative concept of submodelling along with adaptive constitutive modeling was proposed to conduct sophisticated simulations in the near-field of the TBM without increasing numerical complexities. Furthermore, the influence of time-dependent evolution of the properties of soil as well as grout (e.g. hardening and infiltration of its fine particles to the soil) on the surface settlement and structural forces were studied. In the third phase of the SFB 837, subproject A5 mainly focuses on the mechanized tunneling in the soft clay rocks with the potential of swelling.

HYDRO-MECHANICAL BEHAVIOUR OF SWELLING CLAY ROCKS NEAR THE TBM

Tunnel excavation process and its corresponding deformations result in stress redistribution in the underground. Such a stress redistribution can induce an excavation damaged zone (EDZ) in the near-field of tunnel. Within EDZ, the evolution of the shear strain leads to a significant increase in the hydraulic conductivity of the clay rock while it also reduces the shear strength of clay rock due to dilation of the inherent fractures and bedding planes. Therefore, it is essential to examine how the preferential flow path due to higher hydraulic conductivity affects the time dependent flux of moisture towards soft rock that leads to swelling. Furthermore, the influence of the time-dependent swelling on the permeability (self-sealing) will be studied using a double-porosity model.

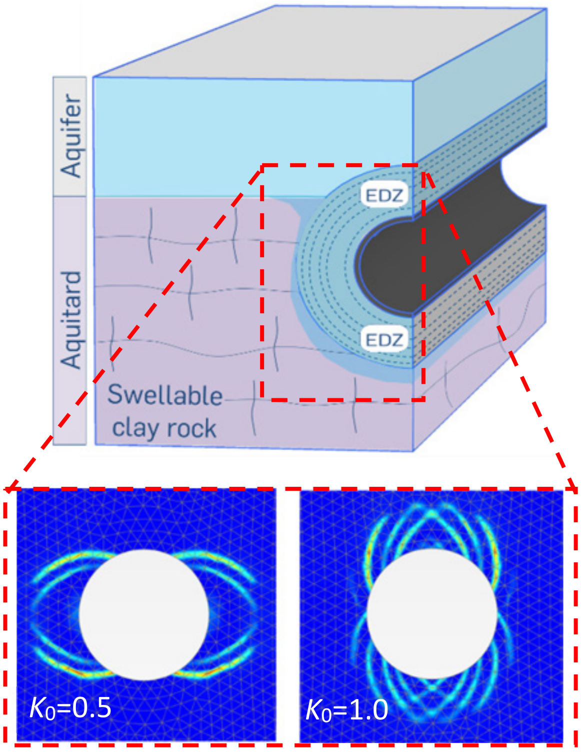

Fig. 2: Excavation damage zone (EDZ) in clay rock

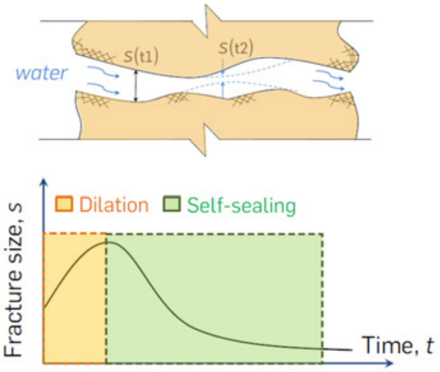

Fig. 3: Viscous deformation in fractures

ANISOTROPIC SWELLING LAW BASED ON SUCTION AND SATURATION DEGREE

Due to the low permeability of clay rocks, they are often initially in an unsaturated condition. Therefore, the water transport is preliminary taken place in an unsaturated clay rock until it becomes saturated. However, the unsaturated flow can take place in a short or long terms depending on the size of EDZ. Therefore, according to the soil water characteristic behavior of clay rocks, the swelling process starts at non-zero suction while the saturation degree is less than 1. Thus, to address the swelling due to unsaturated flow, saturation degree and suction should be considered as state variables. Additionally, position and orientation of bedding planes induces anisotropy in swelling pressure. Furthermore, the interactions between tunnel support (e.g. grout and lining) and clay rocks with the potential of swelling lead to different deformation boundary conditions (e.g. free swelling, volume-constant swelling, and controlled-volume swelling). For such a swelling law, a series of swelling tests under various boundary conditions will be carried out in an innovative swelling cell with adaptive boundary condition.

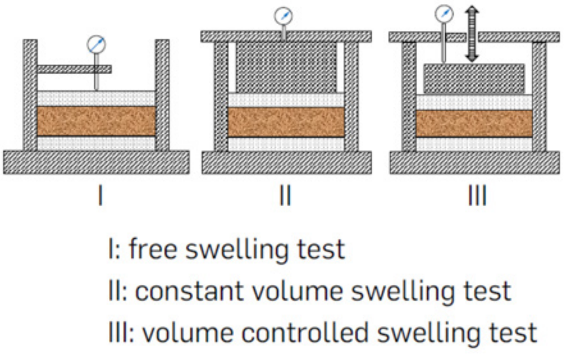

Fig. 4: Swelling tests under various boundary conditions

MODEL ADAPTION IN THE NEARFIELD OF SWELLING PROCESSES

In order to describe the coupled hydro-mechanical processes due to tunneling in clay rocks with the potential of swelling and to address the evolution of permeability and swelling processes, a detailed near-field simulation is required. Accordingly, the lessons learnt within the last phases of the subproject A5 in terms of submodeling will be applied to conduct spatial model adaptation in the near-field. In the model adaption zone (i.e. near-field), development of the swelling pressure is described by the new swelling law for tunneling relevant boundary conditions (e.g. flexible and rigid tunnel support), including the time-dependent state variables. By means of sensitivity analysis, the process of parameter calibration will be simplified by focusing on the constitutive parameters which have dominant influence on the model responses.

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LOCAL TRANSIENT FACE SUPPORT WITHIN HYDRO-SHIELDS

S. Kube, P. Mianji, B. Schößer, W. Baille

FOCUS

The project aims to describe the time-dependent processes at the fluid supported tunnel face during the assembly of the support pressure transfer under simultaneous soil excavation. For this purpose, the soil mechanical, hydro mechanical and rheological transitions of the soil and the support medium during the penetration process need to be explained. The development of suitable theoretical and numerical models deliver the fundamentals for enhanced simulations, which offer the possibility to evaluate the local and global face stability at any point of the excavation process.

In hydro shield tunneling, the slurry penetration and soil excavation act in the same direction (Fig. 1). Cutting tools installed on the rotating cutter head of the shield machine carry out the soil excavation. At the same time, the tunnel face is stabilized by a pressurized bentonite suspension counterbalancing the earth pressure and ground water pressure. During excavation, the zone of the support pressure transfer is periodically damaged and removed by the cutting tools.

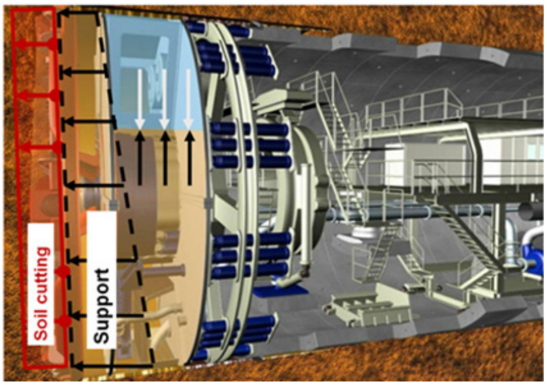

Fig. 1: Hydro shield tunneling (Source: Herrenknecht AG)

Superposition of different time scales of the suspension penetration process and of the soil excavation cycle results in a time-variable support pressure transferred at a local point on the tunnel face with impact on the global face stability (Fig. 2). These repetitive processes of suspension penetration and soil removal are affected by fundamental boundary conditions, e.g. suspension rheology, permeability of the non-cohesive soil, support pressure in the excavation chamber, rotation speed of the cutter head, configuration of the cutting tools and penetration rate of the shield machine.

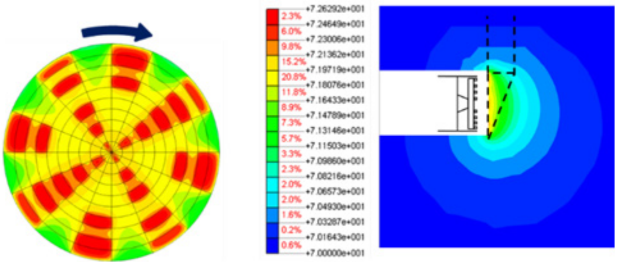

Fig. 2: Rotation of cutting tools on the cutter head during excavation process (left), impacts on the global support pressure transfer at the tunnel face (right) (Zizka, 2019)

In extended experimental studies, the boundary conditions are varied and the specific results are transferred into constitutive approaches for the time-dependent description of soil mechanical, hydro mechanical and rheological impacts.

LATEST RESULTS

Within the last project phase, the effects of the penetration of bentonite suspension into the soil skeleton were in the focus of advanced column tests. Here, the variations of total stress and pore water pressure were measured over time within the penetrated zone. Analysis of the experimental data provided detailed information about the effective stress at a local point within the column, the local flow velocity of the suspension, the in-situ penetration depth within the soil, the pressure gradient of the pore water pressure within the penetrated zone and the transient permeability coefficient of the soil over time. Based on the ratio of cutting depth of the cutting tools at the tunnel face to the penetration depth of the suspension in the soil, two cases were identified. *Case A* describes the complete excavation of the penetrated zone at the tunnel face, where the bentonite suspension penetrates into untreated soil (Fig. 3, left).

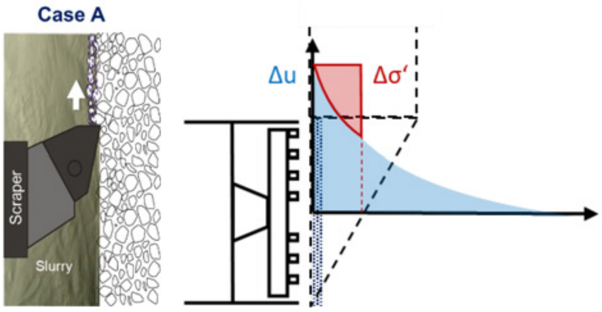

Fig. 3: Case A: local distribution of effective stress $\Delta\sigma'$ and pore water pressure Δu at tunnel axis (Zizka, 2019)

In this case, the pore water pressure Δu in front of the tunnel face is influenced over a spatial area beyond the theoretical sliding wedge, where the acting earth pressure and ground water pressure need to be counterbalanced (Fig. 3, right). In terms of face stability, this case turns out to be more on the "unsafe side". The limited amount of transferred effective stress $\Delta\sigma'$ within the theoretical sliding wedge in front of the tunnel leads to a reduced safety factor for the face stability.

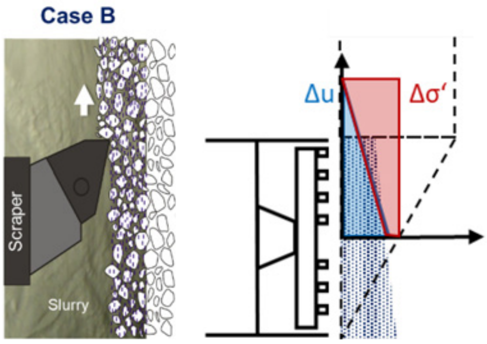

Fig. 4: Case B: local distribution of effective stress $\Delta\sigma'$ and pore water pressure Δu at tunnel axis (Zizka, 2019)

Case B describes the partial excavation of the penetrated zone at the tunnel face. Here, the bentonite suspension re-penetrates in an already penetrated soil (Fig. 4, left). In this case, the amount of the transferred effective stress $\Delta\sigma'$ is larger and restricted to the area within the theoretical sliding edge. This situation leads to a convenient safety factor for the face stability (Fig. 4, right).

GOAL

The transitions of the soil mechanical and hydro mechanical conditions at the tunnel face are established by individual deposition of the bentonite particles within the pore structure of the soil (Fig. 5, left). The structural analysis of the phase composition within a certain penetration depth provides the basic information for the formulation of the multi-phase models (Fig. 5, right). Numerical simulations shall enable the description of the local transient processes during the slurry penetration and an assessment of their influence on the global stability of the tunnel face.

