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RECENT ADVANCES IN TUNNELING RESEARCH

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ACTUE – AUSTRIA CHINA RESEARCH IN TUNNELLING AND UNDERGROUND ENGINEERING

- MONTAN UNIVERSITY LEOBEN, AUSTRIA -

- GRAZ UNIVERSITY OF TECHNOLOGY, AUSTRIA -

SFB 837 – INTERACTION MODELING IN MECHANIZED TUNNELING

- RUHR UNIVERSITY BOCHUM, GERMANY -

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- TONGJI UNIVERSITY, CHINA -

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Content

Degradation of Cracked Subway Tunnel Structure by Crack Propagation and Leakage – Influence Analysis on Subway Tunnel Lining Safety Bring by Defects

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Though the tunnel inspection, structural defects like cracks and leakages has always been found at subway tunnel lining. To guarantee the daily operation of the subway tunnel, the understanding of influence bring by defects is important. Crack propagation and coupling influence bring by crack and leakage are two vital problems need to be analyzed. XFEM is a modern way to simulate the process of crack propagation. The influence brings by crack propagation is analyzed to determine the dangerous position of crack. Coupled influence bring by crack and leakage is involved in determining the safety state of tunnel structure. The parameter research about the crack position, depth, multi-cracks, leakage and surrounding soil are also covered in this work. The degradation of the cracked structure with crack propagation and leakage is discussed to conclude the critical state of the lining.

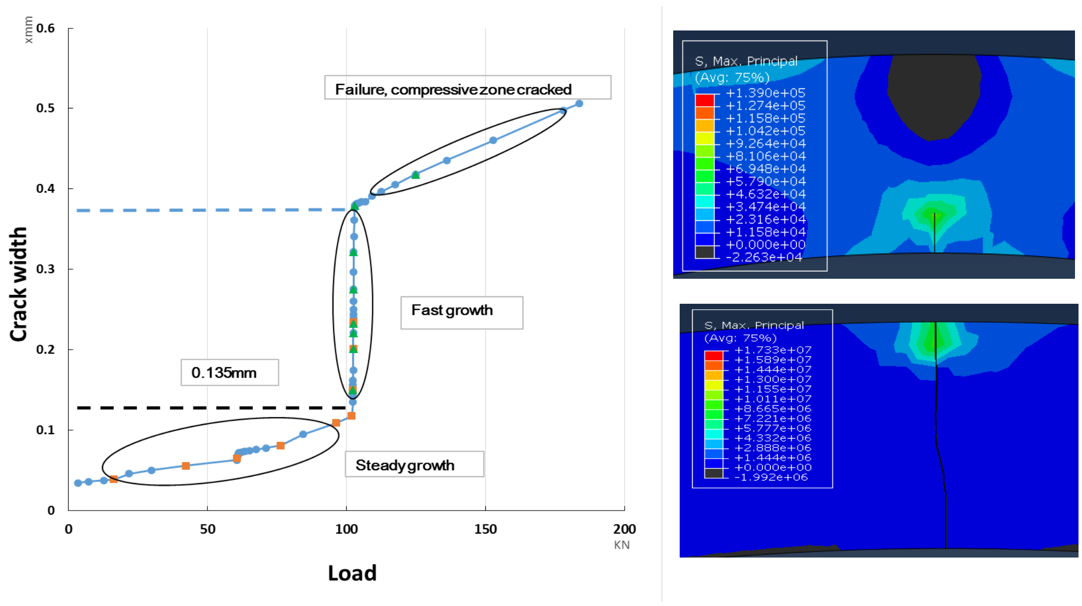

Figure 1: crack growth under overload

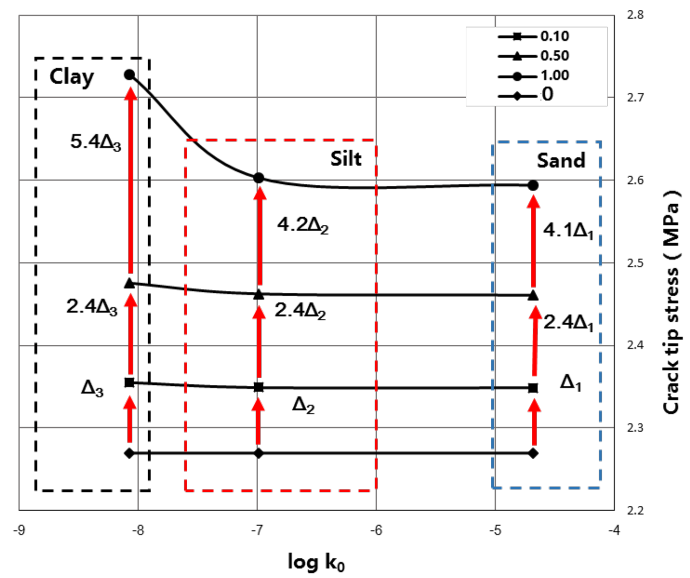

Figure 2: crack tip stress change with leakage under different surrounding soil

Numerical Analysis of Tunnel Face Stability

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The problem of face stability and deformation behavior of shallow tunnels is particularly remarkable not only for the necessity to guarantee the workmanship safety but also because it is directly related to surface deformations, at least for shallow tunnels. The occurrence of excessive face extrusion or the developing of a failure mechanism could cause significant subsidence phenomena, damaging pre-existing buildings and infrastructures.

Several experimental studies have been carried out in the past to assess the stability of an unreinforced face and different analytical or semi-empirical solutions have been formulated.

Since the number of tunnels excavated full face and with traditional techniques is increasing, an analysis of the face stability is required to avoid failure mechanisms or excessive face extrusion. One of the techniques frequently used to improve face stability and reduce deformations is face reinforcement by means of fiberglass bars. In the present work a numerical study of both unreinforced and reinforced tunnel excavation faces by means of 3D FEM analyses is presented. The results, in terms of factor of safety, are compared with those of the traditional limit equilibrium method. Finally the deformation response is assessed.

