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Deutsche Forschungsgemeinschaft
Dr.-Ing. Holger Eggemann
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München, 25. Juli 2022
Unser Zeichen: Sn/Cu

Antrag auf Gewährung einer Sachbeihilfe
Experimentelle Untersuchung zur Eislinsenbildung in gefrorenen Böden

Sehr geehrter Herr Dr. Eggemann,

beiliegend erhalten Sie unseren Antrag zur Gewährung einer Sachbeihilfe für die Bearbeitung der Themenstellung „Experimentelle Untersuchung zur Eislinsenbildung in gefrorenen Böden“.

Wir danken den Gutachtern für die Prüfung unseres ersten Antrags (Ersteinreichung, CU 363/5-1) und die konstruktive Kritik. Wir haben die Anmerkungen und die Verbesserungsvorschläge sorgfältig geprüft und entsprechende Änderungen, Ergänzungen und Klarstellungen vorgenommen. Die Änderungen und Ergänzungen haben wir zu besseren Übersicht gelb markiert. Gemäß der Abstimmung mit Ihnen haben wir zudem ein Begleitschreiben an den zweiten Gutachter zur ausführlicheren Beantwortung seiner Anmerkungen verfasst.

Wir freuen uns auf eine baldige Rückmeldung und natürlich auch auf die Unterstützung der Gutachter und der DFG für die Realisierung dieses mit großer Sorgfalt geplanten Forschungsvorhabens.

Für Fragen und zusätzliche Erläuterungen stehen wir Ihnen gerne zur Verfügung.

Freundliche Grüße

Prof. Dr.-Ing. R. Cudmani

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Project Description – Project Proposals

Prof. Dr.-Ing. Roberto Cudmani, Zentrum Geotechnik, Technical University of Munich

Experimental investigation of ice lens formation in frozen soils

Project Description

Sections 1-3 must not exceed 17 pages in total.

1 Starting Point

Ground freezing is an environmentally friendly construction technique used to temporarily increase the stiffness and strength of the subsoil and provide water tightness. It can be implemented effectively in urban conditions where the risk of using other subsoil improvement, water tightening and dewatering techniques can be high due to complex or partially unknown boundary conditions and the consequences of damage (Orth, 2018).

A major risk of ground freezing concerns the change of the pore volume and the associated soil deformations that can be induced by pore water freezing and thawing. From a physical point of view, the volume changes during ground freezing have two different sources: 1) increase of volume of the frozen in comparison to the unfrozen water, and 2) the formation of ice lenses during freezing. Owing to the negative thermal expansion property of water, the density of water is 9% greater than that of ice and equally, the volume of ice is greater than that of water. Thus, the freezing and thawing processes during ground freezing applications result in volume increase (heave) and decrease (settlements). The volume changes due to the negative thermal expansion property of water can be satisfactorily predicted with existing models (e.g. (Zhou and Meschke, 2013)).

The second source of pore volume changes, i.e., the formation and propagation of ice lenses, is largely attributed to the tendency of ice to actively expel embedded soil particles in the presence of a thermal gradient (i.e., thermal regelation). This leads to the separation of the ice and soil phases in the form of a series of discrete bands of pure ice interspersed by frozen soil layers. The physics of ice lens formation is much more complex than negative thermal expansion. Despite the considerable efforts of the research community, its controlling mechanisms are not yet completely understood (Peppin and Style, 2013). Semi-analytical and semi-empirical prediction methods of frost heave, originally developed four decades ago, are still commonly used to estimate ice lens formation as well as frost heave in ground freezing applications, due to the lack of physically based mathematical models and sophisticated numerical solutions (Zhou et al., 2021).

The extent to which the formation of ice lenses impacts the increase of pore volume during freezing depends principally on the permeability of the soil, the freezing rate and also the drainage conditions. Ground freezing experience shows that pore volume changes during freezing are negligible for coarse soils, such as medium and coarse sands and gravel with very low fine content. However, the susceptibility of soils to form ice lenses increases significantly with increasing fine content. Principally for this reason, the practical application of ground freezing has so far been largely limited to fully saturated alluvial coarse grained soils (e.g. (Orth, 2018)). Nevertheless, even in the case of coarse-grained soils, the risk of volume changes in the frozen region must be taken in account, as alluvial soils are heterogeneous in nature. Thus, they often contain fine-grained soil lenses and zones with varying fine content, which are susceptible to ice lens formation.

In the past decades, damage to surrounding infrastructure due to ice lens formation and related frost heaving has been repeatedly reported in connection with ground freezing measures. For instance, significant heaving of the ground surface was observed during subway constructions supported by ground freezing techniques in Munich (Fillibeck et al., 2005) and Kobe, Japan (Konrad, 2002). More recently, the adverse effects of ice lens formation became evident during ground freezing for a tunnel construction in Rome (Pingue, 2019) and the construction of the new underground station Museumsinsel in Berlin (Vogelsang et al., 2021; Brenner et al., 2019). In both cases, the unexpected ground heave of up to 100 mm led to enormous construction delays and necessitated extremely expensive countermeasures to protect the surrounding historic buildings. From a practical standpoint, these and other historical cases clearly highlight the need to improve our fundamental understanding of the mechanisms of ice lens formation. In addition, the development of advanced and comprehensive modelling and mathematical tools to predict the ice-soil phase separation and the resulting soil deformations are urgently required. Particularly, the mathematical models should be able to capture the rearrangement of the grain skeleton and damage of the soil microstructure induced by alternating freezing and thawing (Kong et al., 2020; Konrad, 1989; Tian et al., 2019). For example, a reduction of macroscopic shear strength and stiffness after freeze-thaw cycles and also cracking has been observed for clays (Wang et al., 2018; Zhou and Tang, 2018). Similarly, laboratory and field investigations by (Konrad, 2002) showed that the heave due to ground freezing is smaller than the settlement after thawing.

Therefore, the ultimate goal of our fundamental research is to develop a comprehensive mathematical model to simulate ice lens formation and predict the elastoplastic soil deformation induced by freezing and thawing. This goal will be achieved in a solely experimental phase (phase I) and an experimental-numerical phase (phase II) with a duration of three years per phase.

This proposal focusses on the experimental investigation of the formation and propagation of ice lenses during freezing as well as on the induced heave (phase I).

In phase I, we plan a comprehensive experimental program to observe, understand and quantify the different underlying mechanisms of ice lens formation. The experimental data will subsequently be used in phase II to develop and validate the numerical model. The specific goals of phase I are:

- To develop a novel, highly advanced test setup to trace ice lens formation spatially and temporally with high-resolution for soils with different susceptibility to ice lens formation (low: fine sand and sandy silt; medium: sandy clay; high: silty clay)
- To study the influence of structure degradation and cracking depending on the soil susceptibility to ice lens formation
- To comparatively observe ice lens formation in the investigated soils for three different temperature boundary conditions (step-, cyclic- and ramp-freezing)
- To determine the volumetric soil deformations for soils with different susceptibility to ice lens formation and under different temperature boundary conditions
- To investigate the similarity of the soil freezing curve (SFC: unfrozen water content dependent on the temperature) determined by means of Nuclear Magnetic Resonance (NMR) tests with the soil water retention curve (SWRC) of the partially saturated unfrozen soil. The soil freezing curve is key for the solution of the THM-problem
- To determine the tensile strength of partially frozen and unfrozen soils at temperatures close to the freezing point, and relate this tensile strength to crack initiation during freezing.

Later, phase II will focus on the development and validation of a novel numerical approach to model ice lens formation and frost heave. It will also include supplementary, more advanced experimental investigations, e.g. the heave and settlement caused by freeze-thaw cycles. The proposal for phase II will be prepared and submitted in collaboration with Prof. Barbara Wohlmuth, Chair of Numerical Mathematics of the Technical University of Munich (TUM). Prof. Wohlmuth's group is currently carrying out preliminary work required to demonstrate the feasibility of her novel mathematical approach to solve the nonlinear differential equation governing the multi-physical problem. Furthermore, the preliminary work will demonstrate its advantages in comparison to the existing approaches based on the Finite-Element Method. The submission of the proposal for phase II is planned during phase I (this project).

1.1 State of the art and preliminary work

1.1.1 State of the art

1.1.1.1 Ice lens formation

For a long time, frost heave was exclusively attributed to the increase in volume as the density of water is approximately 9% higher than that of ice. The experiments of Taber (e.g. (Taber, 1930)) provided the first conclusive evidence that frost heave is primarily related to water flow from unfrozen regions to the frost front (i.e., the boundary between the frozen and unfrozen regions). According to our current understanding, water from the unfrozen soil typically migrates towards the frost front where it freezes into pure ice crystals, leading to a formation of discrete ice lenses (See Fig. 1 and Fig. 2). The ice lenses force the soil particles apart as they grow, which results in an increase of the total solid volume and, under one-dimensional conditions, in heaving of the surface upwards. With sufficient water supply to the frost front and sustained temperature gradients, this process can continue indefinitely and therefore, cause almost an unlimited heaving of the soil surface.

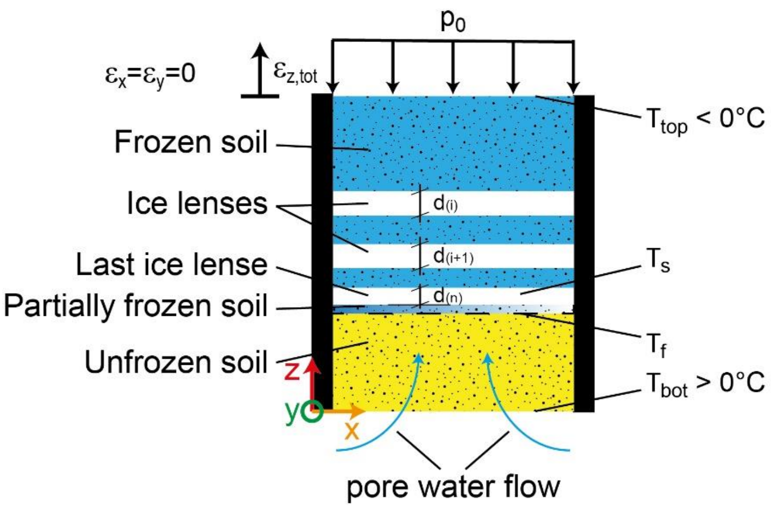

Fig. 1: Schematic view of ice lens formation *

Fig. 2: Ice lens formation observed after a freezing test at Zentrum Geotechnik

* T_{top} and T_{bot} denote the top and bottom temperature boundary conditions, T_s the temperature of the last ice lens, T_f the frost front temperature (which is the same as the bulk freezing temperature T_m) and p_0 the vertical stress. The partially frozen soil is a transition zone where ice and pore water coexist. Ice lenses are the pure ice layers, the last ice lens is closer to transition zone and has not achieved the final thickness yet.

The formation of ice lenses is a complex physical process depending on the granulometric properties of the soil, which determine the permeability, the confining stress as well as the thermal and freezing conditions:

- *Particle size distribution and fine content.* Soils with higher fine content are more susceptible to ice lens formation (Konrad and Lemieux, 2005).
- *Proximity to water reservoir.* Sufficient water migration towards the frost front is necessary to ensure the separation of the ice layer from the soil (Bronfenbrener and Bronfenbrener, 2010)
- *Freezing rates.* Lower freezing rates (i.e., slow moving frost fronts) allow higher water migration towards the frost front and accelerate ice lens formation. On the contrary, if the freezing rate is high enough or intermittent/cyclic freezing is used, ice lens formation may be significantly reduced (Zhou et al., 2009)
- *Confining stresses.* The ice lens formation and the frost heave rates decrease with increasing mean effective stresses (Konrad and Morgenstern, 1982)
- *Thermal boundary conditions and temperature gradients*. Higher temperature gradients lead to larger ice lenses (Penner, 1972). The thermal boundary conditions for freezing (e.g., constant temperature, or constant freezing rate, etc.) affect the type of ice lenses formed (see Sec. 1.1.1.2).

On the pore (micro)scale, five main mechanisms contribute to the formation and growth of ice lenses, 1) freezing point depression and the formation of the *frozen fringe* (i.e., partially frozen zone), 2) *cryostatic suction* (i.e., the pressure difference across the ice-water interface), 3) *De-structuration* and *cracking*, 4) pore ice motion by *regelation* (i.e., pressure/stress melting), and 5) fluid *micro-films*.

Frozen fringe: In the pore spaces, the curvature effects, bonding forces (e.g., adsorption), and chemical components (e.g. salinity) affect the free energy in water leading to a localized depression of the freezing point temperature. This means that a significant amount of water may remain unfrozen in the vicinity of the frost front even at temperatures below the bulk freezing temperature T_m (0°C under atmospheric conditions). In general, bulk water freezes first (highest freezing point), followed by capillary water and even at lower temperatures (strongly) bounded (osmotic) water begins to freeze (Chai et al., 2018). Many experimental studies (e.g. (Smith and Tice, 1988)) have shown that in clays a significant amount of unfrozen water exists even at temperatures below -10°C. In contrast, most of the pore water in gravels, sands and low-plastic silts freezes at temperatures very close below 0°C. Furthermore, there exists a hysteresis-like behaviour of the amount of unfrozen water in the soil freezing and thawing curves, similar to the characteristics of unfrozen unsaturated soils in drying and wetting curves. The presence of unfrozen water implies that the interface between the frozen and unfrozen zones is not sharp. Instead, there exists a transition (or 'mushy') zone where water and ice co-exist in the same pore space. In literature, this zone is commonly referred to as the *frozen fringe* (Miller, 1972) (see Fig. 1). Naturally, the amount of unfrozen water in the frozen fringe follows the temperature gradient (i.e., maximum in the unfrozen zone, decreases with decreasing temperature within the frozen fringe, and approaches close to zero in the frozen zone). Due to the decreasing unfrozen water content the hydraulic conductivity reduces also rapidly with lowing temperature until the soil becomes practically impermeable in the frozen state (Kurylyk and Watanabe, 2013; Watanabe et al., 2010). The sudden change of hydraulic conductivity by up to four orders of magnitude mainly occurs inside the temperature range from -0,2 °C to -0,5 °C as reported by (Watanabe and Osada, 2017).

Cryostatic suction: In the frozen fringe, the surface tension of the curved meniscus between the co-existing pore ice and pore water leads to a drop in the pore water pressure due to capillarity. This pressure drop creates a hydraulic gradient which induces a water flow from the unfrozen regions to the frost front (Everett, 1961). The process of cryostatic suction is similar to the capillary rise of water into a dry porous medium.