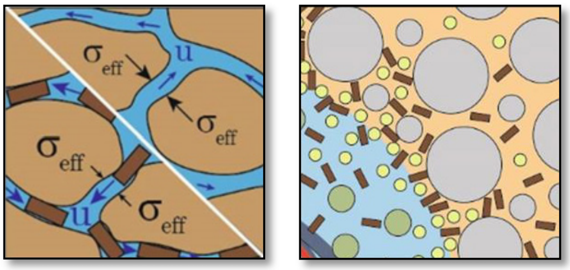

Fig. 5: Constitutive model of phase composition in the slurry penetrated soil (left), transfer into multi-phase model for numerical simulation (right)

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MULTI-MATERIAL MODULAR LINING SEGMENTS FOR ADAPTIVE AND ROBUST TUNNEL LINING SYSTEMS

S. Plückelmann, D. N. Petraroia, R. Breitenbücher, P. Mark

INTRODUCTION

Following two complementary approaches, the subproject members intend to develop multi-material concrete lining segments regarding aspects of safety, durability and robustness. 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.

COMPONENT AND BUILDING LEVEL

Based upon parameterized, numerical 3D models design guiding calculation parameters were identified employing sensitivity analysis methods. Hereby, damage inducing kinematics for typical loading scenarios representing the final state as well as various construction stages were evaluated. As expected, load application as well as load transfer points located in circumferential and longitudinal joints proved to be most critical which was also confirmed by other models employed in cooperation with subprojects A5, B2 and C1.

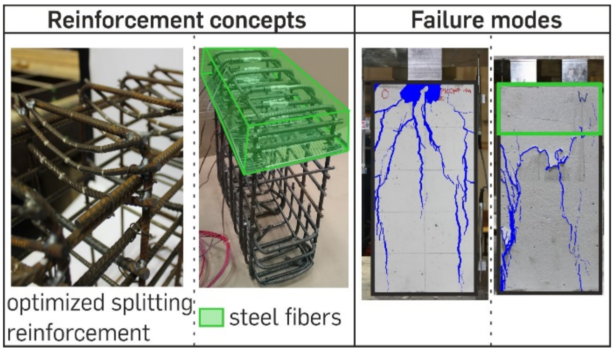

Fig. 1: Optimized reinforcement design (left) and cracking pattern for specimen with conventional and hybrid reinforcement concepts (right)

Using a hybrid topology optimization approach combining truss and continuum elements as an idealization for reinforced concrete within the optimization procedure the material specific characteristics of concrete (compression) and rebar (tension) were incorporated to identify optimal reinforcement layouts. The optimization results were subsequently transferred into actual designs and various specimen were tested experimentally (Fig. 1).

It was found that hybrid elements, combining rebar in bended shapes with SFRC at critical locations, exhibited an improved performance regarding robustness against unintended load eccentricities and loads applied close to the edges. The use of high-performance materials and the adjustment of constructive criteria, as placing the water insulation at the middle of the segment thickness, showed a strength increment of up to 80% (Fig. 2). Cracking patterns showed a relocation of the weak points outside the area of load application and hence confirmed the use of optimization methods in concrete design.

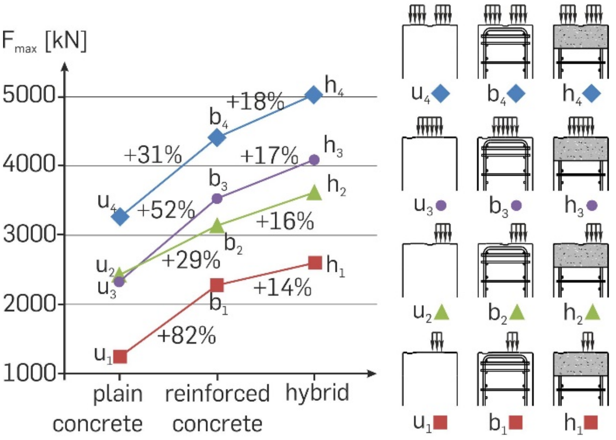

Fig. 2: Optimized hybrid reinforcements (right) and strength comparison (left)

MATERIAL LEVEL

On the material-level two production techniques ("wet on solid" / "wet on wet"") for hybrid lining segments were developed and investigated under the aspects of bonding behavior, bearing capacities and fracture mechanics. The "wet on solid" approach is characterized by the prefabrication of small-sized, tailor-cut components of high performance materials for areas of high utilization integrated in the segmental formwork before casting of a typical lining concrete. To this end, high performance concrete mixtures in combination with different types of fiber reinforcement were developed, tested and the results integrated in numerical analyses performed e.g. in subproject B2. The investigation of the bonding behavior between precast components and the lining concrete under shear load showed load bearing increases of 40-50 % in comparison to plane bonding zones (Fig. 3) depending on geometrical configurations, surface roughening and preloading conditions.

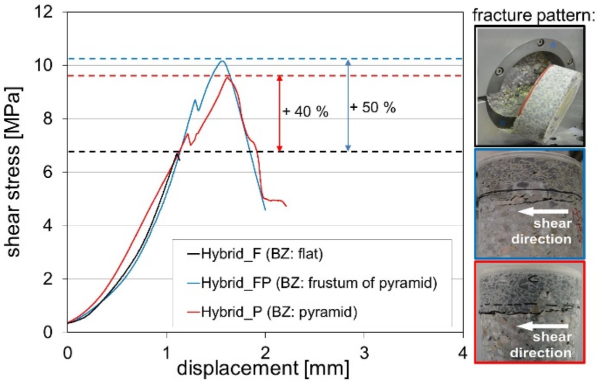

Fig. 3: Shear load – displacement response of hybrid samples and corresponding fracture patterns

For the "wet on wet" approach two different types of concrete are casted simultaneously, initially separated by an additional moveable formwork. During the compacting of the concretes this additional formwork is removed to facilitate interfacial bonding of the two materials. The combination of high performance steel fiber reinforced layers in zones of load application and plain concrete exhibited a continuous monolithic bonding, where an increase of the reinforcement layer thickness led to noticeable load increases in terms of bearable concentrated loads (Fig. 4). However, compared to fully reinforced specimens, hybrid specimens with a reinforcement thickness equal to the load disturbance zone exhibited an almost identical bearing capacity, thus a full range reinforcement is not necessary. Further improvements could be achieved by changing the casting direction in relation to the applied load due to a more favorable orientation of steel fibers.

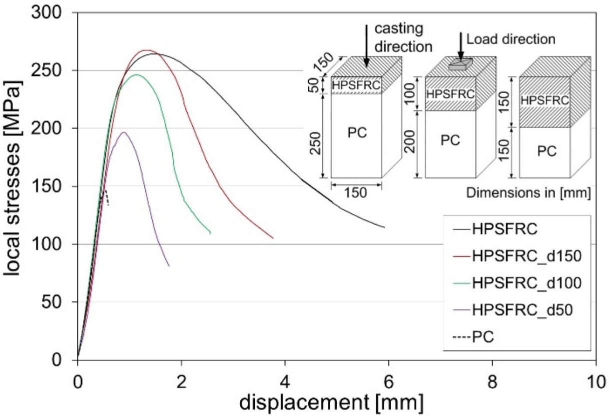

Fig. 4: Stress-displacement curves for hybrid specimens with variable thickness of HPSFRC layer under point loading

Current and future research is focusing on transferring the above-mentioned methods, procedures and results to full size lining segments, reducing the cross-section dimensions to a minimum and at the same time providing resistance to local compressive effects provoked by the surrounding ground. To this end, a layer of soft material consisting of porous concrete is to be added in order to allow ring deformations in a plastic regime.

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DAMAGE ANALYSES AND CONCEPTS FOR DAMAGE-TOLERANT TUNNEL LININGS

G. Neu, T. Iskhakov, M. Hofmann, J. J. Timothy, G. Meschke

GOAL STATEMENT

The goal of subproject B2 is the generation of new design concepts for tunnel lining segments in order to a) enhance segment robustness with respect to construction induced loading conditions (Fig. 1) and b) for use in difficult geological conditions, characterized by large deformations. Enhanced robustness is achieved through optimization of the placement and the model-based design of high performance components (concrete design, fiber reinforcement, hybrid designs) in lining segments using novel numerical simulation techniques.

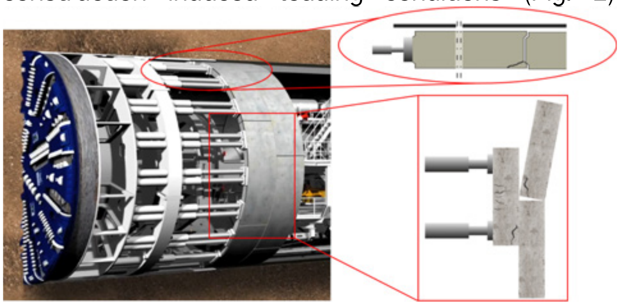

Fig. 1: Possible damage patterns in tunnel lining segments during the excavation process

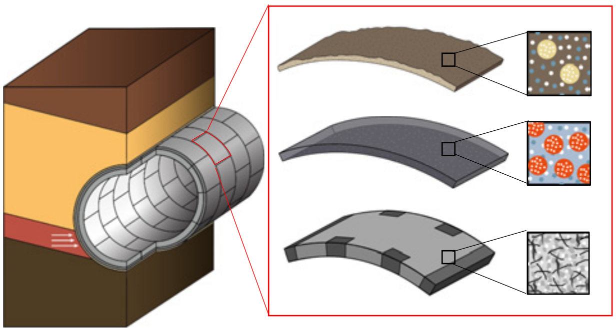

Fig. 2: A multi-layer lining segment (high-performance concrete lining, compressible cementitious outer lining and compressible grout) for tunneling in difficult geological conditions. Multiscale modeling approach: System scale (left), structural scale (center) and material scale (right)

Segmented lining elements with integrated layers of compressible materials in combination with a layer of compressible gap grout enable to accommodate the expected large deformations in a controlled manner without any structural damage. For this purpose, multi-scale models developed in cooperation with the experimental subprojects B1 and B3 are used to generate suitable material and structural designs.

ROBUST DESIGN OF HYBRID STEEL FIBER REINFORCED CONCRETE (SFRC) LINING SEGMENTS

Research in the first two phases of the subproject B2 has been oriented towards the development of a multi-level modeling framework, in which the behavior of FRC segments can be predicted based on the individual components (concrete, fiber, rebar) and their mutual interactions at different length scales.

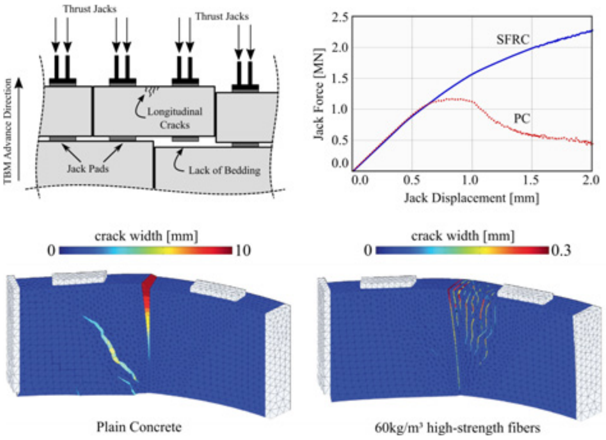

Fig. 3: Structural response of improperly bedded segments subjected to TBM thrust forces

Based on this multilevel scheme, the influence of individual fiber parameters (content, orientation, properties) on the structural response can be assessed and therefore can be directly used for generating optimized FRC and hybrid conventional reinforcement (RC)-FRC designs. To this end, a robust optimization methodology is applied to increase the serviceability performance in terms of crack width under dispersive conditions (construction tolerances, fiber orientation etc.) (see Fig. 3). Multiple segment designs subjected to earth-pressure and thrust jack loadings are analyzed and evaluated in terms of imperfection sensitivity of construction induced loadings.

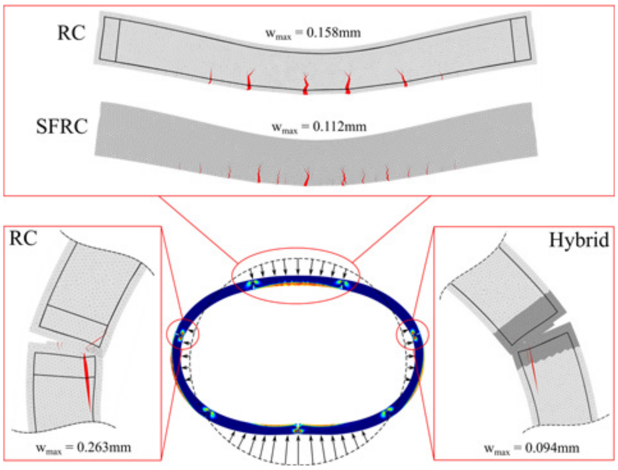

Fig. 4: Evaluation of conventionally reinforced (RC), Fiber reinforced (SFRC) and hybrid segment designs at the structural ring scale

MODEL-BASED DESIGN OF A COMPRESSIBLE TUNNEL LINING COMPOSITE MATERIAL

Cementitious composites with weak inclusions (e.g. EPS) offer considerable deformation capacity. They can be used as a deformable gap grout in the design of a damage tolerant tunnel lining which accommodates large deformations.