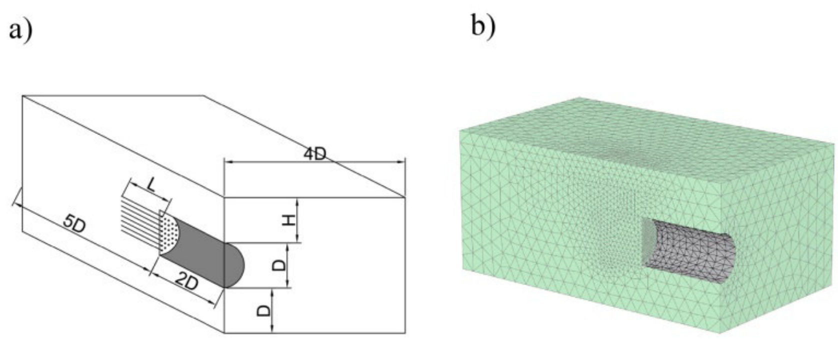

Figure 1: Model dimensions (a) and mesh adopted for the FEM calculations (b)

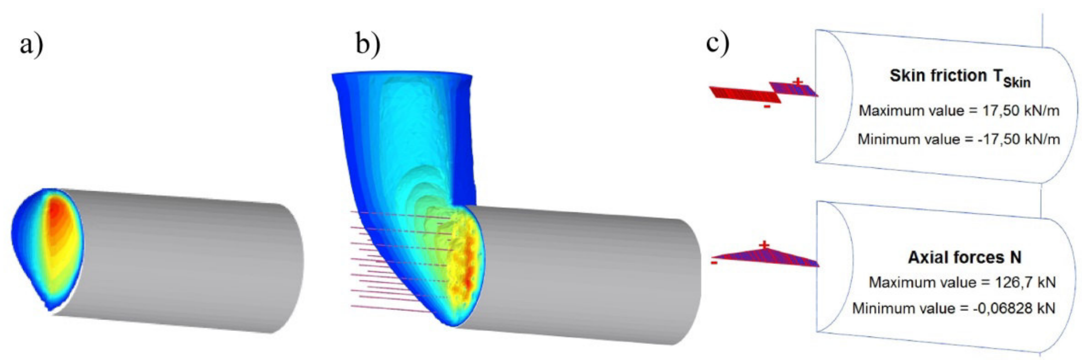

Figure 2: a) Total displacements plot for an unreinforced (a) and a reinforced face (b), skin friction and axial force on an embedded pile (c) (case c'=40, ϕ'=25°, L=D, 40 dowels, after ϕ-c reduction)

Centrifuge Modelling of Parallel Piggy-Back Tunnelling in Clay

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Key words: Tunnelling under existing tunnel, Centrifuge modelling, Field instrumentation, Fibre optics strain sensing, BOTDR, Mobilised strength design.

Advancements in tunnelling techniques and technologies have allowed tunnels to be built safely even in poor soil conditions; leading to an increased demand for more tunnels, causing the inevitable situation where tunnels are constructed very closely together. Asset impact assessment and protection is thus key, to ensure the success of the project. Conventional analyses of these problems are highly reliant upon numerical models, but the understanding of the underlying deformation mechanisms involved is not well understood, creating a high degree of uncertainty with the predicted outcomes. This imposes high level of conservatism to be incorporated in the assessment, which generally translates to time consuming and costly mitigation measures to be designed and mobilised.

A series of centrifuge tests were carried out at 100g to study the effects of new tunnelling under an existing tunnel in clay, at different clear distances. Construction of the new tunnel is modelled by an innovative three-dimensional multi staged volume loss tunnel which simulates tunnelling construction over five progressive advancements. Comparison was made to field instrumentation of a century old cast iron tunnel at London Liverpool Street Station, where a new platform tunnel was constructed 2m directly beneath it in a parallel piggyback alignment. Good agreement was observed from distributed optical fibre strain sensing (BOTDR) and centrifuge modelling data along with a proposed mobilised strength design (MSD) approach. This approach which is based on cavity contraction theory allows for a quick and realistic assessment on tunnelling imposed bending moments with minimal input parameters.