De-structuration and cracking of fine-grained soils during freezing: The development of tensile cracks during freezing and thawing of kaolin, clayey silt and silty/sandy clay has been reported in the literature (e.g. (Azmatch et al., 2012; Jang and Cha, 2021; Nishimura et al., 2021; Sweidan et al., 2021; Wang et al., 2018; Zheng et al., 2020; Liu and Santamarina, 2022). Several factors as the soil type/grain size distribution, mineralogy, freezing temperature, freezing speed and stress state of the soil control crack formation. On the one hand, clays are very susceptible to damage/changes in microstructure (Lu et al., 2016). On the other hand, cracking has not been reported in freezing/thawing tests on sands and silts with non-plastic fines (Herzog and Boley, 2013; Kellner, 2007; Konrad, 1989; Zhou et al., 2014). Konrad (1989) argues that in silts where the coarser-grained particles control the packing (silt with low clay content), structural changes in the soil during freezing/thawing are negligible if the cyrostatic suction does not exceed the maximum past consolidation stress of the soil. To the best of our knowledge, the current understanding is that cracks parallel and perpendicular to the direction of the thermal gradient start to develop in the unfrozen and partially frozen soil due to local exceedance of the tensile strength induced by the cyrostatic suction. Cracks lead to a significant increase of the permeability of the soil with respect to the undisturbed state, which enables water to flow more rapidly to the currently forming ice lens. As the frost front penetrates, the unfrozen water freezes completely shutting of the water supply through the developed cracks. The observed vertical ice lens 'veins' (Azmatch et al., 2012; Peppin and Style, 2013) support the idea of de-structuration and cracking of fine-grained soils during freezing. So far, only few attempts to describe crack initiation for frozen soils can be found in the literature. For instance, (Azmatch et al., 2012) proposed a crack initiation criterion based on stress, strain and temperature. In comparison, crack initiation in fine-grained soils during shrinkage, which presents many similarities with the crack formation in frozen soils, has been extensively investigated and crack initial criteria have been proposed (e.g., (Peron et al., 2009; Vogel et al., 2005; Zeh and Witt, 2006)).

Thermal regelation: Due to differential (normal) pressures between ice and soil particles under a thermal gradient, ice in the frozen zone flows around soil particles through a process of melting and refreezing, thus aggregating into soil-free ice mass, i.e. into ice lenses (Gilpin, 1979).

Fluid micro-films: Massive ice lenses and even multiple secondary ice lenses are often observed, even though the formation of pore ice should render the porous soil matrix impermeable (cutting off water supply). Microscopically-thin films of unfrozen water (also termed as *surface-melted* or *pre-melted* fluid) exist between ice and soil particle surfaces at temperatures below the freezing point T_m (Dash et al., 2006). These micro-films provide a flow path within the frozen soil mass along which water can transport from the partially frozen regions to the base of the ice lens, thereby, making possible the growth of ice lenses.

1.1.1.2 Experimental investigation of ice lens formation

Experimental investigations of frozen soil can be divided into two categories: 1) global observations of deformations over time (macro pore scale) during freezing, and 2) research of single (isolated) mechanisms that drive ice lens formation in a meso/micro pore scale.

Freezing tests (macro pore scale):
Despite a vast amount of research, testing devices to study ice lens formation have not been significantly improved over the last decades (Huang et al., 2020; Zhang et al., 2014). The frost heave characteristics and mechanisms of frozen soil have been usually investigated under 1D freezing conditions in hydraulically open and closed systems, i.e. with and without connection of the soil sample to a free water reservoir. The recent studies mostly differ in sample sizes, freezing directions, thermal gradients and load level. Mainly, two types of freezing boundary conditions have been used in the tests, 1) the *step-freezing*, and 2) the *ramp-freezing*.

Step-freezing: In these tests, the temperature at the warm and cold boundaries of the specimen are held constant (see Fig. 3). During the initial transient freezing phase, there are no visible ice lenses due to the high frost penetration rate. As the rate of frost penetration reduces, very thin and barely visible ice lenses begin to develop. Eventually, the location of the frost front does not change anymore due to the constant-temperature boundary conditions and a major (final) single ice lens grows. The *intermittent/cyclic-freezing* test is a special type of step-freezing test. The warm side (T_{bot} in Fig. 1) is held constant during the entire test duration and the temperature of the cold side of the specimen (T_{top} in Fig. 1) is changed cyclically. Cyclic-freezing slows down the growth of the final ice lens and, thus, the overall frost heave can be significantly reduced. For this reason, intermittent-freezing based on empirical rules is commonly used in practice to reduce frost heave due to ground freezing (Fillibeck et al., 2005; Vogelsang et al., 2021). Laboratory investigations on cyclic-freezing carried out by Zhou et al. (2009) indicate that for a harmonic temperature-time history the amplitude and the frequency have a significant influence on the speed of ice lens formation. However, a systematic method to control ice lens formation during ground freezing based on these findings has not been presented neither by Zhou et al. (2009) nor elsewhere in the literature.

Ramp-freezing: The temperature at both cooling plates changes uniformly with a certain freezing rate to produce a fairly constant rate of frost penetration (see Fig. 3). The frost front continuously penetrates into the soil specimen. Therefore, no last (final) ice lens forms. Ramp-freezing tests are very time consuming and require sophisticated temperature control units (Konrad, 1994). Therefore, there are significantly fewer reports in the literature about ramp-freezing tests (e.g. (Penner, 1986; Zheng et al., 2020) compared to step-freezing tests, although ramp-freezing tests, especially at very small cooling rates, provide ideal conditions to study the mechanisms of ice lens formation and propagation in frozen soils (Penner, 1986).

Freezing tests (meso/micro pore scale):
Generally, the emphasis in these freezing tests is on the isolated investigation of a single (mostly thermo-hydro) mechanism that induces ice lens formation as unfrozen water content, hydraulic conductivity, development of cryostatic suction, etc. (Chai et al., 2018; Kong et al., 2020; Tian et al., 2019; Zhang et al., 2015; Jang and Cha, 2021). The soil is usually tested under isotropic

freezing and thawing. Furthermore, the samples are not connected to a free water reservoir, and for this reason, the typical ice lens formation and significant volume increase during freezing under the constant thermal gradient shown in Fig. 3 do not occur.

To the best of our knowledge, there are currently no comprehensive combined macro and meso/micro scale experimental databases for a wide range of different soils types under all three essential temperature boundary conditions which can resolve ice lens formation and the related phenomena for ground freezing applications. To this end, we are convinced that our project is an important and impactful contribution.

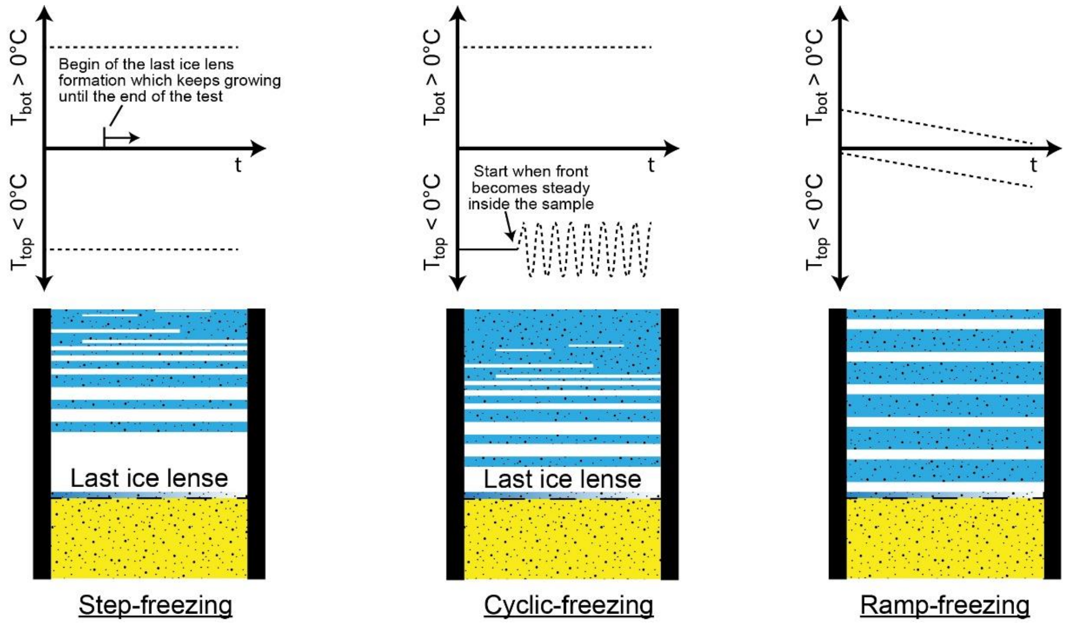

Fig. 3: Typical ice lens distribution observed in different testing conditions

1.1.1.3 Modelling ice lens formation and frost heave

The main modelling approaches for frost heaves can be divided into two main types: 1) empirical and phenomenological models, and 2) first-principle models.

Empirical and phenomenological models are based on laboratory test results which relate the change of the pore volume to the temperature and stress conditions (e.g., (Zhou et al., 2021)). Such models are commonly used in thermo-mechanical simulation of soil freezing to make prediction of frost heave in geotechnical applications of ground freezing. A well-known example of this type of models is the segregation-potential (SP) model (Konrad and Morgenstern, 1981). As the underlying physical mechanisms are not generally captured by these models, extrapolating the empirical relationships, mostly determined under rather simple one-dimensional freezing conditions, to complex three-dimensional field conditions involves large uncertainties. This is the main limitation of these phenomenological material models when used to solve real boundary value problems.

First-principle models apply the principles of thermodynamics in combination with the mass, momentum and energy conservation equations to derive continuum models of the heaving process with varying degrees of macro- and micro-scale details. The models proposed by (Casini et al., 2016; Amiri et al., 2021; Sweidan et al., 2021)) consider the cryostatic suction as the main driver for frost heaves. These models, also referred to as *hydrodynamic models*, can capture the occurrence of frozen fringe and the cryostatic suction effects, but fail to capture the separation of ice and soil particles leading to the initiation and propagation of ice lenses. These models can be combined with empirical and phenomenological models to define segregation criteria to model ice lenses at the frost front to some extent, but this approach fails to explain the occurrence of multiple ice lenses for general boundary conditions, forming in the frozen zone at some distance from the frost front. Other models, also referred to as *rigid ice models*, (e.g., (Fowler and Krantz, 1994)) included the thermal regelation mechanism, which can explain the formation of multiple ice lenses, but only to a limited extent in 1D settings.

A comprehensive experimental database for soils with different susceptibilities to ice lens formation under different temperature boundary conditions (see Fig. 3) is missing, though it is essential for the validation of advanced first-principle mathematical models. For this reason, models as those proposed by Casini et al. (2016) and Sweidan et al. (2021) cannot be comprehensively validated for different soils, stress states and temperature boundary conditions. On the other hand, the model predictions cannot be checked for the combined evolution of volumetric deformation (macro scale) and the evolution of cyrosuction, sudden change in permeability, rearrangement of the pore size distribution as well as cracking of the soil (meso/micro scale) over time.

1.1.2 Preliminary work

Zentrum Geotechnik at the Technical University of Munich (TUM) owns a fully equipped frost laboratory to investigate the mechanical and volumetric behaviour of frozen soil and has extensive experience with the investigation of the behaviour of frozen soils. In addition, within the framework of various basic and applied research projects, several studies have been conducted on frozen soil. For example, wide-ranging experimental investigations (Prof. Jelinek and Prof. Floss) were carried out on the frost sensitivity of coarse and fine-grained soils, which form the basis of the standards used in earthwork practice today (see ZTVE-StB17). For the enlargement of the subway station ”Marienplatz” in Munich, the mechanisms of ice lens formation were investigated for different stress conditions and temperature gradients on sand, clay and kaolin in one-dimensional frost heave tests with different boundary conditions. Furthermore, the surface deformations due to soil freezing were thoroughly measured during the construction of the station. The results of these laboratory and field investigations were reported by Fillibeck et al. (2005) and Kellner (2007). As reported by Kellner et al. (2019), experiments were recently carried out for a major subway project in the Munich area to investigate the creep behaviour and the frost heave of different frozen soils (see Fig. 2). Additional experimental investigations regarding the volumetric and mechanical behaviour have just started for a second major subway project in the western Munich area. These highlight the high quality frozen soil testing capacity at Zentrum Geotechnik as well as demonstrate the demand for ground freezing in practical applications.

Prof. Cudmani has participated in several projects involving ground freezing (Cudmani and Nagelsdiek 2006). He developed material models for the simulation of the rate-dependent mechanical behaviour of frozen soils and implemented those models in commercial numerical Codes (Cudmani, 2006; Cudmani et al., 2018; Cudmani et al., 2022). Particularly, Cudmani et al. (2022) recently published an extension of an existing model to account for the influence of the confining pressure on the mechanical behaviour and to differentiate between compressive and tensile behaviour. Including the tensile behaviour in the constitutive model is important to optimize the design of ground freezing measures, since the tensile strength of frozen soils is considerable, but much lower than the compressive strength. Moreover, this constitutive model will ultimately help to better understand and analyse crack initiation of frozen and partially frozen fine-grained soils at temperatures close to the freezing point. Currently, Cudmani's group is testing a new and promising experimental approach to study the mechanical behaviour of frozen soils for tensile loading using a hollow-cylinder setup. Furthermore, this group is investigating the mechanical behaviour of foam-grouted soils that have striking mechanical similarities with frozen soils (Jessen and Cudmani, 2022; Jessen et al., 2022). These and other advanced testing devices and novel experimental techniques under development at Zentrum Geotechnik (Bock et al., 2022) provide an excellent base for the development of the sophisticated experimental investigations described in section 2.3.

As already pointed out in Sec. 1.1.1.1, there are also essential similarities between the relationship of unfrozen water content and temperature during soil freezing / thawing and that of water content and suction of unfrozen soils during drying and wetting. In this context, the experience and the ongoing research in the field of unsaturated unfrozen coarse- and fine-grained soils at Zentrum Geotechnik (Birle, 2012; Yan et al., 2021a, 2021b; Angerer, 2020) are also indispensable to reach the challenging goals of this project. Here, the investigations of the tensile strength, the formation of cracks during shrinkage and the soil water retaining characteristics of partially saturated soils as well as the available experimental devices at Zentrum Geotechnik related to these phenomena provide an excellent base to analyse de-structuration and cracking of soils during freezing.