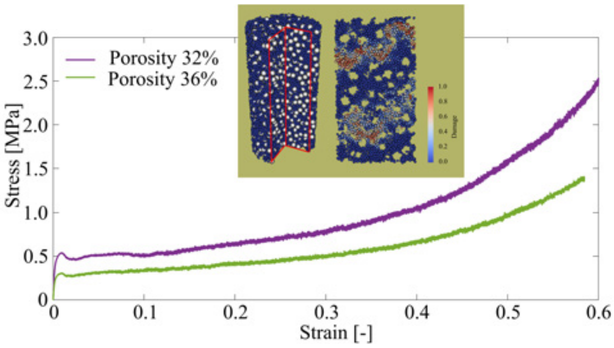

Fig. 5: DEM simulation of the behavior of a compressible cementitious specimen with varying porosity. Inset: Left: Cylindrical specimen with spherical pores (white) color and Right: Pore collapse and damage propagation under confined compression

To this end, the change of the microstructure of a highly-compressible cementitious material in a confined compression test and the corresponding macroscopic response (see Fig.5) has been investigated using the Discrete Element Method (DEM). Fig. 5 shows the influence of the macro porosity on the overall behavior of the composite. The increase in porosity decreases the strength of the composite but allows for further deformation under the same stress. Insight into the physical mechanisms governing such processes and the influence of the microstructure (porosity, inclusions, topology) on the macroscopic behavior allows for the selective design of optimized materials for deformation tolerant tunnel linings deployed in difficult geological conditions.

SUMMARY AND OUTLOOK

In subproject B2, a multiscale modeling framework for the numerical analyses of tunnel lining systems is proposed. This framework allows for the development of novel, hybrid design concepts for tunnel linings under a wide range of service conditions. The main features of the proposed framework is the characterization of the tunnel lining and its behavior across multiple scales. This allows for the direct tracking of the influence of design parameters from microscale (fibers, inclusions, topology) up to the structural scale of the lining. In the third project phase, the focus lies on the development of a virtual laboratory for the design of material and tunnel lining segments tailored to specific geological conditions.

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COMPRESSIBLE ANNULAR GAP GROUTS FOR SQUEEZING ROCK

C. Schulte-Schrepping, R. Breitenbücher

STATE OF KNOWLEDGE AND OBJECTIVE OF SUBPROJECT B3

In mechanized tunneling, a gap of approx. 10 to 20 cm remains between the tunnel lining and the surrounding soil. Immediately after mounting of the segment rings, this annular gap must be filled with an adequate grouting mortar to stabilize the tunnel lining and to minimize surface settlements. Therefore, for soils with low permeability and water-bearing building grounds, two-component-grouts (TCG) are used. Different from one-component grouts, the strength development is based on the reaction between the activator and binder. A grout-soil-interaction does not take place.

The component A of a TCG has to be workable for 72 hours after production, sedimentation-stable and suitable for pumping over long distances. As component B or activator, usually a water glass is used. In the annular gap, the activated grout needs to gel directly in order to ensure an immediate bedding of the tunnel lining and to resist erosion caused by flowing water. The subsequent strength development must be very rapid in order to prevent the tunnel lining from floating and to withstand loads from the construction process. In conclusion, antagonistic requirements are set for annular gap grouts.

The focus of subproject B3 is to develop innovative "more"-component-grouts for different geological boundary conditions. In phase II, the area of application was in less-permeable and water-bearing soils. Therefore, the alkaline activation of suitable substituents for the cement like blast furnace slag, fly ash, etc. was investigated systematically. Next to this, a physical activation with superabsorbent polymers (SAP) was tested. Those SAP have an enormous water absorption potential and therefore cause an internal dewatering and stiffening of the grout. The solidification of the grouts of both approaches takes place inherently in the system without interactions to the surrounding soil.

In phase III, compressible grouts are developed for squeezing rock. Herein, different types of deformable additives and different binder-activator compositions are tested in order to adapt the grout to the process engineering and geological parameters. Next to this, special test setups, like a compression test with lateral expansion obstruction are developed.

METHODOLOGY AND EXPERIMENTAL INVESTIGATIONS

As reference level for the investigations within the approaches, the performance of a typical TCG was evaluated. Herein, the essential material parameters, synchronised to the construction sequence were determined. On this basis and with the proven test setups, the usability of different source materials as substituents for the cement in combination with different activator types was tested. For the physical activation, in a first step, the key properties of the used SAP were determined and the stiffening caused by the injection of the SAP into slightly modified grouts was tested. In phase III, using the gained experience from phase II regarding the adjustment of the binder and activator, compressible annular gap grouts are developed and tested.

GAIN OF SCIENTIFIC KNOWLEDGE

TCG and the primarily used source materials offer a large potential for material optimizations and new approaches. The concept of the alkaline activation shows, that the partial substitution of the cement by blast furnace slag can lead to favourable material properties, especially with regard to the strength development. In addition, as a main part of the investigations, correlations between the properties of the activator (Molar Ratio "MR") and the binder composition (cement/slag-ratio) and its influence on the strength could be found (Fig. 1).

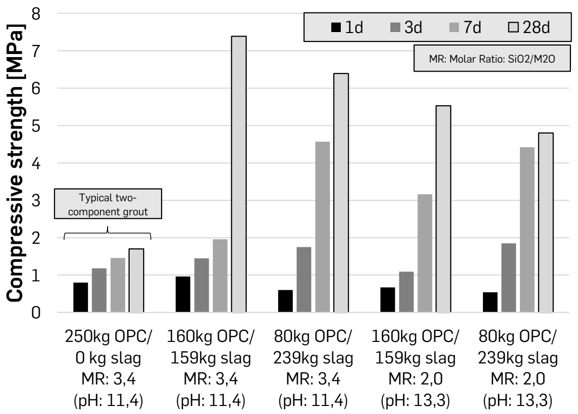

Fig. 1: Influence of the binder- and activator-composition on the compressive strength development

Within the physical activation with SAP, it was possible to achieve a sufficient solidification and shear strength of different grouts with various mix designs and cement contents (Fig. 2).

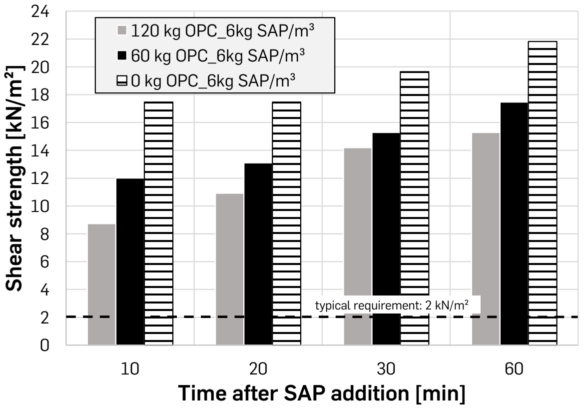

Fig. 2: Influence of the cement content on the shear strength development up to 60 minutes after addition

This concept proves to be controllable with regard to the strength development, but a strict adjustment of the SAP content and the water must be carried out. In addition, the chemistry of the grout is of essential importance for a rapid solidification.

Within the investigations of the compressible grouts as focus of phase III, in a first step a suitable basis mix design was developed. As compressible additives, polystyrene balls and a foaming agent were used. Based on the experiences in phase II, a water glass as activator was chosen. The desired behaviour, a nearly ideal-plastic deformation up to a compression of more than 50% after exceeding the fracture load could be achieved (Fig. 3).

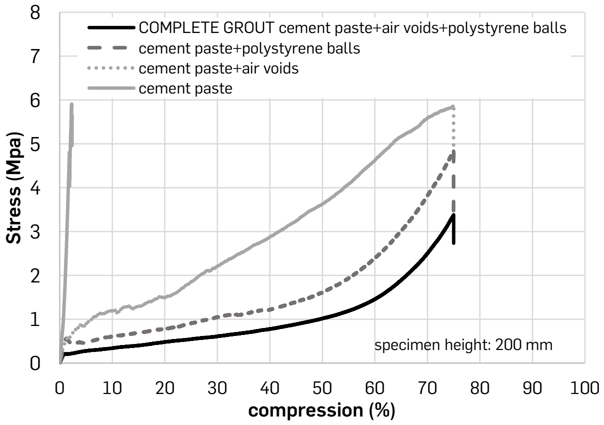

Fig. 3: Stress-deformation-behaviour of a compressible annular gap grout (Divided into the main components)

The fracture load itself can be controlled by the binder composition and the gelation and solidification by the type and amount of the activator.

FURTHER INVESTIGATIONS

In further tests, the solidification process and the strength development of compressible annular gap grouts with different binders and deformable additives will be examined. Therefore, for example the structural behaviour during compression will be tested using ultrasonic measurements. Next to this, the procedural suitability of compressible grouts will be tested with the annular gap grouting device from phase II.

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PROCESS-ORIENTED SIMULATION MODELS FOR MECHANIZED TUNNELING

A. Alsahly, H. G. Bui, B. T. Cao, A. Marwan, R. J. Williams Moises, 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 assistance system for mechanized tunnel construction 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 model accounts for 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. Advanced features considering ground improvement such soil freezing are currently incorporated. For the automation of the model generation, a new BIM-based approach is developed, in which 3D Finite Element Method (FEM) and Finite Cell Method (FCM) are combined (Fig. 2). The BIM model also includes all relevant model parameters (geology, alignment, lining, TBM, buildings) of the tunneling project, which are then incorporated into subsequent FE analysis to assess the safety of the tunneling process, the ground settlements and the damage risk of lining and buildings. It is also planned to utilize the FCM for an interactive tunnel track design.

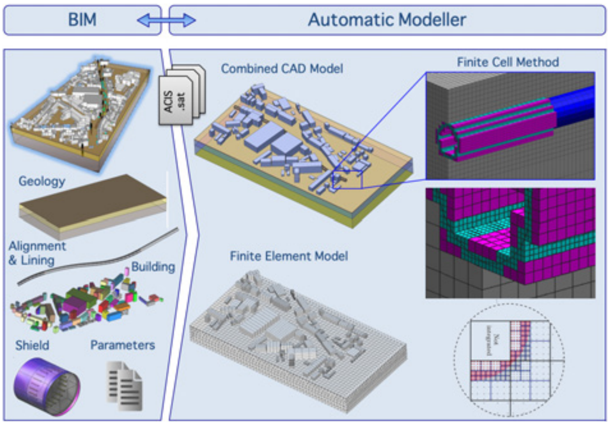


Fig. 2: Automated generation of a FEM-FCM-Model based on BIM for tunnel track design