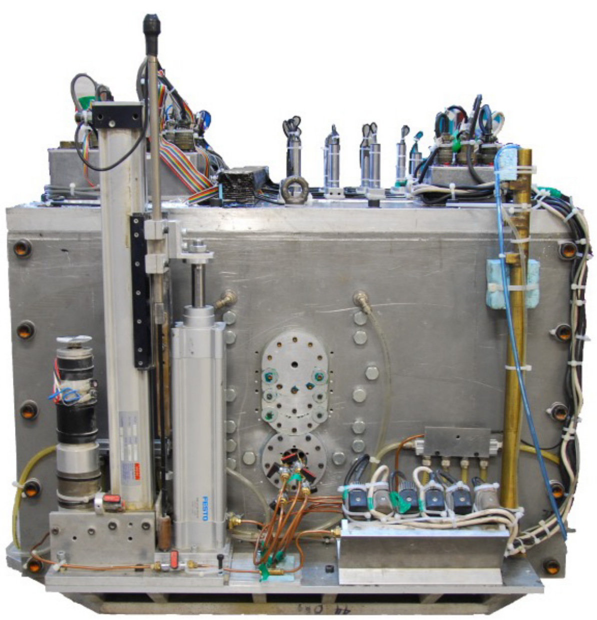

Figure 1: Front view of centrifuge package

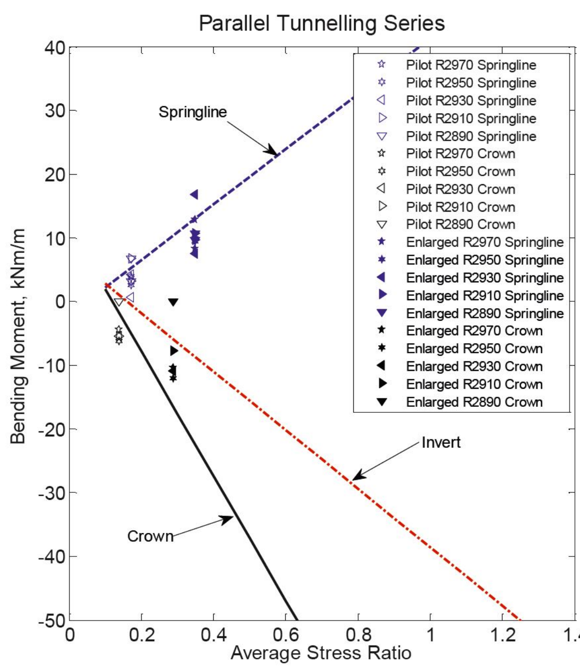

Figure 2: Correlation of MSD approach with BOTDR data

Hybrid Concrete Elements with Splitting Fiber Reinforcement under Strip-Loading

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In the mechanized tunneling the joints of segments are frequently subjected to a highly concentrated compressive force on a limited contact area (i.e. partial-area loading). The constructive design of the segment's longitudinal joints leads to a two-dimensional partial-area loading (strip-loading). Loading scenarios of this kind lead to a load diffusion beneath the loaded area. Due to the resulting deviation of the compressive stresses, large splitting stresses (perpendicular to the load direction) are generated and may exceed the concrete tensile strength. In order to resist these splitting stresses, the state of the art is to place transverse steel reinforcement in zones where the most critical splitting stresses occur. An alternative approach is to add steel fibers to the concrete mixture. Regarding economic concerns, however, it is recommended not to reinforce the entire concrete element with steel fibers, rather in zones where high splitting stresses are expected. Based on this fact, a new design concept to manufacture hybrid concrete elements has been developed.

An experimental study on the load-bearing capacity and failure mode of steel fiber reinforced concrete elements under centric strip-loading has been conducted. For this purpose, hybrid concrete specimens (50 × 25 × 50 cm³) containing both plain and fiber concretes were produced (Figure 1). The reference samples were produced only with plain concrete (PC), while the hybrid specimens were additionally strengthened with a layer of high performance steel fiber reinforced concrete (HPSFRC). The thickness and position of this HPSFRC layer has been varied in order to determine the most efficient and economic configuration of the splitting fiber reinforcement.

The test results have shown that the load-bearing capacity could be enhanced up to 200 % depending on the thickness and position of the incorporated layer of HPSFRC (Figure 2). As a fundamental finding of this experimental study it is shown that the ratio of fiber reinforcement (e.g. the thickness of the HPFSRC layer) was not solely decisive for the load bearing capacity, rather the position of the reinforcement layer according to the location of the crucial splitting stresses.

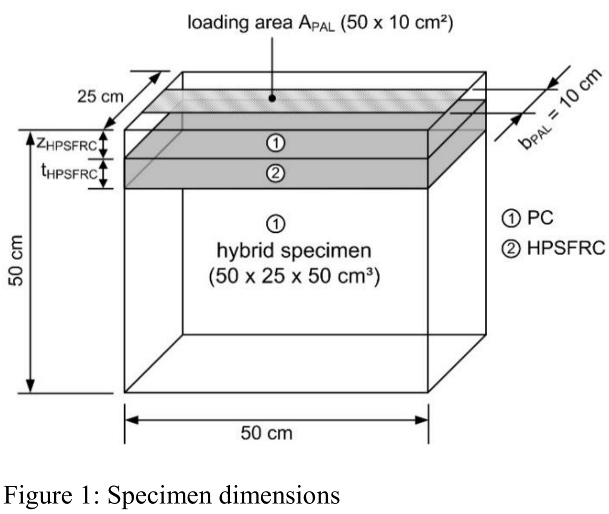

Figure 1: Specimen dimensions

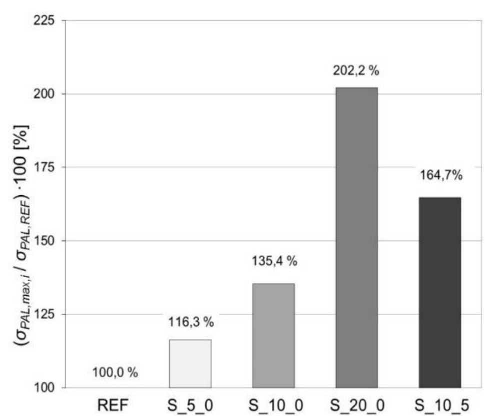

Figure 2: Percentage increase of ultimate stresses

Multi-scale Physical Model of Shield Tunnel Applied in Shaking Table Tests

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Due to the complexity of joints and the enormous volumes of segments, it is difficult to fabricate an ideal physical model for the long-distance shield tunnels. In this paper, a multi-scale method is proposed to design the test models of shield tunnels applied in shaking table tests. The proposed model is discretized into refined parts and coarse parts, i.e. segmental equivalent ring portions (SER) and equivalent uniform tube portion (EUT) respectively. The EUT model is employed to capture seismic response characteristics of the entire tunnel system, whereas the SER model is employed to describe in detail the stress and deformation responses in lining segments and joints at positions of potential damage or interest. The multi-scale model design is based on stiffness equivalence theory, and the bending stiffness of the model tunnel is evaluated through a series of numerical simulations. The proposed multi-scale physical model for shield tunnels is validated through shaking table tests, in which a full refined model is set as benchmark for comparison. The test results reveal that: the proposed multi-scale method provides an effective way for the design of complex segmental tunnel models applied in shaking table tests.