As mentioned above, Cudmani's group is collaborating and working closely together with the research group of Prof. Wohlmuth (Chair of Numerical Mathematics at TUM), which has an important focus on advanced porous media modelling and multi-physics problems (Gupta et al., 2017; Gupta et al., 2020; Helmig et al., 2009; Köppl et al., 2016; Wolff et al., 2013). Wohlmuth's group will also benefit from the high-quality and comprehensive experimental database of this project (see section 2.3) as they are carrying out preliminary work regarding the novel framework for modelling of ice lens formation, which will be in the focus of phase II of the proposed research.

1.2 Project-related publications

Sections 1.2.1 and 1.2.2 together must not exceed 10 publications; please number them consecutively.

1.2.1 Articles published by outlets with scientific quality assurance, book publications, and works accepted for publication but not yet published.

1. Cudmani, R.; Yan, W.; Schindler, U. (2022): A constitutive model for the simulation of temperature-, stress and rate-dependent behaviour of frozen granular soils. *Géotechnique*. https://doi.org/10.1680/jgeot.21.00012
2. Jessen, J.; Cudmani, R. (2022): Rate- and time-dependent mechanical behavior of foam-grouted coarse grained soils. *Journal of Geotechnical and Geoenvironmental Engineering*. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002763
3. Jessen, J., Cudmani, R. and Fillibeck, J. (2022), Bruchbedingungen für schauminjizierte Kiese unter mehraxialer Beanspruchung. geotechnik. https://doi.org/10.1002/gete.202200008
4. Bock, B.; Levin, F.; Vogt, S.; Cudmani, R. (2022): Acoustic Emission of Sand during Creep under Oedometric Compression. *Geotechnical Testing Journal*, vol. 45, Issue 2. DOI: 10.1520/GTJ20210007.
5. Yan, W., Birle, E., & Cudmani, R. (2021). A new framework to determine general multimodal soil water characteristic curves. *Acta Geotechnica*, *16*(10), 3187-3208.
6. Yan, W., & Cudmani, R. (2021b). A general analytical expression for pore size distribution based on probability theory. *Engineering Geology*, 297, DOI: 10.1016/j.enggeo.2021.106501.
7. Kellner, C, Schindler, U., Zwingler, T., Cudmani, R. 2019. Labortechnische Untersuchung des Frosthebungsverhaltens von Böden unter hohen Auflasten. *Mitteilungen der Geotechnik Schw*eiz Heft 178 (pp. 11-20).
8. Cudmani, R., Sun, J., & Yan, W. 2018. A Constitutive Model for Frozen Granular Soils. In *Proceedings of China-Europe Conference on Geotechnical Engineering* (pp. 1345-1349). Springer, Conference in Wien 2018.
9. Cudmani, R. 2006. An elastic-viscoplastic model for frozen soils. Numerical Modelling of Construction Processes in Geotechnical Engineering for Urban Environment. Taylor & Francis Group, London, 177–183.
10. Cudmani, R., & Nagelsdiek, S. 2006. FE-analysis of ground freezing for the construction of a tunnel cross connection. Numerical Modelling of Construction Processes in Geotechnical Engineering for Urban Environment. Taylor & Francis Group, London, 201-210.

1.2.2 Other publications, both peer-reviewed and non-peer-reviewed -NA-

1.2.3 Patents -NA-

1.2.3.1 Pending -NA-

1.2.3.2 Issued -NA-

2 Objectives and work programme

2.1 Anticipated total duration of the project

The foreseen total project duration will be 4.5 years, subdivided into two funding phases:

	planned start	planned end
1st funding phase (this project): phase 1	01.01.2023	31.12.2025
2nd funding phase: phase 2	01.07.2024	30.06.2027

2.2 Objectives

The behaviour of frozen soils to form ice lenses show different features depending on the soil type, granulometric properties, stress state and temperature boundary conditions (e.g., Fig. 3). Despite the efforts made so far, we still lack comprehensive experimental studies to capture comparatively the mechanism of ice lens formation for soils with different susceptibility to ice lens formation under different stress and temperature boundary conditions (see Sec. 1.1.1.2). Nonetheless, sophisticated experimental data are essential for the development and validation of mathematical models to predict ice lens formation (see Sec. 1.1.1.3).

Therefore, **the overarching goal of phase I is the comparative experimental investigation of frozen soils with low, medium and high susceptibility to ice lens formation. We will track the main underlying mechanisms leading to ice lens formation and generate a comprehensive, high-quality experimental database for the development and validation of numerical models.** To achieve this goal, we propose the following specific sub-goals :

- **Sub-goal** 1: Develop an advanced experimental testing device with: 1) continuous local measurement of temperature, strain and pore water pressure, 2) optical measurement for tracking ice lens formation and 3) displacement transducers to capture the heave for different initial stress states for soils with different susceptibility to develop ice lenses under 1D conditions.
- **Sub-goal** 2: Evaluate the influence of stress, permeability and temperature boundary conditions on the formation and growth of ice lenses and the evolution of heave in soils with low susceptibility to crack under 1D conditions (fine sand and sandy silt).
- **Sub-goal** 3: The same as sub-goal 2 for soils with medium and high susceptibility to crack (sandy clay and silty clay).
- **Sub-goal** 4: Evaluate the relationship between the unfrozen water content and the temperature in the partially frozen zones. Estimate the cryostatic suction stress as a function of the unfrozen water content for soils with different susceptibilities to crack.
- **Sub-goal 5**: Determine the tensile stress-strain behaviour and the tensile strength of soils with different susceptibilities to crack as a function of temperature and unfrozen/frozen water content.

2.3 Work programme including proposed research methods For each applicant

In accordance to the sub-goals (see section 2.2), the work programme is divided into five work packages, viz., **Development of a novel experimental device** (WP1)**, Experimental investigation of soils with low** (WP2**) and medium to high susceptibility to ice lens formation and cracking** (WP3)**, Experimental determination of soil freezing curves (SFC)** (WP4) and the **Tensile stress-strain behaviour at temperatures close to the freezing point** (WP5). Publications with a high scientific impact are expected in all WP. An overview of the planned workflow including phase I (this proposal) and phase II is shown in Fig. 2.1.

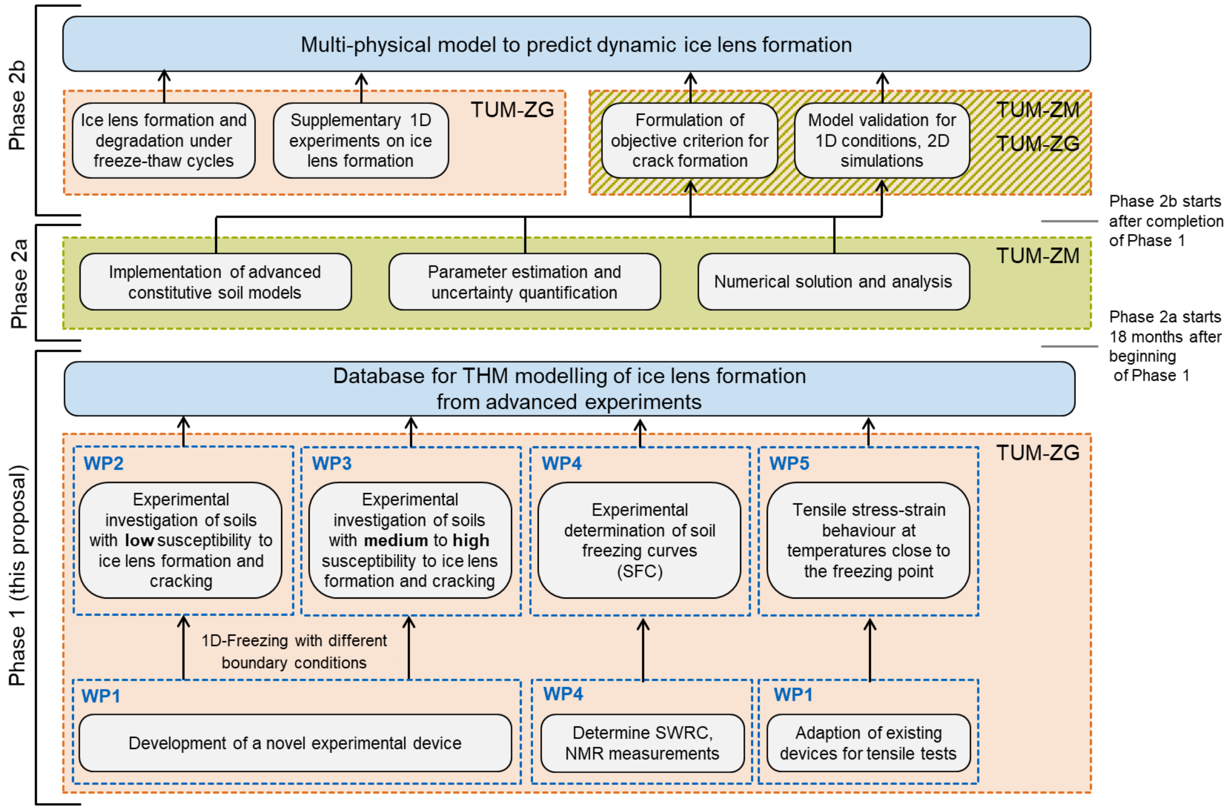

Fig. 2.1: Overview of Workflow (TUM-ZG: Zentrum Geotechnik, TUM-ZM: Chair of Numerical Mathematics)

2.3.1 WP1: Development of a novel experimental device and preliminary tests

A novel device will be developed in this WP to track ice lens formation under different controlled temperature boundary conditions and monitor the relevant physical quantities continuously during freezing. An appropriate sample preparation technique (e.g. air pluviation, moist tamping, sedimentation, homogenization) will be identified by preliminary investigations to achieve homogeneous and reproducible cylindrical specimens in terms of grain skeleton structure, initial density, water content and permeability. The temperature and the stress boundary conditions as well as the water supply will be accurately controlled. Hence, the spatial and temporal evolution of the temperature, the position of the frost front, the pore water pressure in the free water and the frozen fringe as well as the deformations in the frozen and unfrozen zones must be continuously measured. The new device will overcome these challenges and thus, significantly extend the current state of the art on frozen soil testing. The Zentrum Geotechnik's experience in the field of laboratory testing on unfrozen and frozen soils is fundamental in achieving this ambitious goal. A key experimental innovation is the local measurement of the temperature and deformation in the specimens. The novel device will be used in WP2 and WP3 to investigate the freezing behaviour of soils with low, medium and high susceptibility to ice lens formation and cracking for different initial stresses and temperature boundary conditions.

The investigation of ice lens formation requires controlled temperature boundary conditions, enabling fast as well as slow penetration of the frost front into the sample. Ramp-freezing tests (see Sec.1.1.1.2) with cooling rates <0.05°C/day (Konrad, 1994) provide ideal conditions to study the growth and mechanism of ice lens formation. This requires high quality cooling systems with a temperature accuracy of ±0.005°C, which are currently not available at Zentrum Geotechnik. Furthermore, an accurate optical recording of ice lens formation during the experiment is required to track the frost front and the structure of the ice lenses. Fig. 2.2 shows a schematic layout with the main components of the planned device.

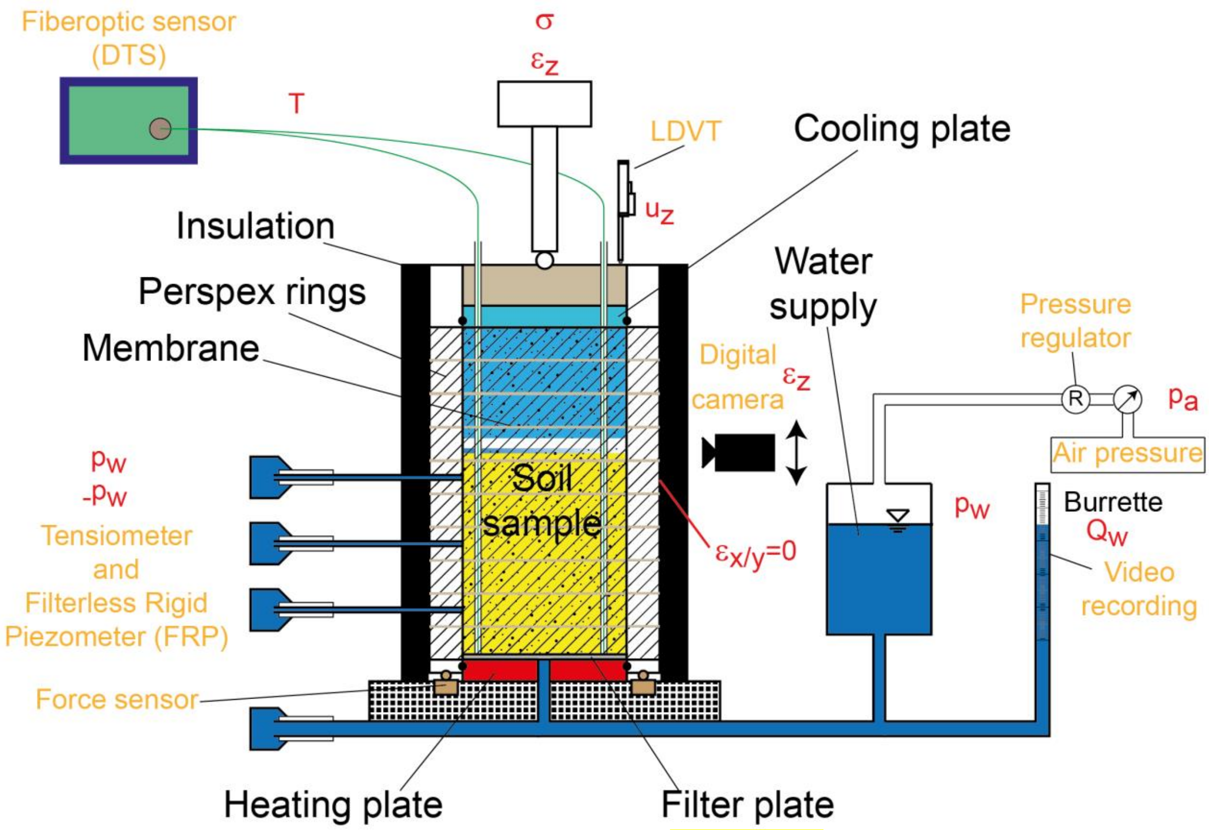

Fig. 2.2: Schematic of the proposed experimental device (FRP added)