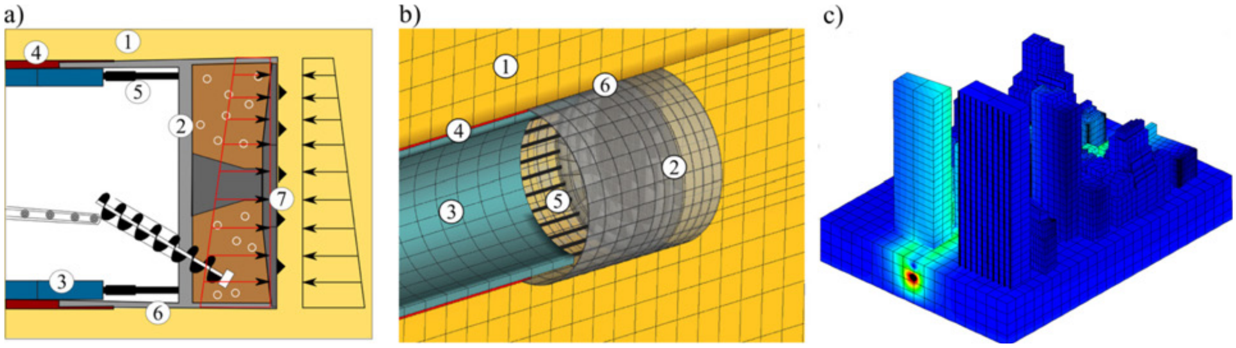
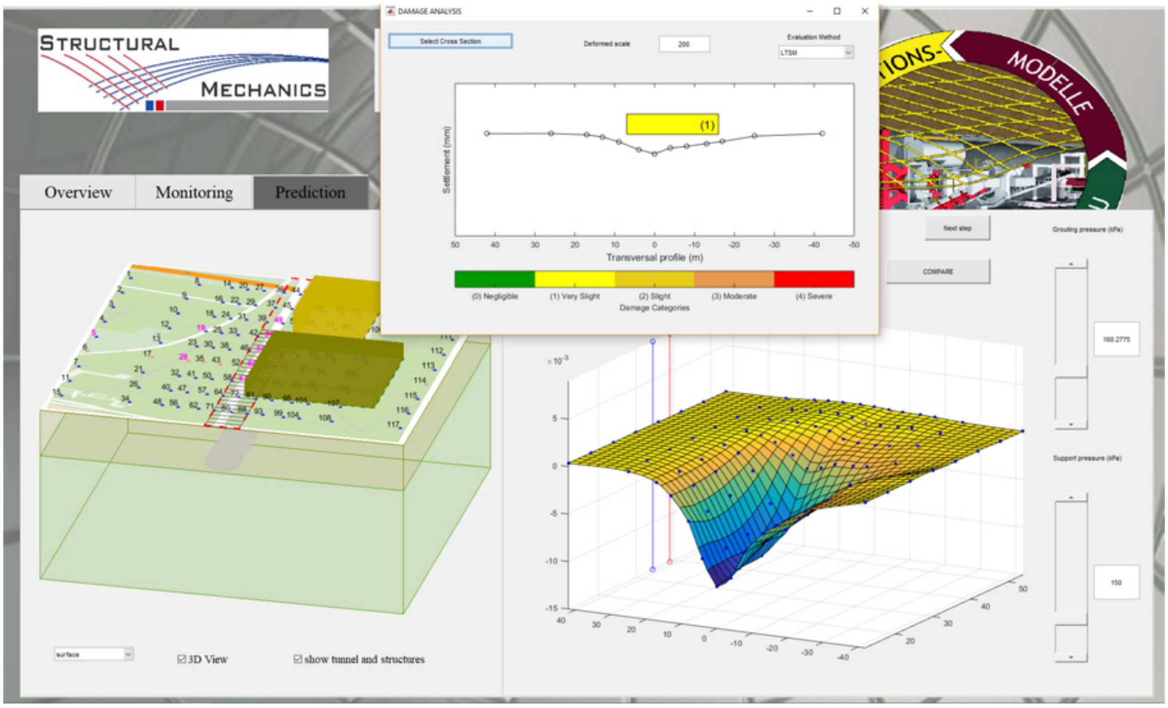


Fig. 1: a) Schematic representation of the components of a TBM drive: (1) soil, (2) shield machine (TBM), (3) tunnel lining, (4) grout, (5) hydraulic jacks, (6) shield skin, (7) cutting wheel und support medium; b) FE simulation model *ekate*;
c) Application of the FEM-FCM simulation model for a tunnel section in a metropolitan area



Deformed scale: 200

Evaluation Method: LTSM

Grouting pressure (kPa): 160.2775

Support pressure (kPa): 150

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

REAL-TIME STEERING ASSISTANT

To assist the TBM drive process, a Simulation and Monitoring-based Assistant for Real-time steering in mechanized Tunneling (SMART) has been developed. The App, which is trained in an offline stage from the results of *ekate* simulations, suggests in real-time suitable operational parameters for the upcoming excavation steps of the tunneling process such that tolerated system responses (surface settlements, risk level of building damages) are not exceeded. Inherent geotechnical uncertanties of the ground conditions (stochastic, interval, fuzzy and polymorphic uncertain data) are also considered. To enable real-time prognoses, Artificial Neural Networks together with Proper Orthogonal Decomposition techniques are employed.

Figure 3 demonstrates an application of SMART during TBM advance. By selecting grouting and support pressures for the next construction steps, the expected surface settlement trough is predicted in real-time, and the corresponding risk level of the existing building is visualized. The risk levels starting from negligible damage (green) to severe damage (red) are computed with a strain-based damage evaluation model developed in subproject D3 of the SFB 837. The asistant system SMART, which is continously updated with machine data and settlement measurements, allows evaluating various scenarios of the tunneling process parameters in real-time to support the TBM steering during construction.

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SYSTEM AND PARAMETER IDENTIFICATION METHODS FOR GROUND MODELS IN MECHANIZED TUNNELING

R. Hölter, C. Zhao, E. Mahmoudi, M. König

PRESENTATION OF THE SUBPROJECT

Numerical simulations of mechanized tunneling process include the complex interactions between subsoil, TBM and surface constructions. A simulation of these interactions requires adequate representation of the constitutive and geometric properties of the subsoil that is challenging. However, an accurate prediction of system responses (e.g. surface or construction deformations) in both the design and in the execution phases can only be realistic when these properties are identified accurately. In the first two phases of this subproject, techniques for the identification, validation, and adaptation of adequate soil models for numerical simulations in mechanized tunneling are developed. Based on the previous results of the subproject, the concept for an optimal measurement design for sensor localization and identification of geomaterial alternation for automatic model adaptation will be developed in the current phase.

PREVIOUS RESULTS

Using the techniques developed in phase I (i.e. sensitivity analysis, metamodeling, optimization-based parameter identification), the work in the second phase aimed to reduce the uncertainties that are faced in the process of model validation. One approach was to question which type of data is used as input in a model-based parameter identification procedure. In this framework, the concept of Optimal Experimental Design is employed to identify the type of sensors and their location that can provide field data, which allows the most accurate parameter identification. Optimized measurement concept is developed and applied on different case studies using global sensitivity analyses and other probabilistic tools (Fig 1). In addition, practical aspects as the number of sensors or their accuracy were investigated with respect to the reliability of the identified soil parameters (Fig 2).

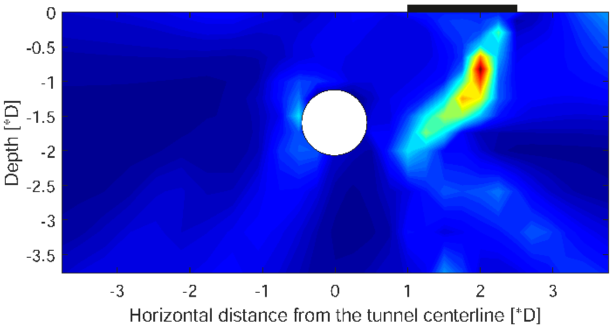

Fig. 1: Sensitivity plot indicating where to measure vertical settlements in case of shallow tunnel

To enable high accuracy model evaluations with time efficiency, the concept of hybrid modeling was developed. Due to the complexity of a tunneling project, it is highly time-consuming to run the simulation model of the excavation process with an overall refined mesh. To address this issue, a computational technique known as submodeling is utilized that makes a refined local model of the area of interest and a coarse mesh that modelled the

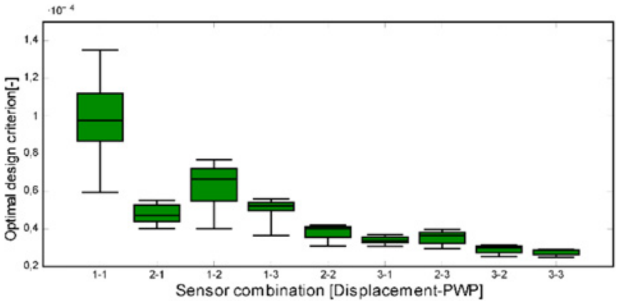

Fig. 3: Expected parameter identification variation in case of increasing number of sensors

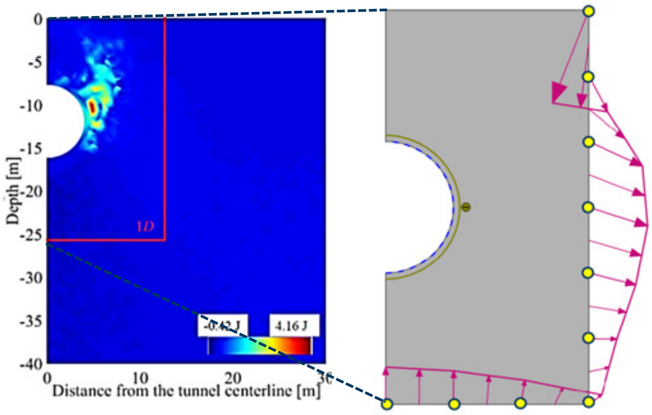

Fig. 2: Visualization of hybrid model arrangement

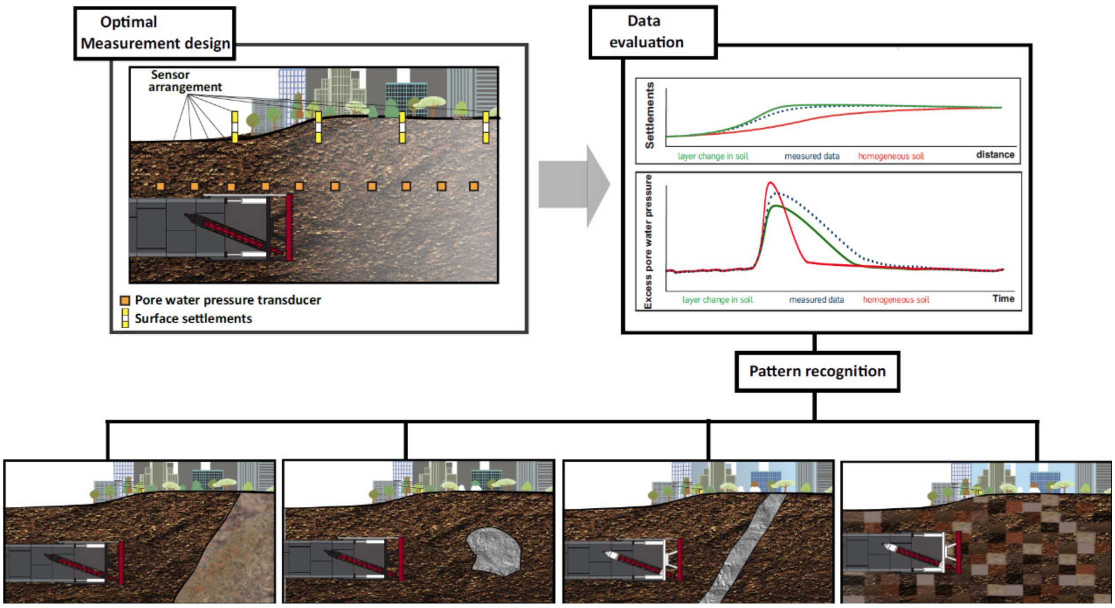

Fig. 4: Concept of Pattern recognition in mechanized tunneling

whole ground (Fig.3). The displacement field from the global model is applied as a boundary condition on the refined model (i.e., submodel). Here, the surrogate modeling approach is combined with the submodeling technique to allows connecting detailed selections of a numerical model with computationally cheaper realizations, performed by metamodels.

IDENTIFICATION OF SUBSOIL ALTERNATION

The developed tools in the last phases aim to identify the model input factors that constitute primarily subsoil mechanical properties for a credible prediction of the ground behavior during mechanized tunneling. However, subsoil properties and conditions can be changing with the tunnel alignment. Thereupon, an updated calibration of the system geometry and conditions during tunnel advancement is necessary for the compatibility between the reality and the prediction conditions. In this regard, a scenario-based approach for mechanized tunnel computational model is adopted which considers some common geometrical alterations of underground conditions in tunnel excavation as layer change, interlayers or an obstacle (Fig. 4). The evaluation of field measurements to mitigate risks caused by uncertain geology in the near field of TBM is to be carried out with the aid of pattern recognition methods. The measurements are supposed to be obtained from an optimal sensor arrangement, using Bayesian updating technique. To reduce the amount of data and improve quality, pre-processing is developed to include measurements and to map the information to a uniform range of values. In the next step, a large number of time series characteristics a.k.a features are extracted by a data mining method named as FeatuRe Extraction based on Scalable Hypothesis to transform the patterns into the feature space. The final classification will be done based on support vector machines, Naive Bayes theory or k-nearest Neighbors algorithm, which assign the characteristics to their related subsoil alternation classes.

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PROCESS SIMULATION IN MECHANIZED TUNNELING: FROM FORCASTING TO REAL-TIME PROCESS CONTROLLING WITH CONTINUOUS MODEL UPDATES WITH PROCESS DATA

A. Jodehl, M. König, M. Thewes

PROBLEM AND MOTIVATION

The availability of mechanized tunneling systems is strongly dependent on the planning and performance of the support and maintenance processes. These processes are based on project-specific boundary conditions and on a variety of assumptions of process durations and performances. An essential goal in the planning phase is to analyse different supply systems and scenarios in order to ensure the most robust project flow possible. Simulation concepts enable a detailed evaluation of various production, logistics and maintenance processes already in the planning phase. Furthermore, possible bottlenecks in the supply chain and disturbances can be evaluated (see Fig. 1). The overall planning quality can be improved.