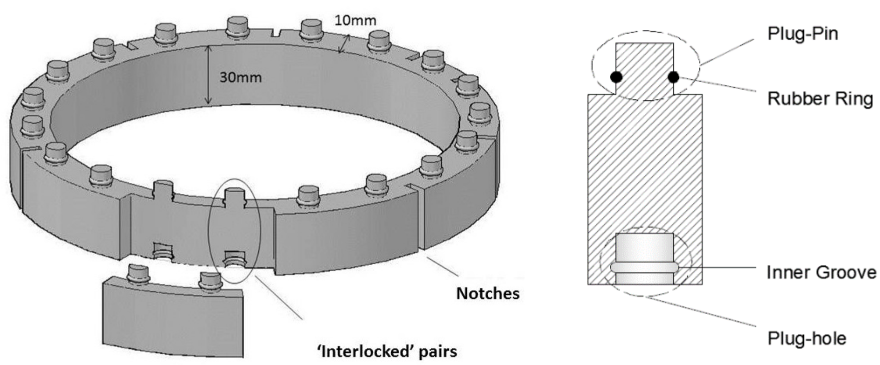

Figure 1: The design of SER rings

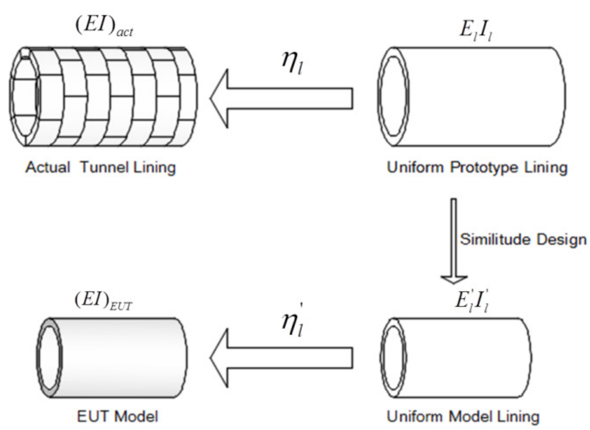

Figure 2: Design of EUT portion based on stiffness equivalence theory

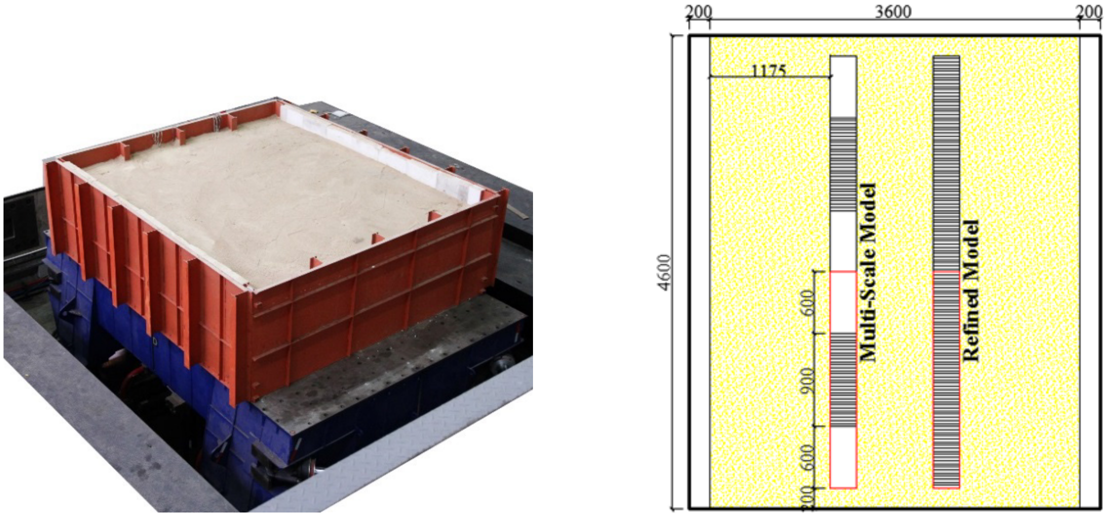

Figure 3: Verification shaking table experiment for the proposed multi-scale model

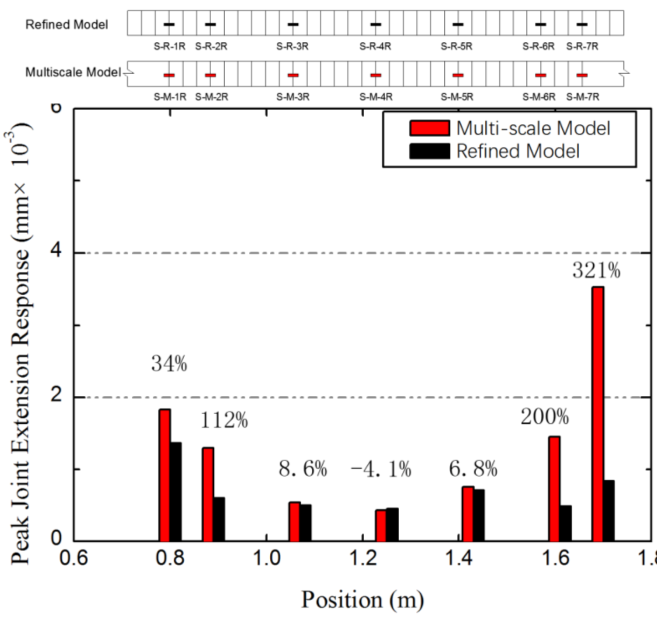

Figure 4: Test results: peak joints extension response for the multi-scale model and the full refined model

Ground and Building Response to Urban Tunnelling in Sand

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Key words: Tunnelling-induced settlement, Building damage, Soil-structure interaction, Centrifuge modelling.

Tunnel construction in an urban environment inevitably causes ground moments that interact with existing structures. Although the understanding of this complex soil-structure interaction problem during the tunnelling works has continuously improved through records of case studies and computational sensitivity analysis, industry lacks in confidence when applying design guide-lines that were drawn from this data. A potential reason for this scepticism is that previous research has not particularly focused on structural details of the buildings. Currently a research project is under way at the University of Cambridge that investigates the effect of tunnelling subsidence on realistic surface structures. The study was conducted in the form of a controlled experimental investigation, with data being gathered via a series of centrifuge modelling tests.

This presentation begins by laying out the experimental program, including the 3D printing technique adopted to replicate realistic surface structures and the simulation of the tunnelling works in dry, dense sand. It will then deal with the instrumentation used to monitor the ground and building performance. The main part of the presentation will address key findings, which are: a) The building-to-tunnel position notably affects the shape and magnitude of vertical surface soil movements while the building position had a minor influence on the soil-structure interaction restraining the horizontal ground movements. b) Nearby structures changed the volumetric behaviour of the soil above the tunnel and the amount of volume loss recorded was affected by the building geometry. c) The soil settlement trough widened due to the presence of existing surface structures. d) Structures that were spanning the hogging/sagging region of the vertical displacement profiles are more vulnerable to building distortions. e) Even greater building distortions were observed as the building length and window openings increased. f) Horizontal building strains are substantially lower than the greenfield ones. In the final part of the presentation, the obtained findings are related to current design approaches and conclusions are drawn.