The whole device is placed in a climate chamber in which the environmental temperature is constant. The soil sample is placed in a hollow cylinder consisting of several perspex half-shells. Small rings are mounted between the half-shells to reduce the friction between the cell wall and

the specimen. The actual friction will be measured by load cells. Vertical stress can be applied at the top of the sample by a hydraulic jack. The bottom of the sample is connected to a water tank, which ensures a permanent, continuous and controlled water supply. The pressure level of the water tank is controlled by an air pressure control unit. The amount of water flow into the sample is monitored by a video-recording system which tracks the water level in the tank.
The suction inducing the water flow from the unfrozen soil to the frost front is recorded by a series of tensiometers (company: Meter Group AG) which are able to capture both the pore-water pressure ($p_w > p_{athmosphere}$) and suction ($p_w < p_{athmosphere}$) in the area of the frozen fringe. This measurement technique has been tested and successfully validated before by for example Herzog and Boley (2013) as well as Yin and Zhang (2020). In addition, we plan to implement a couple of so called “Filter-less Rigid Piezometers” (FRP) developed by Kia (2012) to extend the measurement range and validate the data by comparing both techniques. For this purpose, we will closely work together and benefit from our national and international cooperation partners (see section 4.5 and 4.6) who have either co-supervised the development of “FRP” (Dr. L. Arenson) or extensively tested tensiometers in freezing soils (Prof. C. Boley and Dr.-Ing. Yazhou Zou).
Two cooling units control the temperature conditions at the top and the bottom of the sample. Additional insulation around the cell ensures nearly one-dimensional vertical freezing. The temperature profile inside the sample is measured locally by means of a Distributed Temperature Sensing system (DTS). The optical fibres are located within a cladding tube inside the sample (strain decoupling). Since the diameter of the sample is considerably larger than the cladding tube, the local disturbance of the temperature field caused by the tubes is negligible. To the best of our knowledge, the use of fibre-optic sensors to measure the temperature distribution in the sample is novel in the field of soil freezing. Heave is recorded by means of a linear variable differential transformer (LVDT) placed on top of the setup. The local soil deformation will be monitored by means of optical evaluation (DIC). During the test, a small window will be temporarily opened in the insulation to take pictures of the soil sample through the perspex cell wall at prescribed time intervals. Numerical simulations have already been carried out to evaluate the influence on the window size and the time interval on the temperature field. The resulting selected windows size and time interval in the tests will ensure that the disturbance of the temperature field will be tolerable in comparison to the disturbances reported by Dagli et al. (2018). The local deformations as well as the ice lens formation in terms of their shape and structure will be analysed by means of Digital Image Correlation (DIC). Despite its potential, the use of DIC to track ice lens formation in real-time is in its early stages (Zheng et al., 2020). A tracer will be added to the water to improve the optical differences between unfrozen pore water and ice (especially in the area of the frozen fringe). Arenson and Sego (2006) successfully used Fluorescein as tracer in freezing tests with coarse and fine-grained soils. This tracer does not change the freezing point of the water and it can be traced by means of UV light. In the pictures, the unfrozen water and ice are shown as green and black respectively.

For the development of the novel device, we will have to overcome the following challenges:
- Reduce and assess friction between cell wall and sample as well as thermocouples and sample, measurement of the friction force,
- Minimize and assess disturbance of the sample caused by the installation of sensors,
- Minimize and assess disturbance of the temperature field due to sensors in the sample and temporary removal of the insulation,
- Track the position of thermocouples within the sample as deviations from their initial location will take place as a result of frost heave

The implementation of cutting-edge instrumentation techniques (e.g. local temperature measurement via fibre optic sensors and local strain measurement via DIC) as well as modern techniques of optical detection in a device which integrates the newest experimental innovations found in the literature, will lead to a substantial development of the state of art in frozen soil testing. The validation of the testing device and the assessment and quantification of the described influences are important parts of the development. With this aim, preliminary freezing tests will be conducted to control the reproducibility of the results and to demonstrate the feasibility of local measuring techniques. The latter is particularly important to ensure the quality of the experimental data to be obtained in WP2 and WP3. WP1 also includes the conversion and modification of existing experimental devices to investigate the mechanical behaviour of frozen soils. Details are explained in the corresponding WP5 (see Sec. 2.3.52.3.5).

2.3.2 WP2: Experimental investigation of soils with low susceptibility to ice lens formation and cracking

The samples will consist of 1) fine sand (FS) and 2) sandy silt (sa Si). In these soils, the driving mechanism of ice lens formation is dominated by cryostatic suction in the frozen fringe (Teng et al., 2022). In contrast, osmosis and osmotic pressure play a negligible role. The results of the tests will provide the database to check the ability of mathematical models to assess the susceptibility of soils to ice lens formation, which is a main question in practice. Although we do not expect crack formation in these soils, we will cut frozen samples into pieces after testing and carefully check whether cracks developed during freezing.

The tests will use the three temperature boundary conditions shown in Fig. 3. So far, comparative investigations of the same soil with the three proposed boundary conditions have not been found in the literature. To reduce the influence of the above-mentioned disturbances (Sec. 2.3.1), the height and diameter of the samples will be 400 mm and 200 mm, respectively. In addition, conventional soil tests (soil classification, oedometric compression, triaxial compression, permeability and thermal tests) will be conducted to characterize the investigated soils. The planned soil freezing test series are summarized in Tab. 2.1.

Tab. 2.1: Overview of the one-dimensional freezing tests in WP2

Type of test	stress [kPa]	Thermal boundary conditions $[T_{bot}/T_{top}]$ / cooling rate (ramp)	no. of tests	see Sec. 2.2
Step-freezing	50 and 200	+2/-5 and +10/-10 [°C]	FS: 2×2=4, sa Si: 2×2=4	Phase I
Cyclic-freezing	50 and 200	+2/(-5/-2) and +10/(-10/-5) [°C]	FS: 2×2=4, sa Si: 2×2=4	Phase I
Ramp-freezing	50 and 200	0,1 und 0,2 [°C/day]	FS: 2×2=4, sa Si: 2×2=4	Phase II

2.3.3 WP3: Experimental investigation of soils with medium to high susceptibility to ice lens formation and cracking

Two normally consolidated, low plasticity fine-grained soils, 1) sandy clay (sa CL) and 2) silty clay (si CL), will be investigated in this WP. According to the literature these soil types (see Sec. 1.1.1.1) show medium to high susceptibility to ice lens formation and also to cracking during freezing. In these soils, ice lens formation is driven by both cryostatic suction and osmotic pressure in the frozen fringe. Therefore, the experimental results of WP3 complement those of WP2 by considering the effect of osmosis, de-structuration and cracking on ice lens formation. Altogether, WP2 and WP3 build a unique database for the validation of existing and future mathematical models. The testing conditions (sample size etc.) and boundary conditions are the same as in WP2. The planned test series are summarized in Tab. 2.2. In general, the WP2 and WP3 test programmes (see Tab. 2.1 and Tab. 2.2) are preliminary proposals. They will be adjusted accordingly in terms of material selection, stress and temperature conditions if the previous tests in WP1 unexpectedly yield different results on the freezing characteristics of the selected soils.

Tab. 2.2: Overview of the one-dimensional freezing tests in WP3

Type of test	stress [kPa]	Thermal boundary conditions $[T_{bot}/T_{top}]$ / cooling rate (ramp)	no. of tests	see Sec. 2.2
Step-freezing	50 and 200	+2/-5 and +10/-10 [°C]	sa CL: 2×2=4, si CL: 2×2=4	Phase I
Cyclic-freezing	50 and 200	+2/(-5/-2)	sa CL: 2×1=2, si CL: 2×1=2	Phase I
		+10/(-10/-5) [°C]	sa CL: 2×1=2, si CL: 2×1=2	Phase II
Ramp-freezing	50 and 200	0,2 [°C/day]	sa CL: 2×1=2, si CL: 2×1=2	Phase I
		0,1 [°C/day]	sa CL: 2×1=2, si CL: 2×1=2	Phase II

To gain experience for the second project phase, the settlements during thawing will be measured in 4 of the 8 step-freezing tests. Here, the heating rate will be controlled to approach 1D conditions during thawing. Furthermore, we will determine the permeability of the soil samples after thawing to investigate the influence of cracking on the hydraulic conductivity of the soil, which is important to understand ice lens formation in fine-grained soils. Zentrum Geotechnik offers advanced testing equipment and vast experience in the determination of the permeability of fine-grained soils (see Section 1.1.2).

Our proposed testing program was developed in close cooperation between our national and international partners (see section 4.5 and 4.6) and will cover a unique range from macro pore (step-, cyclic-, ramp-freezing) to meso/micro pore (NMR measurements, tensile shear tests) freezing tests. Thus, we will be able to provide a comprehensive high-quality database to further develop, calibrate and validate numerical models to simulate ice lens formation in frozen soils.
In our research, we consider among other published high-quality experimental data, the existing comprehensive database of Devon Silt starting with the pioneer works of Prof. J.M. Konrad and Prof. N.R. Morgenstern more than four decades ago. The data will be used not only for validation of our own novel experiments but also to establish a comprehensive experimental database including data from the literature and our own experimental results. Our cooperation partner Lukas Arenson and his former colleagues at the University of Alberta provide access to the existing Devon Silt database.

2.3.4 WP4: Experimental determination of soil freezing curves (SFC)

The soil freezing curve (SFC) describes the amount of unfrozen water content at temperatures below 0°C. It is a key component of mathematical models to simulate soil freezing and thawing. In this WP, the SFC will be determined for the soils with medium and high susceptibility to ice lens formation by the nuclear magnetic resonance (NMR) method. We do not consider the influence of increasing freeze-thaw cycles on the soil structure (Nishimura et al., 2021; Tian et al., 2019) in the first part of this project. Instead, we will focus on the impact of freezing temperature and freezing speed on unfrozen water content and link it with the sudden change of hydraulic conductivity during the first freeze-thaw cycle. The NMR tests (T_2 and T_1+T_2 measurements) will be carried out at the Fraunhofer Institute, since the required testing equipment (low-field NMR) is not available at Zentrum Geotechnik (see Section 5.1.2.5). Since no significant amount of unfrozen pore water exists below the freezing point in sands and sandy silts, the SFC for these materials will be estimated based on published data (Watanabe und Wake 2009; Teng et al. 2021). The planned test series are summarized in Tab. 2.3.

Tab. 2.3: Overview of the NMR tests to determine the soil freezing curves (SFC)

Material	Temperature range	Freezing speed	no. of tests series
sandy clay (sa CL)	+20 to -10/-20 [°C]	fast / slow	2 × 2 = 4
silty clay (si CL)	+20 to -10/-20 [°C]	fast / medium / slow	2 × 3 = 6

Alternatively, the SFC can be estimated from the soil water retention curve (SWRC) as proposed by Koopmans and Miller (1966). We found that this approach, which is simpler and cheaper than the NMR, has some disadvantages (Ma et al., 2017). To evaluate the shortcomings of the simplified approach and quantify the differences between the estimated and the more accurately determined SFC, we will experimentally determine the SWRC of the soils shown in Tab. 2.3 based on the approach of Koopmans and Miller (1966). Following, we will compare these SFC results with the SFC determined with the NMR method. Zentrum Geotechnik has the testing equipment and the experience required to determine the SWRC. Furthermore, the measurement of the pore water pressure (see Fig. 2.2) in WP2 and WP3 enables the experimental evaluation of the pressure difference across the curved ice-water interface (P_i - P_w) as a function of the temperature gradient in the partially frozen soil.

2.3.5 WP5: Tensile stress-strain behaviour at temperatures close to the freezing point

As indicated in Sec. 1.1.1.1 ice lens formation in fine-grained soils can be accompanied by cracking of the soil in and above of the frozen fringe. Cracks increase the hydraulic conductivity of the soil, promoting the water flow from the unfrozen to the frozen soil and the formation of ice lenses.

Since cracking is related to the “tensile” resistance of the soil, the stress-strain behaviour of partially frozen and unfrozen soils at temperatures close to the freezing point (temperature range of the frozen fringe) will be investigated by means of tensile tests. There are very few studies on tensile stress-strain behaviour of freezing soils so far in the literature, e.g. (Azmatch et al., 2011; Zhao et al., 2021). Nevertheless, this database is indispensable to develop advanced cracking criterion frameworks for freezing soils. The test on partially frozen soil samples at relatively <u>high frozen water contents</u> will be conducted using a hollow-cylinder device newly developed at Zentrum Geotechnik based on the “sleeve-fracturing testing device” proposed by Perras and Diederichs (2014) in the field of Rock Mechanics (experimental details see also (Al-Khateeb & Buttlar, 2000)). The radial deformation will be measured using the same fibre optic sensors described in WP1. With this goal, the fibres are laced to the outer cylinder mantle at different heights (Konertz et al., 2017, Xu et al., 2022). Strain measurements with DIC are also carried out for comparison.

Furthermore, tests on unfrozen and partially frozen soil samples at relatively <u>low frozen water contents</u> will be conducted with another existing uniaxial testing device (see Angerer, 2020). Angerer (2020) tested unfrozen silty sand with relatively low shear strength under tensile loading. Therefore, it is necessary to adapt the testing device to perform shear tests with partially frozen soil samples as we expect significantly higher shear strength and soil stiffness in the partially frozen state. These works are part of WP1 and will be undertaken internally at our workshop. The planned test series are summarized in Tab. 2.4.

Tab. 2.4: Uniaxial tensile shear tests at three different temperatures close to the freezing point

Type of test	**Experimental rig**	**no. of tests per material**
strain-rate controlled	sleeve-fracturing test (partially frozen with relatively high frozen water contents)	sandy clay: 2 × 3 = 6, silty clay : 2 × 3 = 6
	after (Angerer, 2020) (partially frozen with relatively low frozen water contents)	sandy clay: 2 × 3 = 6, silty clay : 2 × 3 = 6
	after (Angerer, 2020) (unfrozen)	sandy clay: 2 × 3 = 6, silty clay : 2 × 3 = 6

We are aware of possible shortcomings and limitations associated with indirect tensile tests in comparison to direct tensile tests (e.g. (Erarslan and Williams, 2012)). We will tackle these issues and uncertainties by comparing the experimental results with numerical results using the constitutive model by Cudmani et al. (2022). In addition, we will compare the determined stress correlation factors with data from the literature taking into account statistical bandwidths.
The results of WP5 in combination with WP4 will ultimately provide the experimental database, which is required to develop and validate a stress-, strain- and temperature-dependent criterion to predict crack initiation during freezing in phase II of the project.