With the help of the methods developed in phase 1 and 2 of the SFB, the supply chain and maintenance work can be planned and evaluated beforehand. However, deviations often occur during the execution phase, despite detailed planning. A continuous control and situational adjustment of the production, logistics and maintenance processes is therefore inevitable.

In the course of the third phase, concepts for a real time assessment and the computational steering of the logistics and production processes will be developed). The focus lies on a disturbance management and a prognosis of the production and logistics processes during construction.

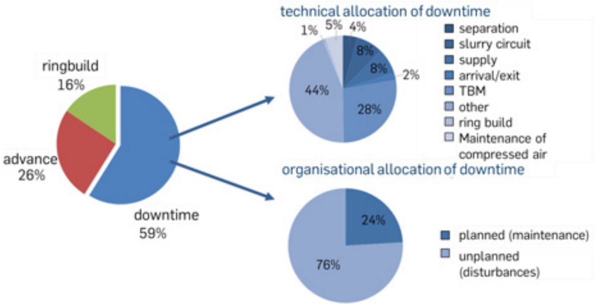

Fig. 1: Analysis of disturbances in mechanized tunneling

RESULTS OF THE 1ST AND 2ND PHASE

Within the first phase, a simulation model for analysing production and logistics processes was developed (see Fig. 2. The core production processes and interdependencies in mechanised tunneling were determined and classified. Further, uncertain boundary conditions were considered, such as geological aspects, which have a significant influence on the performance of tunnel boring machines. Disturbances and their dependencies were systematically analysed and included into the simulation model in order to evaluate their impact on the productivity of the system.

In the second phase, new concepts for an optimized planning of maintenance intervals considering the wear of cutting tools were developed. Uncertainties in the expected geological boundary conditions and steering parameters have a direct influence on the wear behaviour of cutting tools (see Fig. 3).

By developing simulation-based models, the influence of wear of cutting tools could be investigated in the holistic context of tunneling projects.

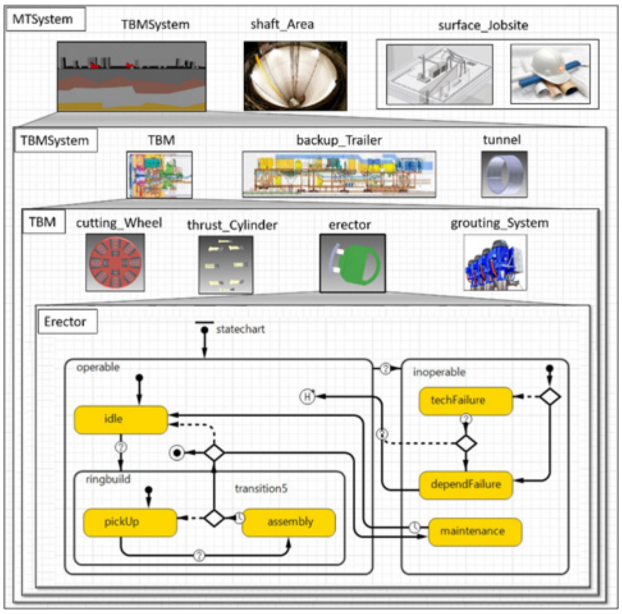

Fig. 2: Simulation model implemented in *AnyLogic* simulation software

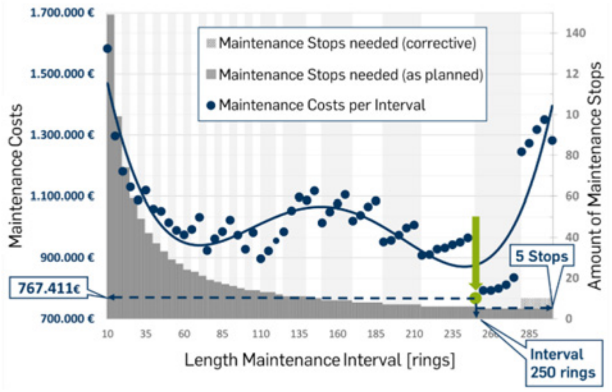

Fig. 3: Maintenance costs depending on the length of the maintenance interval

Therefore, an empirical wear prediction model was implemented into the simulation model to evaluate different maintenance strategies with regard to uncertain input parameters. Considering maintenance costs, different maintenance strategies were compared and evaluated in order to gain an improved and more robust maintenance schedule.

The influence of stochastic input parameters was considered based on Monte Carlo experiments and the simulation model developed was verified and validated using real project data.

GOAL OF THE 3RD PHASE

During tunneling, many parameters deviate from the predicted values. The main reasons are that the assumptions made in the planning phase are subject to uncertainties and fuzziness. Further, unforeseen events can occur during execution that were or could not be considered during the planning phase. Therefore, logistics and production processes must be adapted and controlled continuously. The third phase focuses on a real-time analysis and a steering of logistics and production processes. For this purpose, a control concept in the form of a control loop must be specified, which includes the recording of the current status of the production and logistics processes, the evaluation of the current data and the planning of suitable counter measures (Fig. 4).

In a first step, concepts for an adequate recording of data, which reflects the status of the construction site, will be developed. In mechanized tunneling, a lot of data is already recorded during excavation. However, a structured evaluation of the data obtained regarding simulation-based control of logistics and production processes has not taken place yet. In order to evaluate the current construction progress and to enable an adjustment of the production processes, deviations between the planned and the recorded data are determined. This enables an adaption of the logistics processes and an adjustment of the prognosis. If significant deviations are detected, suitable counter measures can be taken. The effect of deviations in the project flow can be evaluated and counter measures can be proven with the help of simulation models.

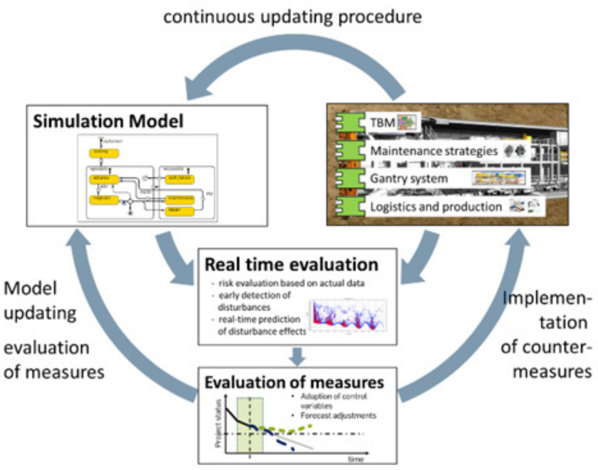

Fig. 4: Control loop for the holistic process simulation approach for tunneling projects

Further, by identifying threshold values, an early detection of disturbances is possible. Simulation models can help to evaluate a real time prediction of disturbance effects and an evaluation of the adaption of control variables.

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

A. R. Leon Bal, S. N. Butt, T. S. Dang, P. Saberi Yahyaei, A. Vogel, G. Meschke

RESEARCH OBJECTIVES

In this subproject, high-resolution computational models are developed for the analysis of the excavation process at the cutter head of the TBM, the subsequent mixing with conditioning foam in the excavation chamber and the transport of the excavated mixture through the screw conveyor. Soft soil as well as hard rock material is addressed. The developed computational models are verified and validated with experiments. In order to carry out large-scale simulations, efficient algorithms and parallelization techniques are required. The goals of this subproject are: (i) to predict the forces acting on the TBM tools during the excavation process and, in result, predict the torque and thrust requirements, tool wear as well as the size distribution of the excavated fragments for the cutter head configuration and geology at hand, (ii) to calibrate the rheological parameters of the mixture in the excavation chamber w.r.t the fragment size distribution of the excavated material and (iii) to characterize the face pressure distribution, material transport and mixing processes in the excavation chamber. The numerical tools help obtaining a better insight into the excavation and transport processes in TBMs and allow for optimized cutter head and chamber designs.

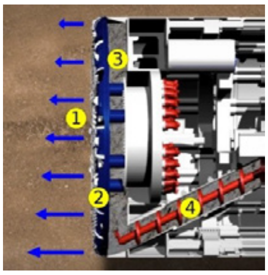

Fig. 1: Schematic of a TBM: (1) face pressure, (2) cutter head, (3) excavation chamber and (4) Screw conveyor

EXCAVATION PROCESS AT THE CUTTER HEAD

Excavation processes at the cutter head are performed by employing drag picks for soft soils and cutting discs for hard rock or a combination of both, depending on the ground geology. In order to model the excavation in soft soils, a computational model was developed using the Particle Finite Element Method (PFEM) with a non-linear, incremental constitutive formulation (hypoplastic model). PFEM allows modeling of large deformations and the corresponding stress state in soil during excavation (Fig. 2, right). Additionally, reaction forces acting on the tool and its abrasive wear behavior are readily obtained.

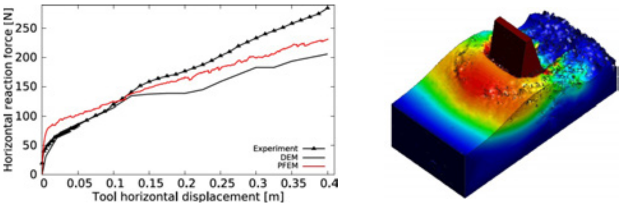

Fig. 2: Comparison of experimental and numerical reaction force-tool displacement evolution (left). A 3D PFEM simulation of soft-soil excavation process, colors indicate the particle velocity (right)

The spatio-temporal evolution of computed reaction forces on a single tool is validated by comparison with measurements and a DEM model in Fig. 2, left. Currently, a full-scale PFEM model for an EPB cutting wheel is developed to assess the ground-TBM interaction.

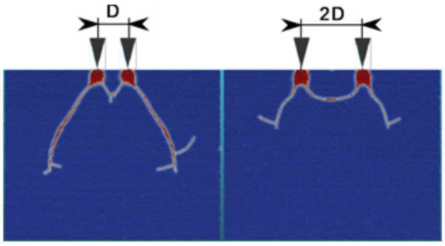

Fig. 3: Peridynamic simulation of double indentation test in a brittle specimen with two different tool spacings

Excavation using disc cutters in hard rock involves crushing, high speed dynamic fracture and fragmentation processes in the rock mass. In order to capture these highly discontinuous phenomena, we resort to the peridynamic theory. Unlike classical continuum theory, the peridynamic formulation can incorporate discontinuous kinematic fields emerging from such processes without an additional evolution criterion. Fig. 3 compares the chipping and fracture patterns obtained in a 2D rock specimen from a double indentation test at two different tool spacings. In Fig. 4, simulation results of a full scale linear cutting test for a single pass as well as multiple passes of the cutting disc are presented.

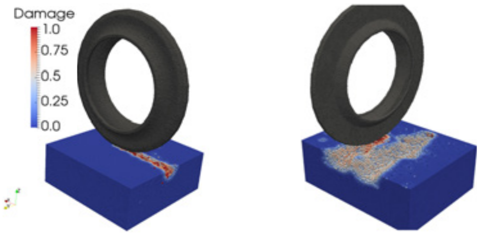

Fig. 4: Peridynamic simulations of rock cutting using a single pass (left) and two passes (right) of the cutting disc

SIMULATION OF MATERIAL TRANSPORT AND ANALYSIS OF PRESSURE DISTRIBUTION

A computational model for the simulation of material transport in different EPB chambers was developed. The interaction of the rotating interior components in the chamber with the soil paste is realized by means of the Immersed Boundary and the Shear-Slip Mesh Update method. Two realistic numerical models based on a Herrenknecht EPB machine with a diameter of 7 m and a Hitachi EBP shield with a diameter of 17.5 m were considered for the study of pressure distribution (see Fig. 5).

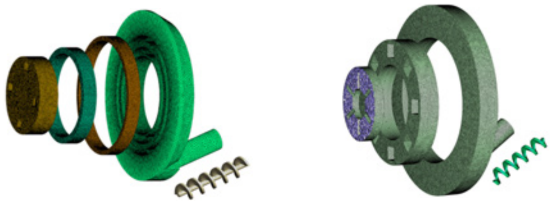

Fig. 5: Computational meshes for EPB shield machines: Herrenknecht (left) and Hitachi (right)

The analyses reveal a large dependency of the pressure distribution on the machine design and the material properties of the soil-foam mixture. An unbalanced pressure between the left- and right-hand sides is observed in the Herrenknecht excavation chamber for a compressible soil paste, which is consistent with in-situ measurements. It was shown, that pressure fluctuation for this design increase with incompressibility (Fig. 6, left and center). Only small pressure fluctuations are observed for the 17.5 m diameter machine (Fig. 6, right).