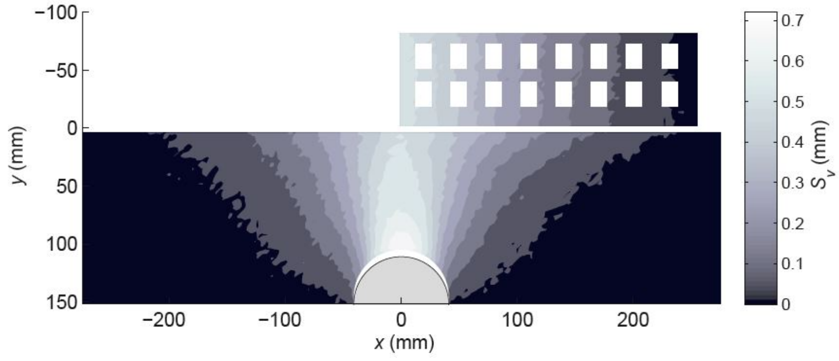

Figure 1: Vertical soil and structure displacements at a tunnel volume loss of 2.0%

Influencing Factors on Tunneling induced Building Settlements and Design of Optimal Sensor Locations

C. Zhao, R. Hölter, A.A. Lavasan and T. Schanz

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This study focuses on the influencing factors on the tunneling induced settlement and tilt of a building. The effects of soil/building properties, tunnel volume loss and embedment depth, geometrical characteristics of the system (e.g. distance between the tunnel and building) are investigated. The tunneling process is simulated by a two-dimensional finite element model and the hardening soil model is adopted to describe the soil behavior. In order to distinguish the relative importance of the system characters, global sensitivity analysis is conducted. The results obtained from global sensitivity analysis revealed the dominant effect of tunnel volume loss on the settlement of building; when the tunnel depth and the mechanical properties of the contact between building and soil notably affect the building's tilt. Nevertheless, soil friction angle governs both settlement and tilt of building. Since uncertainty is inevitably embedded in the soil parameters, updating the tunneling parameters during the construction is challenging for an adequate design of the tunnel. Thus, the position and type of sensors should be carefully selected to increase the information content of measurements for the purpose of identification and correspondingly update of soil parameters in the model. Within this framework, a field sensitivity analysis is conducted to indicate the optimal locations to install the relevant sensors.

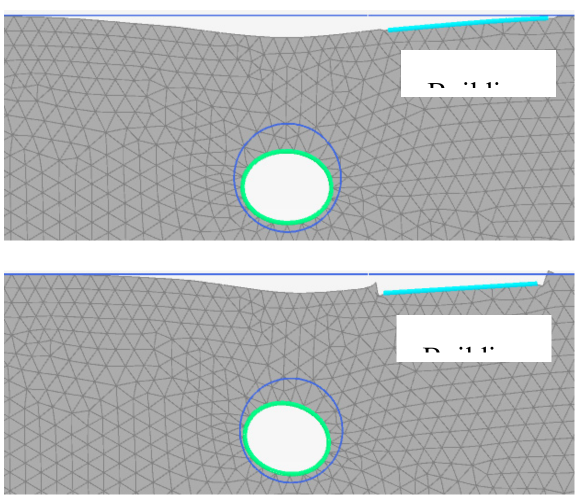

Figure 1: Deformed mesh of the numerical model due to tunnel excavation

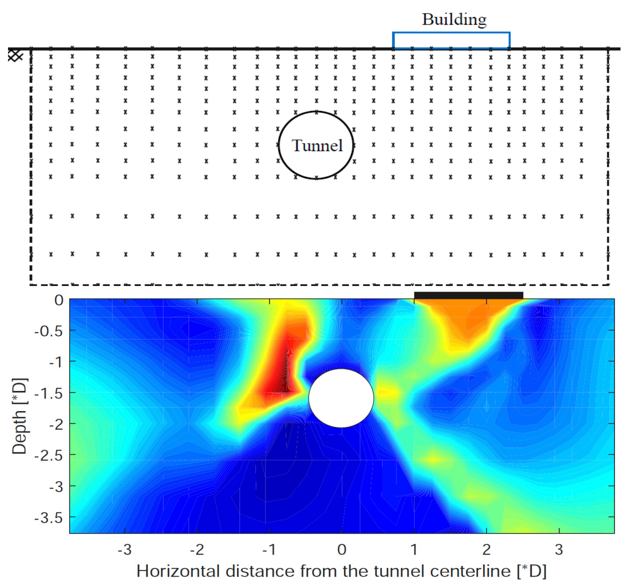

Figure 2: Distribution of synthetic measurement points (up) and sensitivity field for vertical displacements towards friction angle (down)

Stochastic Analysis of Polymer Composites Failure Modeled by a Phase Field Method

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Key words: Phase field method, crack nucleation, Monte Carlo simulation, polymer composites, hyperelasticity, large deformations

Carbon black reinforced natural rubber is a composite material that is increasingly being used in engineering applications. Detailed knowledge of the relationship between the composition of reinforced rubber and its fracture toughness is important for analysis and design of various engineering systems. To this end, a phase field method is then employed to simulate damage nucleation and propagation under quasi-static loading. The phase field hyperelastic model is validated on a set of experimental data available in the literature shown in Fig.1 and Fig.2. To quantify the uncertainty in the failure of these materials, a Monte Carlo simulation is carried out with random ellipsoidal particles distribution. A rigorous stochastic analysis reveals the statistical distributions corresponding to the rupture of polymer composites and provides insight into better design of these materials.

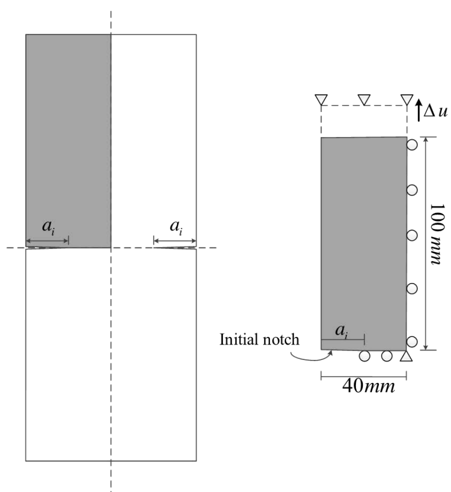

Figure 1: Geometry of the benchmark example with double-edge notches and its boundary conditions.