2.3.6 Timetable see Tab. 2.5

Tab. 2.5: Planned schedule for the execution of the work packages

	Year 1				Year 2				Year 3			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
WP1: Development of an experimental device and preliminary tests	■	■	■	■								
WP2: Experimental investigation of soils with low susceptibility to ice lens formation and cracking			■	■	■	■						
WP3: Experimental investigation of soils with medium to high susceptibility to ice lens formation and cracking						■	■	■	■	■	■	
WP4: Experimental determination of soil freezing curves (SFC)			■	■	■	■	■	■	■	■	■	
WP5: Stress-strain behaviour at temperatures close to the freezing point				■	■	■	■	■				
Reporting / Publications / Conferences				■		■			■		■	■

2.4 Handling of research data

<u>In general</u>

After publication of the results of the research project, the experimental results will be made available to other national and international research institutions interested in the investigations.

The Technical University of Munich (TUM) strongly supports the open-access publication of research results. Here, the former president of the TUM, Prof. Dr. Dr. h.c. mult. Wolfgang A. Herrmann, signed the Berlin Declaration. The Berlin Declaration on 'Open Access to Knowledge in the Sciences and Humanities' is one of the milestones of the open access movement. Furthermore, the TUM Board of Management adopted an open access policy to encourage all researchers at TUM to publish their scientific findings and research results in the spirit of the open access movement. The applicant R. Cudmani focuses on open-access publishing which is evident in his recent publications. For example (Cudmani et al., 2022) and (Jessen and Cudmani, 2022) are fully open-access journal articles. For more details on the TUM open-access strategy, visit https://www.ub.tum.de/en/open-access-strategy.

Data description
Our project mainly creates measurement data (e.g. sample characteristics, temperature and deformation measurements), pictures and videos, evaluation and analysis data of our freezing tests. The data size is expected to be around 50-100 GB.
Documentation and data quality
Our project only creates digital data. Every test and project step will be documented accordingly to ensure a full traceability of our project at any time. We will use analytical commercial software (e.g. Matlab) as well as or own scripted analysis tools (Python and C++).
Storage and technical backup during the project
The data will be stored temporarily on our own institute server. There is a backup every 24 hrs. At the end of the project, the whole data will be secured on servers of the "Leibniz Rechenzentrum der Bayerischen Akademie der Wissenschaften" (State of Bavaria, www.lrz.de) to ensure the highest availability, quality and security.
Legal obligations and framework conditions
No limitations
Data exchange and permanent accessibility of data
After the project, the data will be fully available throughout the LRZ servers and mediaTUM (the media and publications repository of the Technical University of Munich). mediaTUM supports the publication of digital documents and research data as well as the use of multimedia content in research and teaching. More than 230.000 public records, documents and images are available at the moment and indexed by many third-party services such as the German National Library and Google Scholar.
Responsibilities and resources
Stefan Vogt (Research Group Leader/Laboratory manager, more details see section 4.4) will supervise the data handling throughout the project in accordance to the TUM and DFG guidelines. He will also be responsible for curating the data after the end of the project.

2.5 Relevance of sex, gender and/or diversity

There is no relevance of sex, gender and/or diversity in this project. For general information dealing with promoting sex, gender, diversity, and equal opportunities at TUM see Sec. 4.12.1 and 4.13.

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4 Supplementary information on the research context

Section 4 et seq. must not exceed 8 pages.

4.1 Ethical and/or legal aspects of the project -NA-

4.1.1 General ethical aspects -NA-

4.1.2 Descriptions of proposed investigations on humans, human materials or identifiable data -NA-

4.1.3 Descriptions of proposed investigations involving experiments on animals -NA-

4.1.4 Descriptions of projects involving genetic resources (or associated traditional knowledge) from a foreign country -NA-

4.1.5 Explanations regarding any possible safety-related aspects (“Dual Use Research of Concern; foreign trade law) -NA-

4.2 Employment status information

For each applicant, state the last name, first name, and employment status (including duration of contract and funding body, if on a fixed-term contract).

Roberto Cudmani, Prof. Dr.-Ing., Full Professor, Technical University of Munich: supervision and scientific guidance

4.3 First-time proposal data -NA-

Only if applicable: Last name, first name of first-time applicant

4.4 Composition of the project group

List only those individuals who will work on the project but will not be paid out of the project funds. State each person’s name, academic title, employment status, and type of funding.

In addition to the applicant and the DFG funded staff (see section 5.1.1), the proposed research project will include:

- Stefan Vogt, Dr.-Ing., Research Group Leader/Laboratory manager, budget resources; Support in the design of laboratory tests (supervision)
- Emanuel Birle, Dr.-Ing., Research Group Leader, budget resources; Support in the design of laboratory tests (Determination of SFC – WP3)
- Stylianos Chrisopoulos, Dr.-Ing., Research Group Leader, budget resources: Support in the design and performance of uniaxial tensile shear tests (WP5) as well as simulations of shear tests using the constitutive model of Cudmani et al. (2022) for frozen soils

4.5 Researchers in Germany with whom you have agreed to cooperate on this project

- **Univ.-Prof. Dr.-Ing. Martin Ziegler**, RWTH Aachen, will share his extensive knowledge and experience in the field of experimental investigations of frozen soils
- **Univ.-Prof. Dr.-Ing. Conrad Boley**, **Dr.-Ing. Yazhou Zou**, Universität der Bundeswehr München, will share his extensive knowledge and experience in the field of experimental investigations of frozen soils
- **Dr.-Ing. Wolfgang Orth**, Dr.-Ing. Orth GmbH Karlsruhe, will share his expertise in the practical application of ground freezing and especially in the practical approaches and measures to reduce ice lens formation

4.6 Researchers abroad with whom you have agreed to cooperate on this project

- **Univ.-Prof. Dr.-Ing. Wei Wu**, Universität für Bodenkultur Wien, will share his expertise in constitutive modelling and especially in the development of models to describe the mechanical behaviour of frozen soil

- **Dr.-Ing. (ETH) Lukas Arenson**, BGC Engineering Inc. and Adjunct Professor at the University of Manitoba, Vancouver (Canada), will share his expertise in geotechnical, permafrost engineering with specialization on frozen soil mechanics and geothermal modelling.
  In addition, we will strongly benefit from his experimental experience (see publications in section 3 and his Google Scholar profile) regarding the formation of ice lenses in combination with cracking of fine-grained soils throughout all our work packages.

4.7 Researchers with whom you have collaborated scientifically within the past three years

This information will help avoid potential conflicts of interest.

Prof. Wei Wu, Universität für Bodenkultur Wien; Prof. Pierre-Yves Hicher, Ecole Centrale de Nantes; Prof. Antonia Larese, Università degli Studi di Padova; Prof. Fernando Schnaid, Universidade Federal do Rio Grande do Sul; Prof. Arnaldo Barchiese, Universidad Nacional de Cuyo, Prof. Abel Jacinto, Universidad Nacional de Tucumán, Prof. Alexander Scheuermann, Queensland University, Prof. Yong Yuan, Tongji University, Dr. Kai Zosseder, Prof. Fischer, Prof. Thomas Wunderlich, Prof. Veit Senner, Technische Universität München, Prof. Francesca Casini, University of Rome Tor Vergata

4.8 Project-relevant cooperation with commercial enterprises -NA-

If applicable, please note the EU guidelines on state aid or contact your research institution in this regard.

4.9 Project-relevant participation in commercial enterprises -NA-

Information on connections between the project and the production branch of the enterprise

4.10 Scientific equipment

List larger instruments that will be available to you for the project. These may include large computer facilities if computing capacity will be needed.

The Zentrum Geotechnik has well-equipped laboratories with air-conditioned rooms (existing cooling chambers see also section 1.1.2) and suitable tools for carrying out the experiments.

4.11 Other submissions -NA-

List any funding proposals for this project and/or major instrumentation previously sub-mitted to a third party.

4.12 Other information

Please use this section for any additional information you feel is relevant which has not been provided elsewhere.

4.12.1 Educational aspects and fostering of young researchers

PhD candidates and postdocs (e.g., Dr.-Ing. S. Vogt and Dr.-Ing. C. Chrisopoulos) will be employed in all WPs. Topics for the PhD theses will be structured in a way that permits a likely completion within a three years term. This will open the opportunity of funding two dissertations within the lifetime of the research project (5 years, 3 years is the term of this research proposal and a second proposal is foreseen). The TUM Graduate School (TUM-GS) is the comprehensive organisational format for each doctorate at TUM. With its discipline-specific Faculty Graduate Centres and transdisciplinary Thematic Graduate Centres the TUM-GS supplements individual doctoral research with additional elements, which support doctoral candidates and supervisors alike – independent of the context and funding of each individual doctoral project. Since 2014, all doctoral candidates at TUM have been part of the TUM-GS and therefore benefit from the structuring elements, supervision agreement, regular feedback sessions, individual coaching and mentoring, advisory services, as well as gender and diversity-oriented measures. The TUM-GS promotes the development of young scientists at TUM with regard to both scientific and personal development by offering a vast range of courses on scientific and entrepreneurial expertise, good scientific practice, international and interdisciplinary research skills, scientific writing support, career talks and tailor-made transferable skills training. International doctoral candidates especially benefit from the comprehensive welcome and housing services, intercultural workshops, German language courses and social and cultural programmes provided by TUM-GS each semester. PhD candidates are strongly encouraged to present even early and intermediate stages of their work at national and international conferences and in journals.

4.12.2 Previous DFG projects with a similar project reference

We are aware that there are other research projects funded by the DFG (project numbers 134512236 and 409760547) focusing on the volumetric behaviour of frozen soils during freezing. Based on the project descriptions and related publications, we compare below these projects with our proposal and identify the main differences regarding the experimental investigation of ice lens formation.

4.12.2.1 DFG project number 134512236 (Prof. Boley)

This ground freezing related work ended in 2013. On the basis of the project description, the project results, and publications of the Boley group, the results of our comparison are:

DFG project 134512236	This proposal
The focus lies on the influence of soil mineralogy and ion concentration of pore water on cryostatic suction and the development of ice lenses.	Our investigations will focus on the mechanisms of ice lens formation in coarse and fine grained soils under different temperature boundary conditions and stress conditions. The effect of ion concentration is not part of our research.
1D frost heave tests were performed in open-system (i.e., specimen has free access to water reservoir) and closed-system (i.e., specimen has no access to water reservoir) freezing tests. The boundary conditions were limited to step-freezing (Herzog 2012; Herzog et al. 2012; Herzog and Boley 2013b, 2013a). The test device consisted of an acrylic glass cylinder with temperature sensors and pore water transducers spaced at the samples edges. The image recordings during the tests were not used for local strain measurement.	Our 1D frost heave tests will be performed in open-system (see WP1) and will study ice lens formation in step-, cyclic-, and ramp-freezing tests (see WP2 and WP3). Our experimental set-up will use advanced measurement techniques like Distributed Temperature Sensing, image recording during the tests (local strain measurement via DIC), and the use of tracers to get a better understanding of the shape and form of ice lenses. Furthermore, we will directly measure the soil freezing characteristic (SFC) by using the nuclear magnetic resonance method (see WP4).
Even though a wide range of different soil types were investigated, this project did not focus on cracking and de-structuration of fine-grained soils during freezing. The Boley group did not perform sophisticated meso/micro pore scale freezing tests to investigate cracking, nor did they develop a crack criterion for fine-grained soils.	We will investigate the important phenomena of cracking and de-structuration in fine-grained soils by means of thermo-hydraulic meso/micro pore scale freezing tests (SFC in WP4) as well as strain-rate controlled shear tests under tensile loading (WP 5). The high-quality database will ultimately lead to a formulation of an objective criterion for crack formation (phase II).

References

Herzog, F. 2012. “Untersuchungen zum Gefriersog und der Eislinsenbildung bei der Bodenfrostung.” Pp. 37–44 in 32. Baugrundtagung, Forum für junge Geotechnik-Ingenieure, DGGT.

Herzog, F. and C. Boley. 2013a. “Experimentelle Untersuchungen zu Frosthebungen durch Eislinsenbildung im Untergrund von Eisenbahnfahrwegen.” 9. Tiefbaufachtagung der VDEI-Akademie.

Herzog, F. and C. Boley. 2013b. “Mechanisms During Formation of Ice Lenses and Suction in Freezing Soils.” 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.

Herzog, Franziska, Yazhou Zou, and Conrad Boley. 2012. “Gefriersog und Eislinsenbildung bei der Bodenvereisung.” 2. Symposium Baugrundverbesserung in der Geotechnik; Wien.

Zou, Y. and C. Boley. 2008. “Der Gefriersog bei der eindimensionalen Frosteindringung.” *Veröffentlichungen des Institutes für Bodenmechanik und Felsmechanik der Universität Fridericiana in Karlsruhe* 170:231–42.

4.12.2.2 DFG project number 409760547 (Prof. Ziegler and Prof. Markert)

This is an ongoing research project, which started at the end of 2018 (as announced on the geotechnical engineering institute's homepage on 06.11.2018). On the basis of the information provided by the short project description published on the DFG’s website and four publications of the first project results (Niggemann 2019, 2020; Niggemann and Ziegler 2019; Sweidan et al. 2020), the results of our comparison are:

DFG project 409760547	This proposal
The aim of the project is to identify and describe the frost heave behaviour of frost-susceptible soils during ground freezing with strong focus on the practical application to tunnelling.	We focus on the physical mechanisms of ice lens formation, which is one of the main underlying drivers of frost-heave. In our opinion, a reliable prediction of ice lens formation (micro-, mesoscale problem) is a necessary condition for the prediction of frost heave (macro-scale problem).