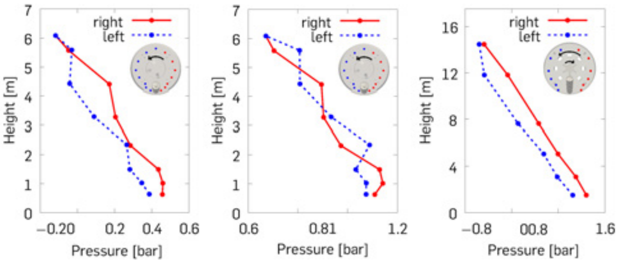

Fig. 6: Computed relative pressure distributions at monitoring points on the bulkhead. Left and center: Herrenknecht shield assuming compressible and incompressible muck, respectively; right: Hitachi TBM assuming incompressible muck properties

In order to resolve the rotating components and to conduct multiple geometry studies efficiently, a parallel, high-performance implementation of the Finite Cell method (FCM) is currently being developed for flow and transport simulations, covering the entire domain from the tunnel face to the screw conveyor. The refinement capability of the method is illustrated in Fig. 7, where the rotating cutter head is recovered by an adaptively refined structured mesh.

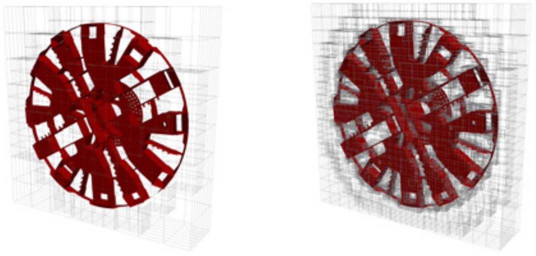

Fig. 7: Adaptive mesh refinement for the Finite Cell method on an Earth Pressure Balance cutting wheel

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CHARACTERIZATION OF THE INTERACTION BETWEEN CUTTING TOOLS AND ROCKS DURING TUNNELLING FROM METALLURGICAL AND ROCK-PHYSICAL POINT OF VIEW

J. Renner, A. Röttger

INTRODUCTION – STRUCTURE OF THE PROJECT

Wear and the associated flattening of cutting edges counteract the degree of ground degradation by the tool impact and thus the efficiency of the overall tunneling process. Until now, knowledge about the acting wear mechanisms and the interactions between minerals and tunneling tools is insufficient for soil and soft rock. Therefore, subproject C5 aims at improving/deepening the understanding of the interaction between tunneling tools and to be penetrated geomaterials. In the second funding period, we focused on soil but will now turn to soft rock and mixed-ground-conditions. Especially mixed-ground conditions subject the tunneling tool to cyclic loads and thus promote failure due to fatigue. To understand the influence of cyclic impacts on the fatigue behavior undercritical crack propagation in hard phase containing materials will be investigated.

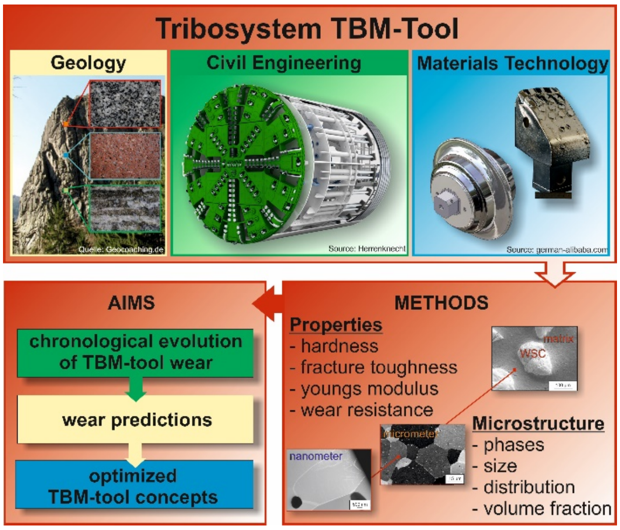

Fig. 1: Mapping of the tribosystem “tunneling tools” to basic aims in the sub-project C5

Hard phase containing materials will be cyclically loaded and the crack initiation and propagation will be investigated by micro-computer tomography. In addition to these fundamental examinations of the fatigue resistance of hard phase containing materials, wear of cutting discs (quenched and tempered martensitic steel) will be investigated. To map the tribological system, a new wear testing device will be developed, thus allowing the wear testing of different cutting discs against different soft rocks. In these tests, the material of the cutting disc, the rock samples as well as the load spectrum will be varied. It is the aim to understand the relationship between the tool wear and the ground degradation efficiency.

The damage development of soft rocks during/by tool impact will be monitored and characterized by rock-physical and geophysical test methods as well as by nanoindentation experiments that resolve phase characteristics. In a further step, we investigate the degradation of rock materials by partially and fully worn tools and the associated degradation mechanisms, such as the mode of crack initiation, propagation and material delamination. The results gained from these investigations will then be used as input parameters for the simulations performed in the subproject C4 (simulation of rock degradation) and C6 (simulation of tool wear).

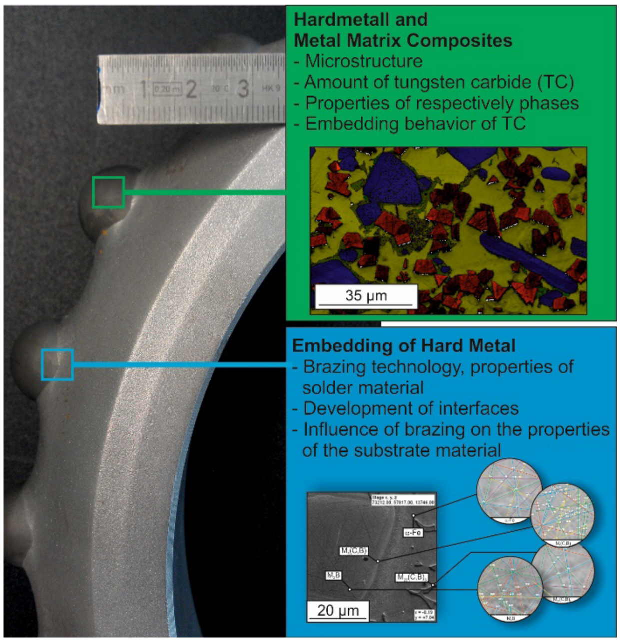

Fig. 2: Investigation of the dominating wear mechanisms of worn tunneling tools using optical and scanning electron microscopy

AIMS AND SCIENTIFIC-TECHNOLOGICAL QUESTIONS

In the second funding period, subproject C5 considered the tribological system “Tools in soil for mechanized tunneling (TBM)", developed a wear prediction, and derived improved tool concepts. In the third funding period, the findings will be extended to cohesive soils, soft rock and mixed-ground conditions. The focus of the investigations are soil heterogeneities which cause cyclic loads and thus promote fatigue wear of the tools. Fundamental investigations will thus be performed to understand the fatigue wear process of tunneling tools. Especially, phase-resolved crack initiation and crack propagation of hard phase containing materials, as used for tunneling tools, will be investigated by scanning electron microscopy and micro-CT-investigations. In addition to homogeneous grounds, heterogeneous and especially anisotropic rocks will be considered to address the impact of changes in strength.

Tool wear likely counteracts the degradation performance, negatively impacting the penetration speed, and thus the economics of the tunneling process. To demonstrate the influence of wear state of the tools on the degradation efficiency, crack initiation, and the associated material removal of the rock must be fundamentally investigated. The damage development and the macroscopic crack propagation in the rock as well as in the individual phases shall be elucidated by experimental methods, like nanoindentation experiments, which can be used to determine the phase-resolved material characteristics. To reach the overall aim, the following scientific and technological questions have to be answered:

Questions in materials technology:

A) How can the dominant wear mechanism of cutting discs on heterogeneous and cohesive soils be described and mapped by laboratory tests?

B) Can fatigue wear on hard phase containing materials be reproduced on a laboratory scale and how can the crack propagation be described?

C) Is it possible to extend wear predictions of tools operating in soil by heterogeneous soil/ soft rock or are these predictions exacerbated by the effects of tool fatigue and brittle fracture?

D) Can regulations or optimization measures be deduced which lead to the production of improved material and tool concepts?

Questions in rock mechanics:

A) Is it possible to identify a few from the large number of possible influencing parameters on the failure of rocks in mining situations and to describe their influence in analytical form?

B) Can the mesoscopic crack propagation and propagation be associated with phase characteristics?

C) How can the results from the experiments be transferred in the best possible way, in the sense of instructions, to the real mining and tunneling situations?

D) What is the interaction between the heterogeneity of rocks and the dynamics and kinematics of tool action with regard to the success of mining and tunneling?

E) What influence does the cutting-edge geometry have on the degradation efficiency? How does the cutting-edge geometry affect the fatigue wear and the abrasive wear and can an optimum determined from minimal tool wear and maximum degradation efficiency?

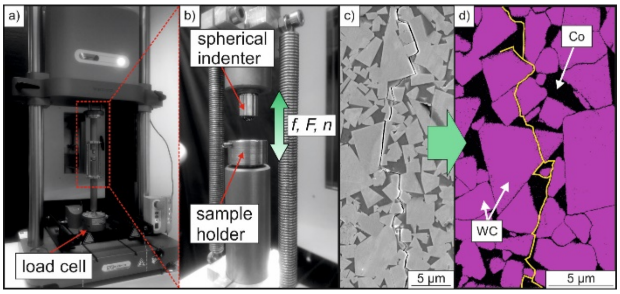

Fig. 3: Investigation of the crack initiation and crack propagation in hard-phase containing materials, a) and b) experimental set up of the testing device, c) microstructure of cemented carbide after testing, d) investigation of the phase-resolved crack growth by means of EBSD investigations

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MULTISCALE MODELING, SIMULATION AND OPTIMIZATION OF CUTTING TOOLS REGARDING THEIR TRIBOLOGICAL BEHAVIOR

G. Hoormazdi, D. Wingender, D. Balzani, K. Hackl

INTRODUCTION AND MOTIVATION

The efficiency of the tunnel boring machines (TBM) is strongly influenced by the wear of the mining tools. Thus, the objective of this subproject is to model the wear of mining tools from the microscopic level up to the macroscopic part and therefore to obtain a deeper understanding of the involved processes like abrasion and surface disruption. For this, mechanisms such as plasticity, damage and crack propagation must be numerically analyzed at different scales, which still brings up major challenges in solid mechanics. The aim is to gain a deeper understanding of the wear mechanisms on the microscopic as well as on the macroscopic level in order to make reliable predictions for the life time of the cutting tools depending on the nature of the excavated soil. In a further step, the geometry and structure of the mining tools as well as the morphology and the material properties of the components on the microscale are optimized regarding wear resistance, so that the efficiency of the mechanized tunnel boring process is increased. In this context, collaboration with subprojects C4 and C5 is essential.

SIMULATION OF ABRASIVE WEAR ON THE CUTTING TOOL

From macroscopic point of view, the interaction between mechanical tools and materials, such as soil and rock, cause abrasive wear in tunneling process. The procedure for predicting abrasive wear has two steps, which leads to the extension of results from a single scratch test to the wear of mixtures. In the first step, a coupled damage-plasticity material model is developed to help understanding and modeling the abrasion process of a single particle. For this purpose, a regularization strategy based on gradient enhancement of the Helmholtz free energy function for a coupled damage-plasticity model is implemented. The enhancement is through the application of Hamilton's principle for non-conservative continua, which yields a field equation for the damage function. This algorithm is improved based on a finite element/finite difference scheme along with an operation split, for a fast update of the field function. Fig. 1 shows the application of this developed material model for the indentation of an abrading particle, triangular tip made of Quartz, into a steel surface, i.e. St. 52. This example should be repeated for different shapes and sizes of the indenter and extended by considering the relative movement between the specimens in contact.

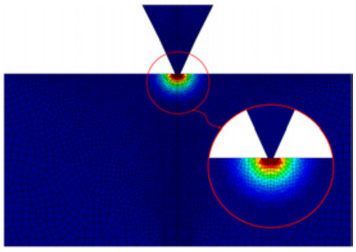

Fig. 1: Damage distribution for the indentation example with coupled damage-plasticity material assignment

In the second step, the results of single scratch tests should be extended to the wear of mixtures by means of equations for the number of contacts and normal contact forces that are obtained from Discrete Element Method (DEM) simulations. The total wear rate of a material is the sum of wear rates of particles that are in contact with the tool surface, $\dot{V}_{Total} = \sum_{i=1}^{N_c} \dot{v}_i = N_c \dot{v}$, where N_c is the number of contacts per unit area from DEM simulations for homogeneous material or particle mixture [1].