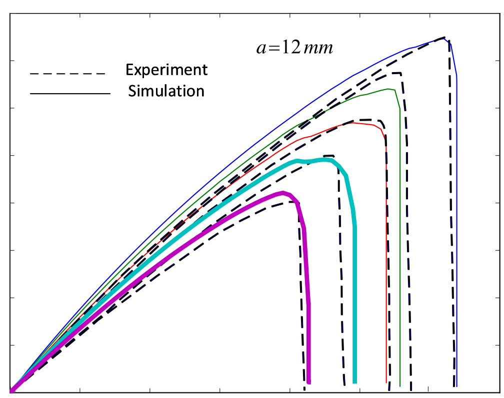

Figure 2: Snapshots of the rupture of a double edge notch specimen with initial notch length of a=12 mm.

Fibre Optic Monitoring and Modelling of a Deep Excavation Adjacent to Existing Tunnels

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Underground construction in congested urban environment has been increasingly challenging over recent decades. To ensure construction safety, distributed fibre optic sensing (DFOS) is emerging as an innovative monitoring tool for continuous strain measurement of underground structures (e.g. diaphragm wall (D-wall)). To monitor a D-wall, a fibre optic strain cable is usually instrumented along a reinforcement bar to obtain the strain distribution, along with a standard telecom cable for temperature compensation.

In this study, behaviour of a diaphragm wall was monitored using DFOS during deep excavation for a train station. This train station was constructed using top-down excavation method where two existing tunnels underneath the site was demolished during construction. The strain development in the D-wall was recorded at each excavation stages. In particular, the analysis of DFOS measurements evaluated the influence of the existing tunnels on the D-wall behaviour along with results from inclinometer data and 3D finite element simulations.

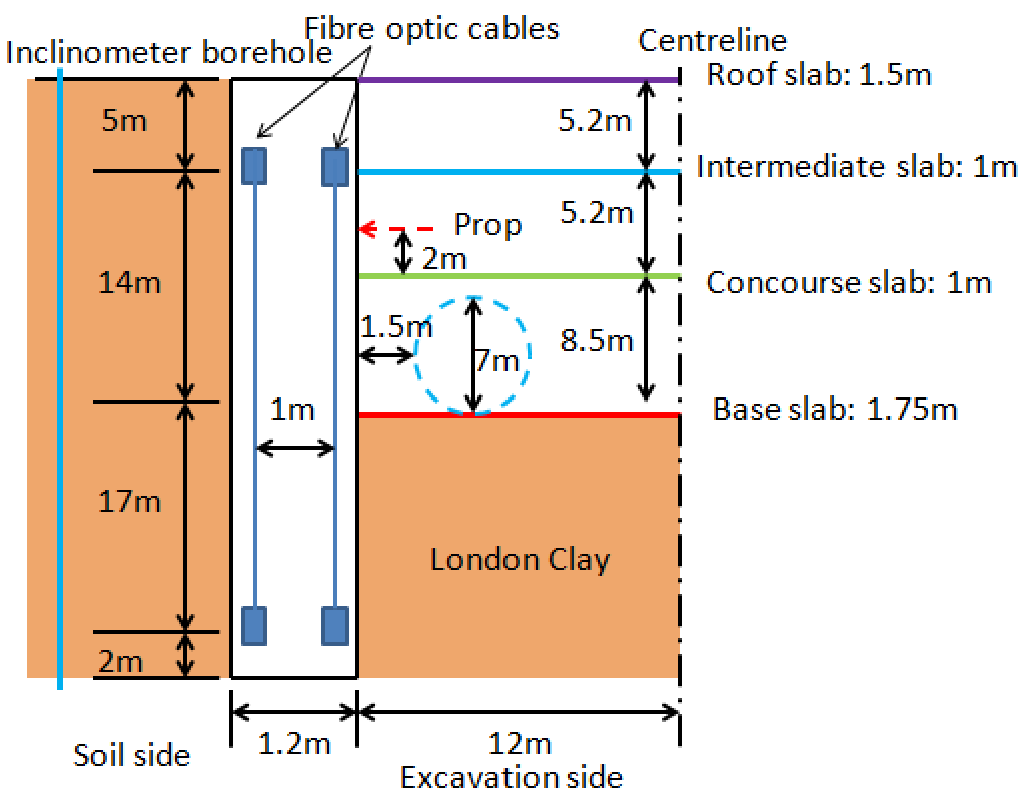

Figure 1: Diaphragm wall main box at Paddington Station (not to scale)