DFG project 409760547	This proposal
Cylindrical soil samples with dimensions d=250 mm and h=200 mm are used.	We will use cylindrical specimens of 400 mm height and 200 mm diameter.
The samples are located in a test cylinder, which consists of eight ring elements to reduce friction. The frictional force is not measured during the tests.	Our soil samples are placed in a hollow cylinder consisting of several perspex half-shells with small rings between the half-shells (reduction of friction between the cell wall and the specimen). Furthermore, the friction will be estimated via force sensors.
The investigation focuses on the influence of the freezing direction on frost heave and other frost heave parameters. According to Niggemann (2019), only step-freezing tests are planned. Furthermore, only freezing tests with a very low vertical stress of less than 5 kN/m^2 have been conducted so far (Niggemann 2020).	We will investigate the influence of different temperature and stress boundary conditions (50-200 kPa) on the formation of ice lenses (WP2 and WP3). We will perform step-, cyclic- and ramp-freezing tests with four different soil materials (fine sand, sandy silt, sandy clay and silty clay). The experimental investigation of different boundary conditions is essential for the development and validation of the multi-physics mathematical model, we intend to develop.
For the experiments a sandy, silty clay (CL) is used which is sensitive to crack during freezing.	We will perform freezing tests with a wide range of different soil types (fine sand, sandy silt, sandy clay and silty clay) to cover frozen soils with low to high susceptibility to ice lens formation and cracking.
Niggemann (2020) and Sweidan et al. (2021) report longitudinal and horizontal cracks along the sample height during the freezing tests. Nevertheless, a meso/micro pore scale explanation for the initiation of cracks is not presented in the project due to a lack of sophisticated meso/micro scale freezing tests.	Our project and work packages strongly focus on meso/micro pore scale mechanisms contributing to the formation and growth of ice lenses. This includes the de-structuration and cracking of fine-grained soils during freezing. WP4 (SFC) and WP5 (shear tensile tests) deal with sophisticated meso/micro pore scale freezing tests to investigate cracking of fine-grained soils. Our cooperation partner Lukas Arenson (see Sec. 4.6) will share his expertise (see publications in Sec. 3) regarding the formation of ice lenses in combination with cracking of fine-grained soils. In phase II, we will also consider the influence of freeze-thaw cycles on ice lens formation and de-structuration as well as cracking. Our experimental database will significantly improve our fundamental understanding of ice lens formation in fine-grained soils. It will ultimately lead to a formulation of an objective criterion for crack formation (phase II).
The temporal and spatial distribution of water in the soil sample is investigated. According to (Niggemann 2019), the amount of water sucked into the sample is measured by means of a load cell connected to the water tank. Based on the experimental setup described by Niggemann (2019), it appears that the cryostatic suction in the sample is not measured. In addition to that, there is no information about the determination of soil freezing characteristics of the tested material or about other meso/micro pore scale freezing tests.	We will monitor the temporal and spatial distribution of frozen and unfrozen water in the soil sample with the use of tracers and image recordings (WP1). The amount of water sucked into the sample will be measured by means of a video recording system (WP1). We will measure the cryostatic suction in the sample which induces a water flow from the unfrozen regions to the frost front with the use of tensiometers and “FRPs”. Furthermore, we will directly measure the soil freezing characteristic (SFC) by using the nuclear magnetic resonance method (see WP4). We will compare the obtained data and further assess the differences between the direct and indirect measurement of the SFC (WP4).
The temperature is measured by means of thermocouples spaced at the sample edges. The PVC sample container is not transparent.	We plan an experimental rig to run freezing tests with a continuous high-resolution monitoring system that consists of local temperature (DTS)

DFG project 409760547	This proposal
Therefore, there are no optical recordings of the sample during the experiments.	and local strain measurements (DIC) inside the sample (see WP1, WP2 and WP3).

References
Niggemann, K. 2019. “Untersuchung der Frosthebungen für die Randbedingung einer künstlichen Baugrundvereisung.” *Fachsektionstage Geotechnik der DGGT , Würzburg* 426–31.
Niggemann, K. and M. Ziegler. 2019. “Neues Verfahren zur Bestimmung von Frosthebungen infolge künstlicher Baugrundvereisung im Tunnelbau – Versuche und verbesserte Berechnungsansätze.” *STUVA-Tagung 2019, Internationales Forum für Tunnel und Infrastruktur, 26.-28. November 2019, Frankfurt, Ernst & Sohn Verlag* 164–69.
Niggemann, Katharina. 2020. “Investigation of frost heave considering the boundary conditions of artificial ground freezing.” Pp. 273–83 in *Transportation Soil Engineering in Cold Regions, Volume 2*. Springer.
Sweidan, A. H., Niggemann, K., Heider, Y., Ziegler, M., & Markert, B. (2021). Experimental study and numerical modeling of the thermo-hydro-mechanical processes in soil freezing with different frost penetration directions. *Acta Geotechnica*, 1-25.

4.13 Gender equality and diversity

The Technical University of Munich is an equal-opportunity employer and all investigators currently employ students and postdocs with different nationalities and genders. For the project, they naturally commit themselves to following the principle of equal opportunity in regards to hiring procedures. TUM is committed to the goal of becoming the most attractive technical university in Germany for female students and female academic staff. In March 2007, TUM was the first university in Germany to sign the ‘Charta der Vielfalt’ (Charter of Diversity). Gender equality figures prominently in the TUM Mission Statement, the TUM Charter, the university development plan and in its target agreements with the Ministry of Education. Since 2013, TUM has been in phase 3 of DFG Research-Oriented Standards of Gender Equality. Furthermore, the topic is included in the TUM Faculty Tenure Track, the TUM Graduate School Statute and the Mission Statement ‘Excellence in Teaching and Learning at TUM’. In spring 2012, central equality principles were incorporated into the TUM Diversity Code of Conduct.

5 Requested modules/funds

Explain each item for each applicant (stating last name, first name).

5.1 Basic Module

5.1.1 Funding for Staff

- 1 scientific assistant (Dipl.-Ing., M.Sc.), TVL-E13, Doctoral researcher or comparable, 36 months
- 1 technical employee (Precision engineer for modification of the experimental rig), TVL-E10, Other research assistant, 4 months
- 1 technical employee (Laboratory assistant for support during the tests), TVL-E7, Non-academic staff member, 10 months
- 1 Student research assistant (“geprüft”), 7 hours/week, other personnel resources, 36 months, 414 €/month (see Appendix “Vergütungssätze”), plus 9,30 % social benefits, corresponding to a gross amount of 16.293 €

The construction of further experimental equipment (WP1) will be done by the in-house workshop. For this purpose, the personal costs are applied for a precision engineer (4 months). As shown in Sec. 2.3 and Tab. 2.5 it is planned to perform in total 100 freezing tests (36 tests in WP2-WP3, 10 NMR-tests in WP4, 54 shear tests in WP5) throughout the work packages that need to be carried out simultaneously. Furthermore, the project includes the following additional experimental work for four different materials (fine sand, sandy silt, sandy clay and silty clay):

- Sample preparation and post-processing after the tests
- Classification of the tested materials
- One-dimensional compression tests (unfrozen soil)
- Triaxial compression tests (unfrozen soil)
- Permeability tests on the flow of water through saturated voids of unfrozen water
- Thermal tests on the conductivity
- Preliminary freezing tests to validate the novel test apparatus, to control the reproducibility of test results and to demonstrate the suitability of the proposed local measuring techniques

- Test for determining the soil water retention curves and unsaturated characteristics
- Permeability of the thawed soil samples after all freezing tests of WP2 and WP3 to investigate the influence of cracking on the hydraulic conductivity

Soil freezing tests belong to the most challenging tests in the soil mechanics laboratory. In contrast to the majority of the freezing tests found in the literature, we carry out tests on comparably large samples (cylindrical specimens of 400 mm height and 200 mm diameter) that are instrumented by a rather large number of sensors incorporating sensors that are specially adopted for the purposed studies. The sensors need to be carefully placed within the procedure of sample preparation. Since we are assembling a new device, we will need strong support from our workshop during the project. This result in increased effort compared to existing studies in the field of ice lens formation. The time-consuming step- and cyclic-freezing tests that include sample preparation, the general set-up of the experimental rig including the initiation of the measuring sensors and measuring electronics, the duration of the testing itself and the sample postprocessing will at least take in between two and three weeks for each test. Regarding the complex control and because of the slow rate of thermal loading during ramp-freezing tests, we assume a total time of up to 6 weeks for each test.

Therefore, the single PhD candidate cannot perform all of the experimental work on his own. Hence, for the planned period of approx. 2.5 years (WP1, WP2, WP3, WP4 and WP5) a technical employee/laboratory assistant is required for 1/3 of that period (in total approximately 10 months) to support the PhD student during the experimental studies.

5.1.2 Direct Project Costs

The costs of the new experimental rig including measuring instrumentation are listed below (see Tab. 5.1 and Tab. 5.3). The consumables (e.g. soil samples) will be provided by the Zentrum Geotechnik. The running costs for the equipment as well as for administration and office operations are covered by the budget of the chair.

For the scientific quality and success of our project, we are convinced that we do need all of the requested services and devices that were listed within the proposal. We have already restructured our budget by expanding our own finance budget significantly. In particular, we will completely finance all consumables, fees, devices and others cost that are below 1.500 € each by our own budget. At the same time, we only ask for a funding of 50% of the cost for equipment, software and consumables up to 10.000 €.
The distributed fibre-optic measuring system type Luna ODiSI-system (see Tab. 5.3) represents a far-reaching innovation and promising novel technique for frozen soil testing and monitoring ice lens formation. This device is a very important part of our project as it plays a key role in locating temperature and strain changes at a comparably high spatial resolution enabling an innovative observation of effects inside the sample. Therefore, we ask for a funding covering 35% of the costs of the Luna ODiSI-system. 65% of the costs are covered by our budget. In this context, it is also inevitable that we consider the Luna ODiSI-system with four channels to (see "Offers") be able to simultaneously measure the temperature distribution during the freezing tests in WP2-WP3 as well as the radial strains during the tensile shear tests in WP5. Moreover, regarding the large number of different fibres needed for this project we will strongly (also financially) benefit from the "Luna ODiSI-System: Key Generator" (see Tab. 5.1). The key-Generator software offers the possibility to create own sensor fibers specifically for certain applications (flexibility in fibre length and texture) which is key to the success of the planned and challenging application of this advanced measurement technique within this project (see also further explanation regarding "Luna ODiSI-System: Key Generator" in the Appendix "Offers").

5.1.2.1 Equipment up to € 10,000, Software and Consumables

Tab. 5.1: Equipment up to Euro 10,000, Software and Consumables

Amount (unit)	Equipment	Total price (gross)
1 (piece)	Construction of the novel experimental rig: Cylinder made of PMMA 300 x 200 mm (height x diameter); Diaphragm, seals, lubrication; Hydraulic jack including sintered metal filter made of V4A; Sample base including sintered metal filter made of V4A; Fluid system with pipes, connections, couplings and ball valves (Swagelok type); Water supply of V4A; Insulation; 2x cooling plates; 3x Force sensors (friction cell wall) [Total price (gross): 9.520 €: 50% are requested through this project]	4.760 €
1 (piece)	Microprocessor-controlled air pressure controller: "APC-3/XX " (see 'Offers') [Total price (gross): 10.056 €: 50% are requested through this project]	5.028 €
1 (piece)	DTS: Luna ODiSI-System: Splicer with transport case (see 'Offers' and 'Explanation "Key Generator" Polytec' in the appendix) [Total price (gross): 3.213 €: 50% are requested through this project]	1.607 €
4 (pieces)	Tensiometer for pore pressure and suction measurement [UMS Mini-Tensiometer T5 or T5x] ('Offers') [Total price (gross): 2.171 €: 50% are requested through this project]	1.085 €
2 (pieces)	Filter-less Rigid Piezometer after Kia (2012) including among others: FISO: Fiber-Optic Pressure sensor Model FOP-MIV-PK; SGE Analytical Science Pty: PEEKSil Tube 5.000 € are requested through this project, additional costs are covered by our own budget	5.000 €
1 (piece)	DTS: Luna ODiSI-System: Key Generator - Software for generating fibre codings (see 'Offers' and 'Explanation "Key Generator" Polytec in the appendix) [Total price (gross): 14.280 €: 50% are requested through this project]	7.140 €
2 (pieces)	Polyscience PP15R-40 15ltr Refrigerated Circulator (see 'Offers') [Total price (gross): 11.319 €: 50% are requested through this project]	5.660 €
1 (piece)	Cooling Chamber (Electrolux RI16R1G) (see 'Offers') [Total price (gross): 8.532 €: 50% are requested through this project]	4.266 €
*Offers: 2020-2022. Higher costs are expected (inflation) and will be covered by our own budget.		**34.546 €** *

5.1.2.2 Travel Expenses

International Conferences (1 each in years 2 and 3, estimated 2.000 € each) **4.000,- €**

5.1.2.3 Visiting Researchers (excluding Mercator Fellows) -NA-

5.1.2.4 Expenses for Laboratory Animals -NA-

5.1.2.5 Other Costs

Tab. 5.2: Other costs: Third-party contracts

Amount (unit)	Equipment	Total price (gross)
1 (piece)	Modification and adoption of low-field NMR equipment at Fraunhofer Institute (see 'Offers' and references Fraunhofer Institute in the appendix) [Total price (gross): 3.808 €: 50% are requested through this project]	1.904 €
10 (pieces)	Determination of the SFC (low-field NMR) (see 'Offers' and references Fraunhofer Institute in the appendix) [Total price (gross): 23.324 €: 50% are requested through this project]	11.662 €
*Offers: 2020. Higher costs are expected (inflation) and will be covered by our own budget.		**13.566 €** *

5.1.2.6 Project-related Publication Expenses

Results of the project will be published in international peer-reviewed journals, some of which are charging publication fees to the authors:

Publication Expenses: 2 × 750 € (year 2 and 3) **1.500,- €**

5.1.3 Instrumentation

5.1.3.1 Equipment exceeding € 10,000

Tab. 5.3: Equipment exceeding Euro 10,000

Amount (unit)	Equipment	Total price (gross)
1 (piece)	DTS: Luna ODiSI-System [Total price (gross) of the equipment: 128.377 €: 35% of the equipment costs are requested through this project, 65% of the equipment costs are financed by own budget] (see 'Offers')	**44.932 ***

*Offer: 2022. Higher costs are expected (inflation, currency change Dollar/Euro) and will be covered by our own budget.

Operation and Utilization concept

Use of the requested device

Device	Use per year	Application areas	Contact person	Location
ODiSI 6104 Fiber optic measurement system	250 days	Current application: Temperature and strain measurement at high spatial resolution	Dr.-Ing. Stefan Vogt Zentrum Geotechnik	Building 2601 Room G 013

Operation concept

The fiber optic measurement system will be used at the chair Zentrum Geotechnik (Building 2601) of the Technical University of Munich (TUM). For the operation of the device, no special requirements are required. The instrument is stored with existing optical measurement devices in a separate storage room in building 2601.