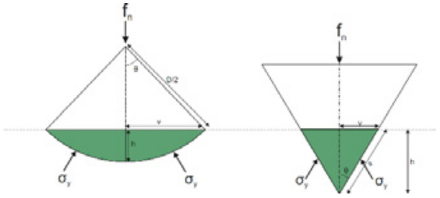

Fig. 2: Schematic picture of particles and their corresponding groove area

Fig. 2 shows the two different particle shapes (spherical and triangular particles) used in DEM simulations. The ultimate abrasion model is then calibrated using the methods developed on a microscopic scale and used to calculate the change in shape of entire tools.

MODELING WEAR ON THE MICROSCALE

In order to increase the wear resistance of the tools, protective coatings made of hard metals are applied mainly to the chisels but also to the discs. The wear behavior herein is dominated by surface spalling (Fig. 3) due to soil particles hitting the tool's surface. Here, subcritical crack propagation through the material's microstructure takes place. Since this process is mainly governed by the morphology of the microstructure and the mechanical behavior of the individual phases, simulations at the microscale enable the design of improved materials. In this part of the subproject, a method for the modeling of this process is developed.

The approach is based on the eigen-erosion framework for crack propagation and a new computational scheme is developed wherein a fine volumetric integration of the microstructure is realized by the Finite Cell framework. Whenever the crack enters a finite element, the cells are transformed to individual finite elements, which are connected to the neighboring elements through hanging nodes. Here, a specific cell arrangement is constructed which minimizes the required number of cells for a given microstructure morphology. Based on this computational approach, comparatively large finite elements can be used, which enables a significant reduction of computing time while keeping the accuracy of the crack propagation high. For the phases at the microscale a finite strain plasticity formulation is applied and parameters are chosen in line with experimental data.

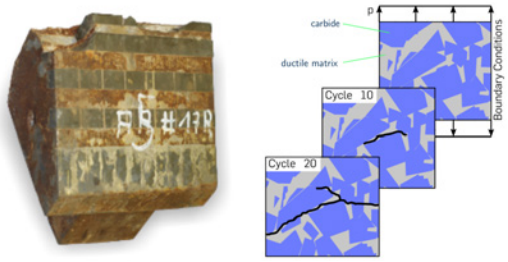

Fig. 3: left: Worn out chisel, right: Schematic illustration of crack propagation in hard metal microstructure under cyclic loading

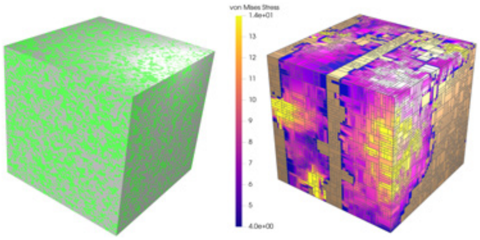

Fig. 4: left: CT scan of original microstructure with titanium (green) and an iron matrix (gray), right: Contour plot of von Mises stress

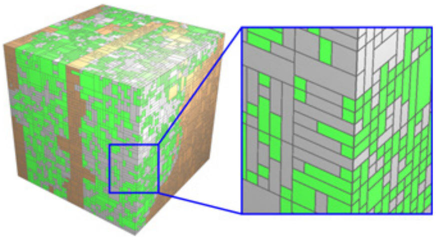

Fig. 5: Crack (gold) through a simulated hard metal microstructure consisting of titanium (green) and an iron matrix (gray)

The microstructure is obtained from µ-CT scans of the hard metals obtained from project C5 (Fig. 4, left), which are then discretized using the above mentioned scheme (Fig. 5). In numerical simulations where cyclic loading is applied, the crack grows with increasing number of cycles due to plastic flow and the change of the loading history caused by the previous crack propagation. Based on these simulations, the microscopic crack propagation can be analyzed (Fig. 4, right) in order to develop improved material concepts. In order to further reduce the computational effort, the concept of statistically similar representative volume elements will be used. Therein, artificial microstructures with a significantly reduced complexity and thereby less finite elements are considered which still represent the morphology statistics as good as possible. To obtain an efficient wear model at the mesoscale still taking into account the micro-heterogeneity, the results of the microscopic simulations may be homogenized to obtain the input data for a mean field formulation.

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VIBRATION-BASED MONITORING OF INTERACTIONS AT CUTTING WHEEL – DETECTING WEAR

I. Müller

MOTIVATION

Wear and reduced service life of TBM-tools has been under investigation within the SFB in the last phases, as it counteracts improved efficiency of tunneling processes. Especially unplanned maintenance activities, like necessary unplanned replacement of the cutting discs or even replacement of the complete disc mounting system leads to increased process time and soaring costs. Within C7 the detection and identification of wear and damages of cutting discs is focused. An online monitoring system should continuously check the current disc state and allows to adapt process parameters and maintenance activities.

For stationary rotating machinery like gas turbines or bearings, the use of vibration measurements to monitor the condition of the machinery has proven to be successful and sensitive also for minor damages long before failure, enabling condition-based maintenance. As the measurement directly at the disc seems to be impossible for TBM and the tunneling process is not stationary compared to the rotation of a gas turbine, the use of vibration measurement seems to be promising only if it is combined with intelligent feature extraction and pattern recognition. For monitoring systems, which are operating under changing environmental and operational conditions, different means of data analysis enable to distinguish between their influences and damage. These concepts need to be adapted for the tunneling process, where the operating conditions as well as changing soils and rock are supposed to dominate the vibration.

PROJECT AIMS

Subproject C7 aims to develop a monitoring system to detect and identify wear and damages of cutting discs at the cutting wheel during the cutting process using vibration-based features to enable efficient use of tunnel boring machines.

PROJECT STRUCTURE

To realize these aims, three workstreams need to be considered. Using numerical models with different levels of detail within WP1 as well as experimental investigations in WP2, different causes of vibration are analyzed, and data is generated for the data-based analysis of the cutting wheel. For the specific application, methods of pattern recognition and novelty detection are applied and adapted in WP3 to ultimately enable the monitoring of disk wear, based on data of the undamaged state.

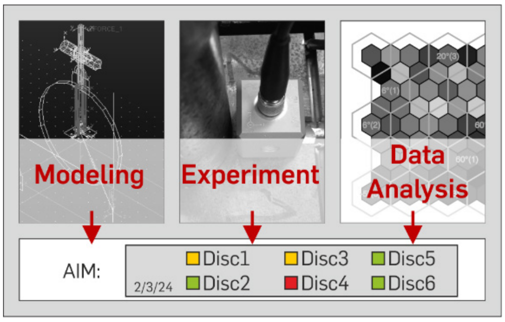


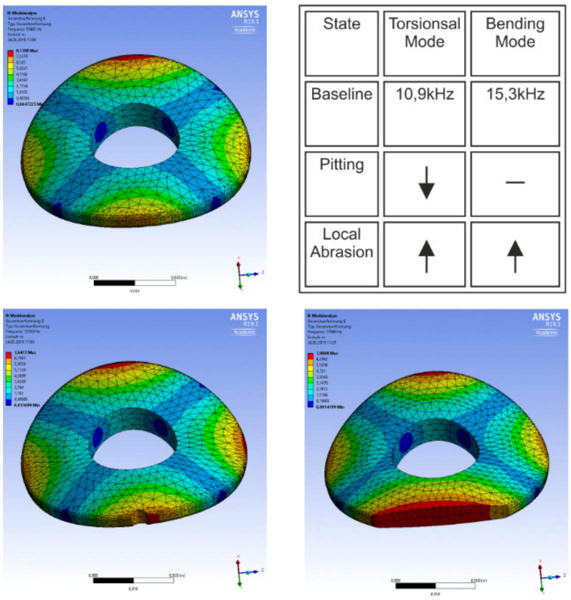
Fig. 1: Project structure

The three workstreams are closely interlinked, enabling in-depth understanding of underlying mechanisms leading to changing vibrational patterns and validated numerical models. Moreover, the close cooperation with other projects like C4 to C6 regarding the modeling and the experimental investigations ensures the usability of the results and necessitates concepts of integrated measurements, paving the way to future realization in industrial context.

PRELIMINARY RESULTS

To extract information about the cutting disc out of vibration data, either modal parameters of the disc need to be changed by possible damages and to be visible in the measured frequency spectrum or revolution frequencies of a point-like damage can be evaluated from the vibration data. For a first feasibility study, three aspects have been investigated.

The first aspect under investigation is the influence of simple disc damages on the natural vibration behavior and its natural frequencies. An exemplary disc from a miniaturized test bed based in Leoben was used. With numerical simulations using ANSYS® it could be shown that the influence of damage on the different modes is very diverse. For the simulated damage of small to medium pitting, the torsional modes are more sensitive than bending modes. Larger local abrasion is visible in bending modes and torsional modes, leading to larger shifts of the natural frequencies.



State	Torsional Mode	Bending Mode
Baseline	10,9kHz	15,3kHz
Pitting	↓	—
Local Abrasion	↑	↑

Fig. 2: Modal parameters of the supported disc

In a second preliminary study, the extraction of natural frequencies from vibration data is focused. As measuring directly at the disc is not possible for discs mounted at the cutting wheel, it must be tested if measurements at the mounting systems contain information about the discs natural frequencies. Therefore, vibration data was measured directly at the disc and at the mounting system. A miniaturized test bed from Montanuniversität Leoben was used to conduct measurements with a triaxial accelerometer. Using different types of excitation, the frequency response of all measurements consistently shows a frequency peak around 13000 Hz, which has proven to be one of the natural frequencies of the mounted disc. Using methods like stochastic subspace identification, this frequency is detected already for a modal size of 30 DOF.

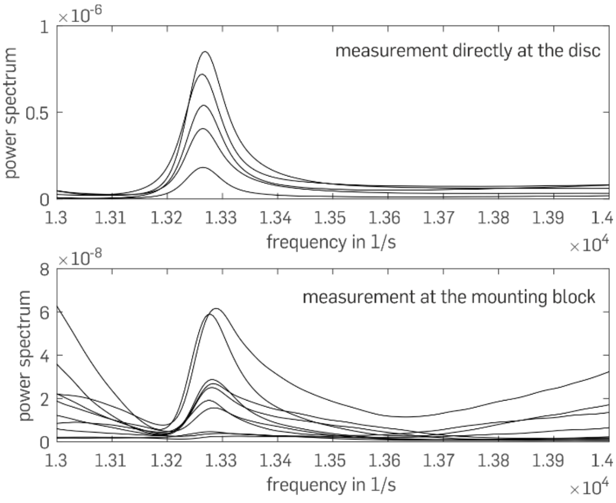


Fig. 3: Power spectra at two measurement points

For these studies, the influence of environmental and operational conditions is reduced to a minimum.

A third aspect under investigation is the influence on the revolution frequency. While the general concept is charmingly easy and already used for bearing monitoring, for the process of tunneling, the influence of the rock and excavation process is supposed to be large. With a simple multibody-system, modeled in Adams®, the influence of the rock is tested taking into consideration material coefficients of literature data, while the influence of the cutting and chipping process is neglected. The results show that the material coefficients have major influence on the excited frequency spectrum of the cutting force and that it overlaps with interesting revolution frequencies impeding the feature extraction.

ACKNOWLEDGEMENTS

The experimental investigations at the model-size disc cutting test bed have been conducted at Montanuniversität Leoben with impressive support by Prof. Robert Galler and his group, which is gratefully acknowledged. The preliminary studies are partly conducted within the ongoing Mastertheses of Mr. Yuquiao Huang and Mr. Ahmad Alabd Allah, whose work is also gratefully acknowledged.

INTERACTIVE EXPLORATION AND ASSESSMENT OF TUNNEL ALIGNMENTS

A. Vonthron, A. Jodehl, M. König, M. Thewes

PROBLEM AND MOTIVATION

The comprehensive planning of tunnel alignments involves the consideration of a multitude of boundary conditions and requirements to allow an optimal selection of the preferred design alternative with respect to risk-avoidance and cost-efficiency. An automated checking and assessment approach should support the modeling process interactively, so that valid alternatives can then be compared to each other. Therefore, the results from the first phase provide an integrated information model to explore model data and possible interactions. The results of second phase additionally provide routines to incorporate and assess interactions due to their qualitative outcome.

RESULTS OF THE PREVIOUS PHASES

As an extensive result from the former phases, an Integrated Tunneling Information Platform (TIM) has been developed (Fig. 1). The first phase predominantly dealt with the product modeling of the different domains, such as creating intelligent information models for the tunnel, the TBM, the built environment and geological data like boreholes and derived ground models. Also, active measurement data have been integrated, including observed settlements and monitoring data, to combine them into a 4D time-dependent settlement analysis.