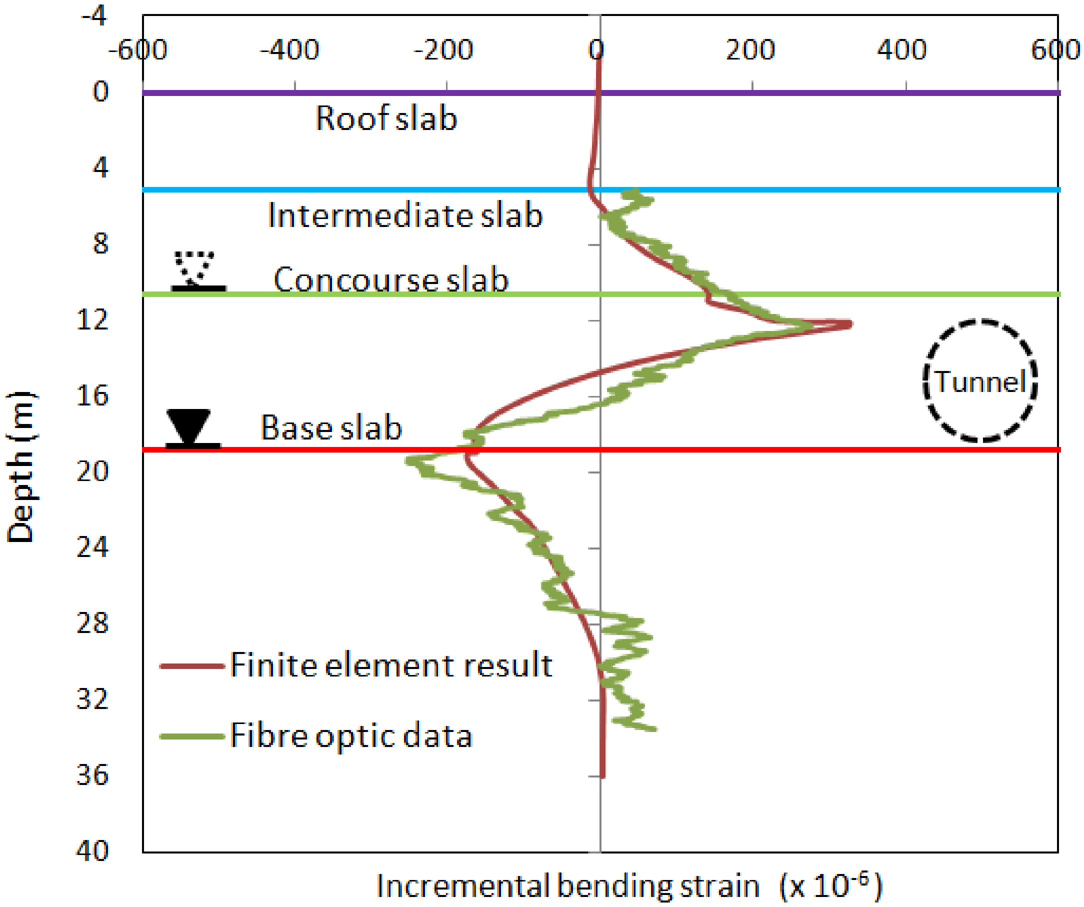

Figure 2: Bending behaviour of the D-wall during concourse excavation

BIM-to-FEM: Incorporating Numerical Simulations into BIM Concepts with Application to Real Tunneling Projects

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Finite element (FE) simulations are an integral element of the planning and design process for mechanized tunneling projects. The models needed for these simulations are typically manually generated using 2D-CAD drawings, which is a laborious and time-consuming process. Recent trends incorporating Building Information Modeling (BIM) concepts offer opportunities to simplify this process by using geometrical BIM sub-models as a basis for performing structural calculations. However, considerable problems occur in transferring structural data, such as geometrical boundary conditions, to the FE-model. This work presents a novel "BIM-to-FEM" technology, that automatically extracts the relevant information (geology, alignment, lining, material and process parameters), needed for a FE-simulation from BIM sub-models and subsequently performs an FE-analysis of the tunnel drive. The necessary boundary conditions and construction sequences are automatically incorporated based upon the design data. This simplifies the information flow and limits errors that jeopardize the structural analysis. The results of the analysis are stored centrally on a data server to which the user has continuous access. A case study from the Wehrhahn-Line metro project in Düsseldorf, Germany, is presented and discussed to demonstrate the efficiency and the applicability of the proposed BIM-to-FEM workflow. Both the design and the construction stages are considered.

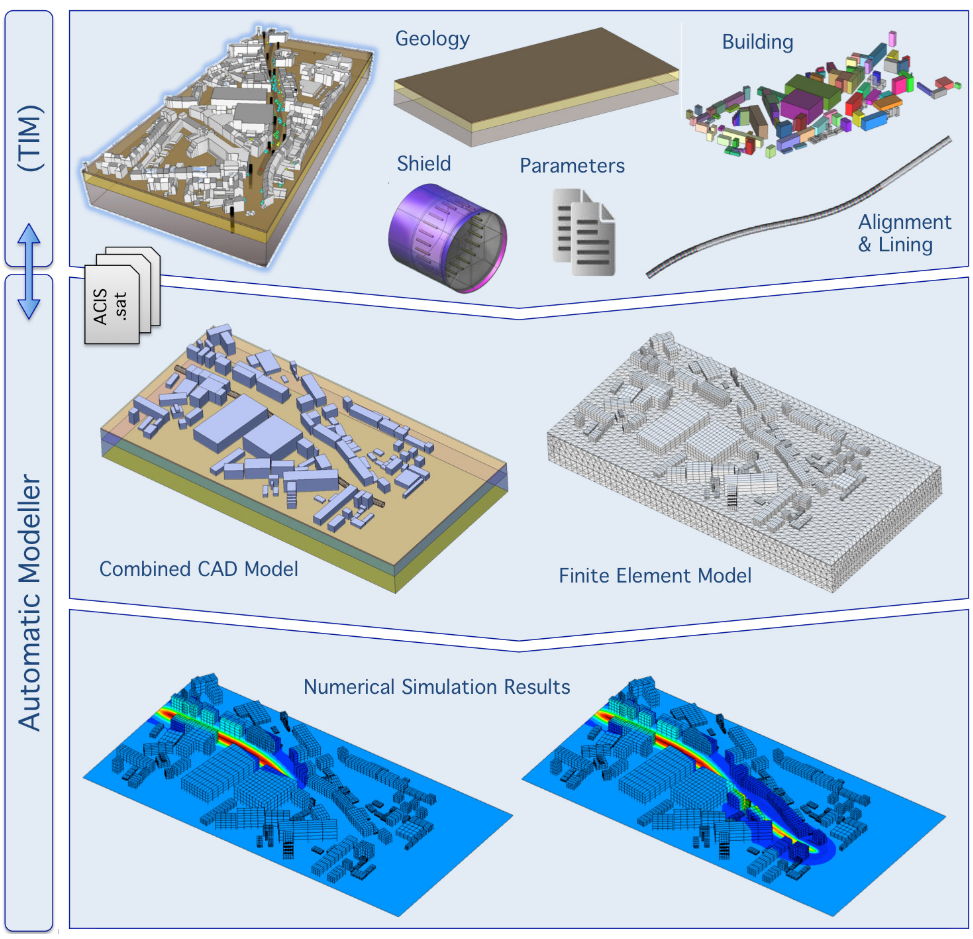

Figure 1: Interaction schematic of the TIM interacting with the automatic modeler for WHL project