All the experimental investigations (WP1 preliminary tests, WP2 and WP3 step-, cyclic- and ramp-freezing tests as well as shear tests WP5) will be carried out with this high-resolution local fiber optic temperature measurement technique. Due to the very time-consuming freezing tests (single test duration: >15 days) a useful life of the device of at least 250 days per year is assumed. The use of the device by other scientists is not intended during this project (next 5 years).

Follow-up costs

With the assistance of the company of Polytech GmbH it has been calculated and estimated respectively that the operating and maintenance costs of the ODiSI 6104 fiber optic measurement system are incurred annually:

Operating cost (resources):	
Optical fibres (self-made fibres, 50 m in total)	450,00 €
Glue and splice material for the proposed experiments	560,00 €
Electricity (< 200 Watt)	400,00 €
Estimated maintenance costs (ongoing calibration and minor repair works):	2.500,00 €

The operating and maintenance costs of the device are covered by the Zentrum Geotechnik and are not part of the applied fundings.

Market research / comparative offer

Considering the technical specifications of competing measurement systems, we concluded that no appropriate alternative devices that may be used in the proposed experiments exists. This coincides with the statement of the company of Polytech GmbH, which holds the sales rights for the Luna ODiSI 6104 fiber optic measurement system in Germany (see letter of company Polytech GmbH). The enclosed letter confirms the unique technical specifications listing patents protecting the measurement device.

5.1.3.2 Major Instrumentation exceeding € 50,000 -NA-

5.2 Module Temporary Position for Principal Investigator -NA-

5.3 Module Replacement Funding -NA-

5.4 Module Temporary Clinician Substitute -NA-

5.5 Module Mercator Fellows -NA-

5.6 Module Workshop Funding -NA-

5.7 Module Public Relations Funding -NA-

5.8 Module Standard Allowance for Gender Equality Measures -NA-

Covering letter for the second reviewer

Review of the first submission

We are grateful to the second reviewer for the effort to review our first proposal. We have checked the extensive review comments and suggestions very carefully and we introduced changes accordingly to improve our proposal. Nevertheless, owing to the limit of 17 pages for section 1-3, we could not address all reviewer's comments with the required detail in the main document. This refers especially to the comments regarding the consideration of existing frost heave data on Devon Silt from other universities in our project. Therefore, this covering letter provides supplementary information and addresses the review comments in more detail.

Comment 1 of the second reviewer

I recommend the authors review the PhD thesis by Mohammadali Kia (2012) 'Measuring Porewater Pressure in Partially Frozen Soils' at the University of Alberta for details on a measuring system that will allow for these internal pore pressure measurements.
Weakness: Lack of internal pore pressure measurements during frost front advance

We have carefully studied the excellence work and promising new developed "Filter-less Rigid Piezometers" (FRP) by Kia (2012). In addition, we contacted our cooperation partner Dr.-Ing. (ETH) Lukas Arenson (see section 6.5 of the former proposal, section 4.6 of our current proposal) who co-supervised the PhD thesis of Kia at the University of Alberta (see acknowledgement in (Kia, 2012)). In our proposal, we have already proposed using tensiometers to capture both the pore-water pressure (positive pressure) and suction (negative pressure) in the area of the frozen fringe. According to the User Manual provided by Meter Group AG the tensiometer "T5" or "T5x" can measure pore-water pressure of up to +100 kPa and suctions of up to -160 kPa:

Measuring range		
T5	-85 kPa ... +100 kPa	
T5x	min. -160 kPa ... +100 kPa	
Water tension	-85 kPa (-160 kPa) … 0 kPa	(Tensiometer)
Water level	0 kPa … +100 kPa	(Piezometer)

The successful use of tensiometers in frozen soils has been reported and validated before:

Herzog, F. and C. Boley. 2013. "Mechanisms During Formation of Ice Lenses and Suction in Freezing Soils." 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.
Yin, J., & Zhang, X. (2020). Suction Measurement in Freezing Process Using High-Suction Tensiometer. In Geo-Congress 2020: Geotechnical Earthquake Engineering and Special Topics (pp. 907-912).

In addition, there are many experimental studies dealing with the measurement of the cryostatic suction (see also section 1 of our proposal) in the area of the frozen fringe, for example:

Bronfenbrener, L., & Bronfenbrener, R. (2010). Modeling frost heave in freezing soils. Cold Regions Science and Technology, 61(1), 43-64.
Herzog, F. and C. Boley. 2013. "Mechanisms During Formation of Ice Lenses and Suction in Freezing Soils." 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.
Rivière, A., Jost, A., Gonçalvès, J., & Font, M. (2019). Pore water pressure evolution below a freezing front under saturated conditions: Large-scale laboratory experiment and numerical investigation. Cold Regions Science and Technology, 158, 76-94.
Bansal, T., Knutsson, S., & Laue, J. (2021). Suction measurement in freezing soils using pore pressure transducers. In IOP Conference Series: Earth and Environmental Science (Vol. 710, No. 1, p. 012066). IOP Publishing.

These studies indicate that the measurement range of the selected tensiometers for our experimental program is sufficient for ice lens formation in fine-grained soils such as sandy and silty clays under our proposed vertical stresses and temperature gradients in WP2 and WP3.
Nevertheless, based on the reviewer comment, we are now planning the additional implementation of a couple of "FRP's" developed by Kia (2012) to further extend the measurement range and compare the data obtained with both techniques. For this purpose, we contacted our cooperation partner L. Arenson to get in touch with M. Kia. We realized that there is a patent for

the developed “FRP’s” belonging to M. Kia, Prof. KR. Morgenstern and Prof. DC. Sego: https://patents.google.com/patent/US9140615. Therefore, we need the permission of the patent owner to build the sensors. Furthermore, it seems like the “FRP’s” are not available commercially. Nevertheless, we have contacted the patent owners to achieve a legal agreement for the use of the “FRP” in our research. Hence, we are planning to rebuild them with the help of our workshop and our cooperation partner L. Arenson, who according to him (personal communication) and Kia (2012) technically supported the development as co-supervisor.
Summarizing, we have implemented the valuable reviewer’s recommendations in our proposal. We believe that the use of “FRP’s” in our novel testing apparatus will improve the scientific quality and contribute to the success of our project.

Comment 2 of the second reviewer

The proposed test program will provide valuable experimental data but I would encourage the applicants to access the rich frost heave data sets that exists on Devon Silt from University of Alberta and Laval University in Canada.
Weakness: Accessing extensive frost heave data from other Universities to guide work

The reviewer pointed out that many ice lens formation tests have previously been carried out and are reported in the literature and that we are aware of these works as demonstrated by the references in our proposal. We have closed agreements with several national and international experts in the field of frozen soil testing (with special focus on ice lens formation) to exchange information and data during our project. Through this scientific collaboration and exchange, we will incorporate and benefit from available sophisticated experimental databases and the available experimental experience in the field of frozen soils. Among international experts, we intentionally selected and gained the support of Lukas Arenson because he is a renowned geotechnical scientist in frozen soil and permafrost engineering with specialization on frozen soil mechanics and geothermal modelling. In fact, Arenson was Post-Doc in Prof. Sego’s group at the University of Alberta and reported many ice lens formation tests, among others, on Devon Silt, for example:

Azmatch, T. F., Sego, D. C., **Arenson**, L. U., & Biggar, K. W. (2012). Using soil freezing characteristic curve to estimate the hydraulic conductivity function of partially frozen soils. Cold Regions Science and Technology, 83, 103-109.
Azmatch, T. F., Sego, D. C., **Arenson**, L. U., & Biggar, K. W. (2012). New ice lens initiation condition for frost heave in fine-grained soils. Cold Regions Science and Technology, 82, 8-13.
Azmatch, T. F., Sego, D. C., **Arenson**, L. U., & Biggar, K. W. (2011). Tensile strength and stress–strain behaviour of Devon silt under frozen fringe conditions. Cold Regions Science and Technology, 68(1-2), 85-90.
Arenson, L. U., Azmatch, T. F., Sego, D. C., & Biggar, K. W. (2008). A new hypothesis on ice lens formation in frost-susceptible soils. In Proceedings of the ninth international conference on permafrost, Fairbanks, Vol. 1, pp. 59-64.
Arenson, L. U., Springman, SM, & Sego, DC. (2007).The rheology of frozen soils. Applied Rheology, 17(1),12147-1.
Arenson, L. U., Sego, D. C., & Take, W. A. (2007). Measurement of ice lens growth and soil consolidation during frost penetration using particle image velocimetry (PIV). In 60th Canadian Geotechnical Conference, (pp. 2046-2053).
Arenson, L. U., & Sego, D. C. (2006). The effect of salinity on the freezing of coarse-grained sands. Canadian Geotechnical Journal, 43(3), 325-337.
Arenson, L. U., Xia, D., Sego, D. C., & Biggar, K. W. (2006). Change in ice lens formation for saline and non-saline Devon silt as a function of temperature and pressure. In Current Practices in Cold Regions Engineering (pp. 1-11).
Xia, D., **Arenson**, L. U., Biggar, K. W., & Sego, D. C. (2005). Freezing process in Devon silt-using time-lapse photography. In 58th Canadian geotechnical conference.

In addition, Arenson co-supervised two PhD thesis [Kia, M. (2012), Azmatch, T.F. (2013)] dealing with frozen soil testing at the University of Alberta. Our proposed testing program has been developed in close cooperation between our national and international partners and will cover a unique range from macro pore to meso/micro pore freezing tests. Thus, we will be able to provide a comprehensive high-quality database to further develop, calibrate and validate numerical models to simulate ice lens formation in frozen soils. In our research, we consider among other published high-quality experimental data, the existing comprehensive database of Devon Silt starting with the pioneer works of Prof. J.M. Konrad and Prof. N.R. Morgenstern more than four decades ago. The data will be used not only for validation of our own novel experiments but also to establish a comprehensive experimental database including data from the literature and our own experimental results. Our cooperation partner Lukas Arenson and his former colleagues at the University of Alberta provide access to the existing Devon Silt database.

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Personal data

Birthday: 25th March, 1967
Born in Tucumán, Argentina
Nationalities: German, Argentine
Country of residence: Germany since 1994
Family status: Married since 1994, three children (21, 22 and 25 years old)

Education

Civil Engineer
Master of Science
Doktor-Ingenieur
Post-Doc

Languages

Spanish (mother tongue)
German (fluently spoken and written)
English (fluently spoken and written)
Portuguese (fluently spoken and written)
French and Italian (basic knowledge)

Academic education

2000/10 – 2004/12	Post-Doctor at the Institute of Soil Mechanics and Rock Mechanics of the University of Karlsruhe, Germany. Main research topics "dynamic soil behaviour during strong earthquakes", "soil improvement" and "numerical methods in geotechnics", "soil-structure-interaction"
2000/11	Doktor-Ingenieur. Title of the doctoral thesis: "Static, alternating and dynamic penetration in cohesionless soils" at the Institute of Soil Mechanics and Rock Mechanics of the University of Karlsruhe, Germany
1994/07	Master of Engineering Sciences (Geotechnics). Title of the master thesis: "Study of the load-settlement behavior of residual soils based on plate loading testing (PLT) and the finite element method"
1992/03	Civil Engineering Diploma (Structural Engineering) at the National University of Tucuman, Argentina

Professional and academic experience

From 2015/09	Full Professorship and Director, Research Center and Chair of Soil Mechanics, Rock Mechanics, Foundation Engineering and Tunneling of the Technical University of Munich
2012/01 – 2015/08	Managing Partner, Smoltczyk & Partner GmbH (Geotechnical Consultant)
2011/07 - 2011/12	Senior Geotechnical Consultant, Smoltczyk & Partner GmbH (Geotechnical Consultant)
2006/10 - 2011/07	Head of Geotechnical Design Group, Bilfinger Berger Civil GmbH (Construction Company)
2005/01 - 2006/09	Project Engineer, Project Manager of the Technical Department, section foundations and tunneling division of the company Ed. Züblin AG (Construction Company)
2000/10 - 2004/12	Senior research assistant / Lecturer (category: C-1 Beamte) at the Institute of Soil Mechanics and Rock Mechanics, University of Karlsruhe, Germany (Karlsruhe Institute of Technology)
2003/09 - 2006/09	Lecturer in "constitutive soil modeling and numerical methods in geotechnics" at the Institute of Soil Mechanics and Rock Mechanics, University of Karlsruhe, Germany (Karlsruhe Institute of Technology)
1994/09 – 2001/09	Research assistant at the Institute of Soil Mechanics and Rock Mechanics, University of Karlsruhe, Germany
1992/01 – 1994/08	Research assistant at the University of Rio Grande do Sul, Porto Alegre Brasil (CNPQ-Stipendium)
1991/06 - 1991/08	IAESTE scholarship at the executing planning ofice „Projektový a vývojový ústav VUT“, Brünn, Czech Republic
1988/05 – 1990/04	Student assistant at the Institute for steel and concrete constructions at the University of Tucumán
1987/10 – 1988/04	Student assistant for the Institute surveying at the University of Tucumán

Basic education

1980/03 – 1984/12	Secondary school "Gregorio Aráoz de Lamadrid" (Military Gymnasium), Tucumán
1973/03 – 1979/12	Primary school "Escuela Bartolomé Mitre", Tucumán

Memberships

German Society of Geotechnical Engineering (member of the task group research and development)

DIN Standards Committee (member of the task group Soil Dynamics)

Deutsches Talsperren Komitee e. V. (German Dam Committee)

European Committee for standardization (German Representative in the task group “Tailings”)

Independent consultant of ORSEP (Organismo Regulador de Seguridad de Presas – Argentina)

Vice-Chair TC 221 “Talings and Mine Wastes”, International Society of Soil Mechanics and Geotechnical Engineering.

List of 10 most important Publications

a)

R. Cudmani (1999). Zyklische Torsion eines Rohrs in Sand. *Geotechnik*, **4**, S. 244-250.

V.A. Osinov, R. Cudmani (2001). Theoretical Investigation of the cavity expansion problem based on a hypoplasticity model. *International Journal of numerical and analytical methods in Geomechanics*, 25, S. 473-495.

R. Cudmani, V.A. Osinov (2001). The cavity expansion problem for the Interpretation of cone penetration and pressuremeter tests. *Canadian Geotechnical Journal*, 38: 622-638.

R. Cudmani, M. Thomas, W. Schwarz, F-W. Geressen (2002). Versuche zur Optimierung des Coplan-Stabilisierungsverfahrens (CSV). *Geotechnik* 2, S. 114-119.