During the second phase the framework has been extended. Model View Definitions (MVDs) enable content filtering due to specific requirements of applications to provide only relevant data. A multi-model container approach helps to not only structure the project's contents properly, but also to model interrelations between domain models and measurement data in a sustainable manner. In case of the 4D settlement analysis, for example, non-transient linking between TBM advancement, built ring segments, settlement data and TBM performance data has been established. Furthermore, the user interface has been migrated to a web-based application to support centralized and collaborative usage (Fig. 2). This also required the inclusion of more efficient modeling approaches that reduce redundant representations, such as using shared geometries for tunnel rings.

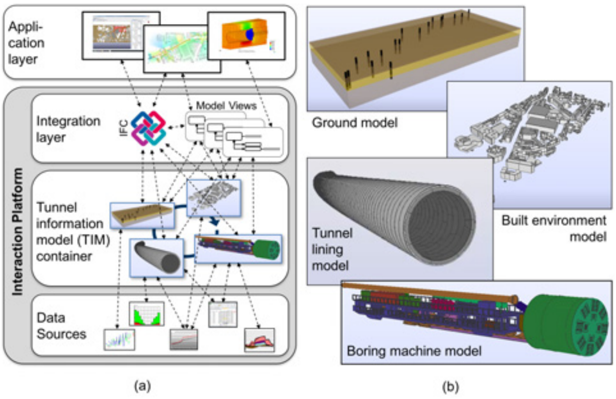


Fig. 1 TIM interaction platform, providing product models, model linking and model views for specific applications

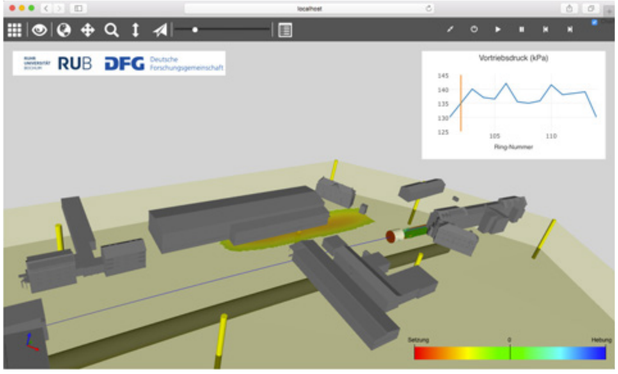
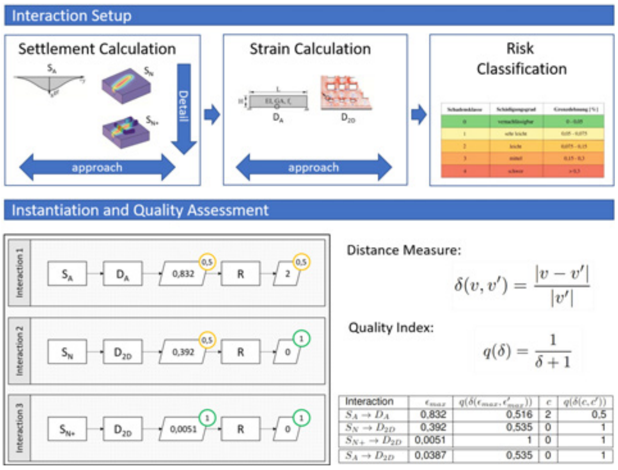


Fig. 2: Web-based interface to apply actual interaction in the TIM

In addition, the second phase focused on developing methods for the integration and assessment of problem-specific interaction chains. An interaction chain addresses a specific goal, which is solved by the concrete implementation of subproblems. These can often be performed using different approaches, which differ by level of detail or by concept (Fig. 3, top). Therefore, different concrete implementations are instantiated and compared. These are visualized



Distance Measure:

$$\delta(v, v') = \frac{|v - v'|}{|v'|}$$

Quality Index:

$$q(\delta) = \frac{1}{\delta + 1}$$

Interaction	ϵ_{max}	$q(\delta(\epsilon_{max}, \epsilon'_{max}))$	c	$q(\delta(c, c'))$
$S_A \rightarrow D_A$	0,832	0,516	2	0,5
$S_N \rightarrow D_{2D}$	0,392	0,535	0	1
$S_{N+} \rightarrow D_{2D}$	0,0051	1	0	1
$S_A \rightarrow D_{2D}$	0,0387	0,535	0	1

Fig. 3: Possible realizations of an interactions chain (top), which results are compared by building quality indices (bottom)

using directed graphs and adopting elements from SysML to provide a semantical outline of the information flow. Furthermore, the nodes of the graph are visualizing related results and quality measures. The comparison of interaction results is based on normalized quality indices, which have been derived from more specific quality measures (Fig. 3, bottom). Thus, the selection of an optimal result is possible with respect to accuracy or processing time.

OBJECTIVES OF THE THIRD PHASE

To develop a comprehensive approach for planning tunnel alignments, several challenges must be addressed. This includes the identification and classification of necessary restrictions and boundary conditions. Here, not only do geometric specifications, such as cross-section designs or limitations to driving dynamics apply, but further influences like socio-cultural aspects or safety criteria must be considered. Based on these criteria, formal definitions must be derived and then stored in a digital knowledge base in a standardized and sustainable manner. Also, evaluation criteria like potential settlements as well as cost estimates should be integrated at this early planning stage. An evaluation will be performed by implementing a multi criteria analysis approach.

The developed concept further includes the examination of digital modeling methods and hardware devices which support the interactive creation of alignments, including multi-touch tables to enable simultaneous modification and collaborative planning. Finally, the interaction chains will be directly integrated so that results from coupled interactions can be adjusted parametrically (Fig. 4).

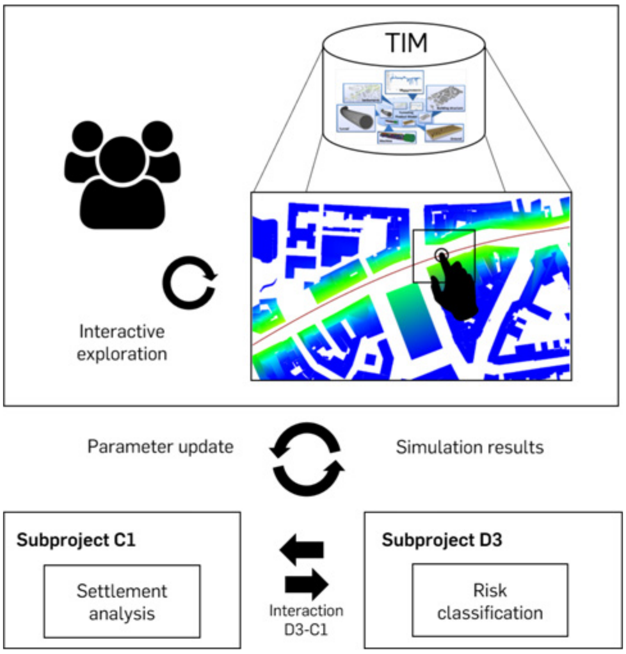


Fig. 4: Interactive alignment manipulation causing a parametric update of instantiated interaction chains

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MODEL-BASED RISK ANALYSIS FOR HETEROGENEOUS EXISTING STRUCTURES

M. Obel, P. Mark

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. Subproject D3 vitally aims to assess potential damages on structures along entire tunnel alignments due to settlements induced by mechanized tunnelling. Essential is to develop and apply a sound multi-level concept to idealize and compute structures subjected to settlements as well as to identify and strictly include relevant uncertainties in damage prognoses and risk assessments derived thereof. Efficient idealisation is achieved primarily by pattern recognition techniques able to detect external structural characteristics reliably.

CONCEPT FOR DAMAGE ASSESSMENT

The developed concept consists of three fundamental modules: settlement prognosis (a), structural idealization (b) and damage assessment (c). Each module offers alternative methods of graded precision and processing efforts (e.g. a1-a4). Fig. 1 illustrates these alternatives. Thus, structural idealisation optionally bases on a comprehensive city model or more classical on documentation and construction drawings. Such information might be combined with analytical or numerical evaluation of settlements in green-field conditions or employing holistic or even simplified computational models. Damage assessment by means of categories from 0 (negligible) to 4 (serious) relies on limit strains ε_{lim}, originally defined by Boscardin and Cording, obtained from structural inclination, a surrogate elastic beam or 2 or 3 dimensional finite element simulation.

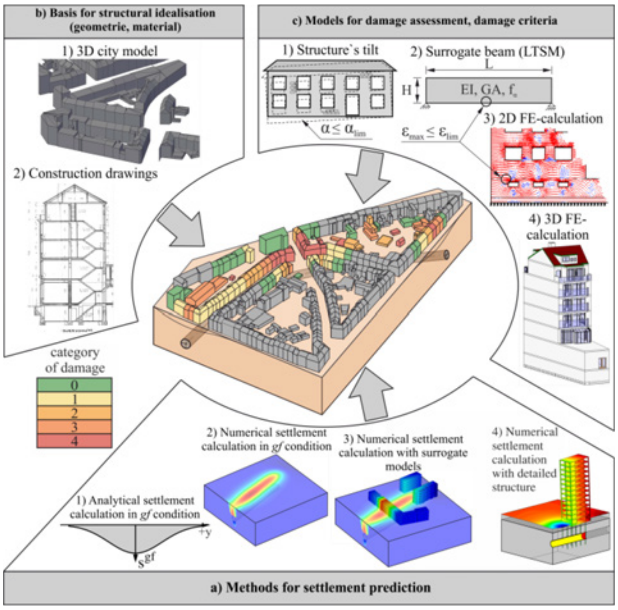

Fig. 1: Modular risk assessment for buildings on-site

TREATMENT OF UNCERTAINTIES AND SENSITIVITY ANALYSES

The impact of uncertain parameters on damage prediction has been assessed by Sobol's indices an established method for sensitivity analyses (SA). In case of green-field conditions and employing Peck's equations the soil parameter K has been identified most relevant (cf. Fig. 2). It dominates the other two model parameters – depth of coverage (c) and outer diameter of the tunnel (D) – significantly.

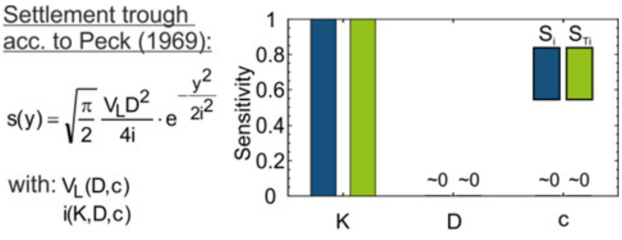

Fig. 2: Sensitivities of the settlement trough

TUNNEL ALIGNEMENT SELECTION

Fig. 3 gives an overview of three alternative alignments with potential damage to the buildings. The evaluations were carried out using analytical models for the settlement trough and damage assessment. It is clear that the upper and lower alignment (Fig. 3 top & bottom) both have a large number of buildings with high damage categories. On the contrary, the central alignment shows only a few critical buildings and is therefore preferable to the first two.

Fig. 3: Three alternative tunnel alignments

PATTERN RECOGNITION TECHNIQUES TO DETECT EXTERNAL BUILDING CHARACTERISTICS

Most important characteristic for vulnerability of façades subjected to settlements is its quota of windows or openings. To get this quota rectified façade images are used. Employing a computer-vision-based detector the portion of windows in façades is gathered efficiently and in adequate precision. At the top, Fig. 4 presents two building façades with detected openings in case of trained and calibrated classifier. At the bottom, numerically determined damage categories of three different structures employing detected and exact opening ratios are contrasted.

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.

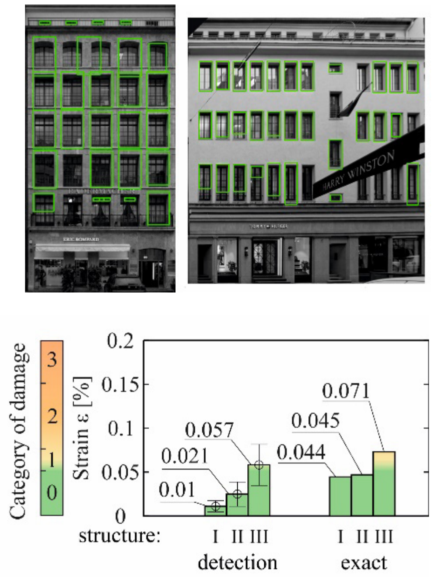

Fig. 4: Detection rates exemplified on two façades (top), comparison of computed damages employing detected and exact opening ratios (bottom)

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