Nonlinear Numerical Simulation for the Mechanical Behavior of Shield Tunnel Linings Strengthened by Epoxy-Bonded Filament Wound Profiles

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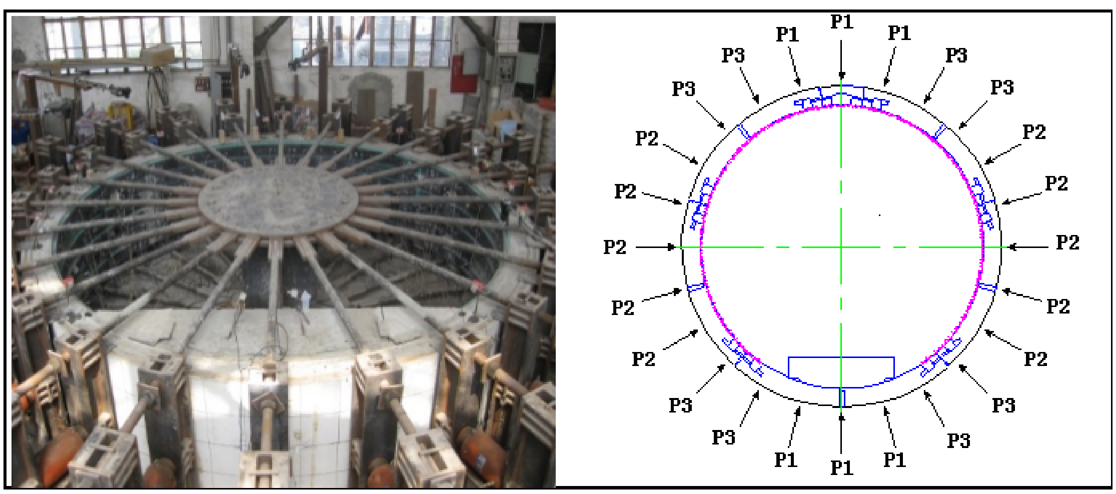
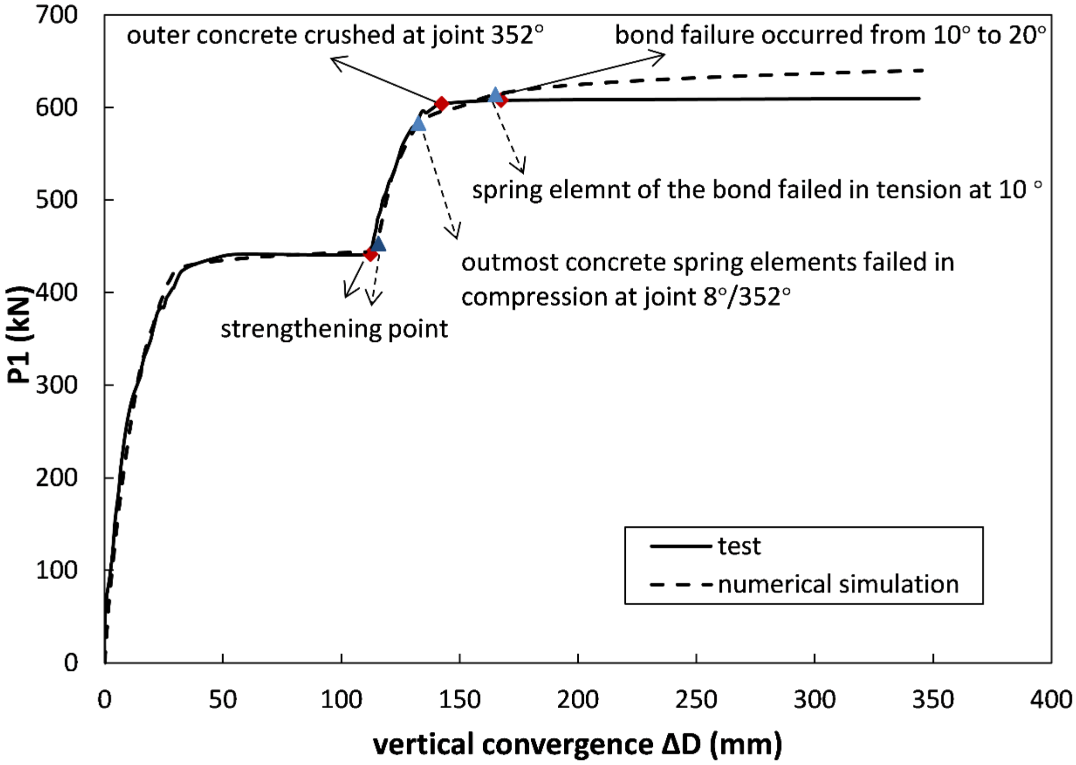
Shield tunnels are environmentally friendly and mechanically effective. Shield-driven tunneling has been used extensively for more than 50 years. Large structural deformations may occur if the tunnel is subjected to unfavorable loading conditions concerning the underground soil. As a remedy, an efficient strengthening method was proposed. It is based on epoxy-bonded filament wound profiles (FWP). This method has proven to be safe and easy to be applied. Full-scale experiments were conducted in order to investigate the mechanical behavior and the failure mode of structures strengthened by means of this method. In this paper, a highly-efficient simplified numerical model was adopted for investigating the nonlinear response of shield tunnels strengthened by epoxy-bonded FWPs. Fiber-beam elements were used to simulate the concrete segments and the FWPs, while discrete-beam elements were applied for the simulation of the joints of segmental linings as well as of the bond between the FWPs and the concrete segments. A comparison between the numerical results and the experimental results from the full-scale tests was performed to validate the developed model. The nonlinear load–deformation response and the failure mechanism were captured and interpreted.





outer concrete crushed at joint 352°
bond failure occurred from 10° to 20°
spring elemnt of the bond failed in tension at 10 °
outmost concrete spring elements failed in compression at joint 8°/352°
strengthening point
test
numerical simulation
P1 (kN)
vertical convergence ΔD (mm)
0
100
200
300
400
500
600
700
0
50
100
150
200
250
300
350
400

Notes

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SFB 837 - Interaction Modeling in Mechanized Tunneling

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