G. Gudehus, R. Cudmani, M. Bühler, A.B. Libreros-Bertini (2003). In-plane and antiplane shaking of soils systems and structures. *Soil Dynamics and Earthquake Engineering journal*, 24, S. 319-342.

R. Cudmani, G. Sedlacek (2006). Analytische und numerische Standsicherheitsanalyse der Schlitzwandherstellung in einem weichen marinen Ton in Oslo, Norwegen. *Geotechnik*, 29. S. 272-288.

S. Richter, R. Cudmani, C. Slominski (2011). The behaviour of a spread footing over reinforced ground with gravel interface during strong earthquake, *Geotechnik* 34, Heft 3.

Levin, F., Vogt, S., & Cudmani, R. (2018): Time-dependent behaviour of sand with different fine contents under oedometric loading. *Canadian Geotechnical Journal*, *56*(1), 102-115.

Cudmani, R. Manthey, S. (2019). A novel vibro-penetration test (VPT) for the investigation of cohesionless soils in the field. *Soil dynamics and Earthquake Engineering*, Volume 126 (pp. 1-22).

Cudmani, R., Yan, W. & Schindler, U. (2022): A constitutive model for the simulation of temperature-, stress and rate-dependent behaviour of frozen granular soils. *Géotechnique*. https://doi.org/10.1680/jgeot.21.00012

Selected research projects / geotechnical consultancy at the Institute of Soil Mechanics and Rock Mechanics, University of Karlsuhe

1994 – 1996	DFG - Research Project „Dynamic Penetration“
1996	Geotechnical Interpretative Report, „Control of soil vibrations during the installation of a sheet pile wall for the construction of a road underpass", Auftraggeber: Stadtwerk KA
1996 – 1999	BMBF-Research Project, „Remediation and Stabilization of damps and damp slopes consisting of soils susceptible to spontaneous liquefaction“
1996 – 1999	BMBF-Research Project, „Construction on damps consisting of fine-grained soils from brown coal mining in the Mitteldeutschen Revier“
1997	Geotechnical Interpretative Report for the construction of the synchrotron radiation facility ANKA“ Auftraggeber: Forschungszentrum Karlsruhe
1998	Geotechnical Report, „control of the deep soil improvement for the reduction of settlements of the foundation of the synchrotron radiation facility ANKA. Auftraggeber: Forschungszentrum Karlsruhe
2000 – 2001	R&D-Project, „model tests for the optimisation of the Coplan-soil stabilisation technique“. Auftraggeber: Fa. Bauer
2001	Geotechnical Report, „Treatment plant Breisgauer Bucht in Forchheim. Investigation of the damage of am sewage treatment basin 1“, Auftraggeber Abwasserzweckverband Breisgauer Bucht
2001	Geotechnical Report, „Excavation for the lock Uelzen: Laboratory tests and determination of parameters of the hypoplastic model for the FE-modelling“, Bundesanstalt für Wasserbau
2001	Geotechnical Report, „Excavation for the lock Uelzen: Interpretation of CPT for the determination of the relative density of the foundation ground “, Bundesanstalt für Wasserbau
2001 – 2002	R&D-Project, „numerical investigation of the pressure induced by railway tracks on underlying balast“. Auftraggeber: Deutsche Bahn AG
2002	Geotechnical Report, „Interpretation of CPT for the determination of the relative density and the stiffness for the settlement calculation of a high-rise building“, Erweiterung RZVK, Köln, Auftraggeber Fa. Züblin

2002 – 2003	R&D-Project, „Development of a calculation method for the design and quality control of deep vibro-compaction (vibroflotation): Pilot Study I“. Auftraggeber: Fa. Keller Foundations
2003	Geotechnical Report, „Project 02.73 – Construction of a retaining structure for the bypass of railway plot: Finite Element calculation of wall displacements. Auftraggeber: Ingenieurbüro Bührer
2003 – 2004	R&D-Project, „Development of a calculation method for the design and quality control of deep vibro-compaction (vibroflotation): Pilot Study II“. Auftraggeber: Fa. Keller Foundations
2001-2004	DFG-Research Project 461, „Strong Earthquakes: A Challenge for Geosciences and Civil Engineering“
2003-2004	DFG/BMZ- Research Project, „Development of methods to assess stability and serviceability of ductile geotechnical structures subjected to strong earthquakes“
2004	Geotechnical Report, „Experimental Investigation of the Cone Penetration Resistance of (calcareous) Dubai Sand in a Large Calibration Chamber“, Auftraggeber: Fa. Keller Foundations
2004	Geotechnical Report, „Interpretation of the cone penetration resistance in (calcareous) Dubai sands for the control of density after the deep compaction of the reclaimed land for the Palm Islands in Dubai“. Auftraggeber: Fa. Keller Foundations
2004	R&D-Project, „improvement of the deep soil stabilisation technique CSC (Cement-Stabilisation-Columns) and investigation of the applicability in soft soils mit experimental and numerical methods“. Auftraggeber: Fa. Bauer Spezialbau GmbH
2004	Geotechnical Report, „Numerical investigation of the seismic response of damps from the brown coal mining and determination of the soil amplification factors according to DIN 4149“. Auftraggeber: RWE Rheinbraun AG

Selected projects Ed. Züblin AG

2004 -2005	Metro Nord-Süd Cologne, Los Süd, “Static FE-Calculations of frozen soil measure for the construction of the tunnel cross connection QS1, Station Severinstrasse”
2004-2005	Metro Nord-Süd Cologne, Los Süd, “Thermal FE-calculations of the frozen soil measure for the construction of the tunnel cross connection at the Station Kartäuserhof”
2004-2005	RandstadRail, Rotterdam, „Development of a 3D-Model for a tunnel based on the results of boring and CPT-results, 3D-FE Calculation of a steel-lining connection for the construction of a tunnel cross connection”
2005	Sorenga, Oslo, Norway, “Verfication of the stability of a diafragm wall in a marine soft soils with numerical and analytical methods and monitoring of soil deformation during construction”
2005-2006	Railway Slab-Track System, Xian, China, “Assessment of the geotechnical, geological and hydrogeological site conditions, Assessment of the influence of collapsible soils and the feasibility of proposed soil improvement measures, Assessment of seismic hazard and soil liquefaction susceptibility of the ground”
2005-2006	R&D-Project, “Investigation of the behaviour of shallow foundations for wind turbines in the North Sea” (project leader)
2005-2006	R&D-Project, “Development of a constitutive model for frozen coarse soils” (project leader)
2005	Geotechnical Report, „Interpretation of CPT for the determination of the relative density of sandy damps from the brown coal mining in the zone of the damp NA3 at the mine Grazweiler” (project leader)
2005-2006	City Tunnel Leipzig, “Design of a tunnel cross connection, including tunnel lining for the connection with the main tunnel, recommendations for tunnel driving using frozen soil and air pressure”
2005-2006	Finnetunnel, “Preparation of tender design of tunnel cross connections”
2006	Orlowski Tunnel, St. Petersburg, “Preparation of tender, Planning and supervision of subsoil investigation”

Selected projects Bilfinger Berger AG / Bilfinger Berger Civil

2006-2008	Golden Ears Bridge, Vancouver, Canada, "Main Crossing and 30 km Highway construction. Geotechical re-design of Transcanadian Highway and Barnston drive underpasses. Advice and support of the construction team in different foundation, seismic and embankment design issues"
2006-2008	Ulmeav and Stocke Bridges, Botniabahnan, Sweden, "Geotechnical Interpretative Report (GIR). Geotechnical design of bridge foundations and temporary works"
2006-2008	Gbaran Ubie, Offshore Port Facilities, Nigeria, "Geotechnical Interpretative Report (GIR). Design of offshore pile foundation. Pile testing"
2006-2008	Nora Länken, shallow tunnel, "Recommendation for soil investigations. Factual report. Geotechnical Interpretative Report and Recommendations for construction"
2006-2010	E18, Norway. 35 km Highway, "Independent checking of geotechnical design, re-design of a failed embankments on quick-clay at Timenes"
2007	Indian River Bridge, USA, "Checking of geotechnical foundation design for bidding"
2007	Upgrading Katsina Airport, Katsina, Nigeria, "Pavement design"
2007-2011	Central Bank of Nigeria, Lagos, Nigeria, "Planning and supervision of subsoil investigation, Geotechnical Interpretative Report, Foundation Report, Design of Excavation Support, Planning, supervision and evaluation of Pile Loading Tests, geotechnical design of construction pit and dewatering system, supervision and quality control of foundation works, monitoring"
2007-2008	Port Mann Highway 1, "30 km highway (new/widening) with main span above the Fraser river. Geotechnical tender design of different foundations, embankments and soil improvement measures"
2007-2008	R&D-Project, "Development of a model for the prediction of the damage of prefabricated RC-piles during impact driving"

2008	Research & Development Project, “Geotechnical earthquake design of disconnected pile-footing Foundations”
2008	Panama Canal Extension, Third lock complex. “Geotechnical tender design of the pacific lock complex. Checking of geotechnical Design of the Atlantic lock complex. General coordination of geotechnical tender design”
2008-2011	Lekki-Ikoyi Bridge, Lagos, Nigeria, “Planning and supervision of subsoil investigation, Geotechnical Interpretative Report, Foundation Report, Planning, supervision and evaluation of Pile Loading Tests, supervision and quality control of foundation works, monitoring”
2009-2011	Metro Nord-Süd Cologne, Los Süd, “Waidmarkt Station, Investigation of the failure of the excavation pit. Study of the Influence of external excavations on the diaphragm wall of the failed pit”
2009-2011	Port Botany Expansion, Sydney, Australia, “Large port facility at the Port Botany bay. Consultancy for different geotechnical topics, including soil improvement, settlement calculations, soil improvement, prediction of settlement of a quay wall during earthquakes”
2010-2011	Research & Development Project, “Development of a numerical method for the one-dimensional calculation of settlement in soft soils including consolidation and creep”
2010-2012	Ship-lift Niederfinow, “Internal checking of the subsoil investigation data and geotechnical interpretative report. Numerical simulation of the construction process with the FE-Method, Planning a monitoring concept and application of the observational method during construction”

Selected projects Smoltczy & Partner GmbH

2011-2014	Katharinen Hospital, Stuttgart, “Subsoil Investigations, Geotechnical Interpretative and foundation report. Geotechnical Consultancy during construction”
2011-2014	3. Orinoco Bridge, Venezuela, “Checking geotechnical soil investigations, checking foundation design, supervision and checking pile loading tests, geotechnical soil investigations for temporary foundations and earth dams, support of structural engineers for the design”
2011-2014	The Grand Mosque of Algiers, “soil investigation program, geotechnical interpretative report, geotechnical calculations, supervision of soil investigation, pile and diaphragm walls testing and construction”
2013-2014	National Institute of legislative studies, Abuja, Nigeria, “geotechnical interpretative report, geotechnical calculations and recommendations for construction”
2013-2014	Water Treatment Plant “Aguas del Paraná”, Buenos Aires, Argentina. Geotechnical consultancy related to the failure of several deep excavations supported with diaphragm walls
2011-2013	Sir Al Gharbiyeh School, Lebanon, “Soil investigation program, geotechnical interpretative report, geotechnical calculations, supervision of soil investigation”
2011-2013	Photovoltaic cell production plant, Algiers, “Soil investigation program, geotechnical interpretative report, geotechnical calculations, supervision of soil investigation, design of soil improvement with stone columns, design and supervision loading test on group of columns, supervision of installation of columns”
2011-2015	Karlsruhe city-tunnel (Kombi-Lösung), “Geotechnical consultancy of the KASIG (client) during construction”
2012-2015	Stuttgart 21, Main Railway Station, “Geotechnical consultancy for the construction of the main station. Planning, supervision and interpretation of pile loading tests, 3D-FE-Element calculations of the main station, including soil-structure-foundation-interaction”
2013	Hydropower House 6, Kakhovka, Ucraine, “Geotechnical consultancy for the construction of a new power house in an existing hydropower station, including planning soil investigations, stability and seepage

	calculations of concrete structure, earth dam and construction process"
2014	Renkeltobel Bridge, Oberallgäu, "Geotechnical Independent Checking of geotechnical issues including soil investigation, slope stability and monitoring and bridge foundations"
2014	JiJi Hydropowerstation, Burundi, Africa, "Geotechnical Consultancy for a feasibility study for the construction of a hydropower station, including subsoil investigations, geological and geotechnical ground model, soil impermeabilization, slope stability, numerical calculation of dam stability and settlements of different structures (Spillway, intake, earth dam). Geotechnical Consultancy for a feasibility study"
2014	
2013-2016	German Embassy in Bishkek, "Soil investigation program, supervision of soil investigation, geotechnical interpretative report, geotechnical calculations"
2013-2016	Buenos Aires, Argentina, UTE Aguas del Paraná, "Analysis of the causes of damage during the construction of deep underwater excavations. Analysis of the project information, geotechnical report, participation in the negotiations between the construction and the assurance companies"
2013-2016	Ecuador, Presa Hidroeléctrica Manduriacu, "Analysis of a slope failure. Analysis of the project information, geotechnical report, participation in the negotiations between the construction and the insurance companies"

Selected projects Technische Universität München

2015-2016	Bridge B 10 Neu-Ulm, Günzburg (Europa road), “Geotechnical recommendations for the foundation of the North and South Abutments with a piled raft foundation”
2015-2018	Development Volksbank Raiffeisenbank Rosenheim, “Planning of soil investigation, “Geotechnical Interpretative report for a building in soft soils”, conception and geotechnical design of the construction pit and the foundation, monitoring program”
2016	Offshore Wind Farm Merkur, Electrical Offshore Substation (EOS), “Independent checking of the Calculation Basis Geotechnical Design”
2016-2017	Photovoltaic cell production plant, Algiers, “Geotechnical consultancy in the framework of an international lawsuit (ICC procedure)”
2016-2017	Linde AG, Engineering Division, “Thermal Energy Storage for Aksai Project 1, Experimental and numerical investigations for the foundation of salt melting tanks for energy storage” (Project Aksai 3710BCPA)
2016-2017	Extension of the bypass road „Mittlerer Ring“ (B2R), “Geotechnical interpretative report for the Tunnel Landshuter Allee”
2016-2017	SIOT – Tank farm Triest, Tank 24 – Investigation of the causes of the excessive tank settlements and geotechical design of a remediation measure for the tank foundation.
2016-2017	West bypass road B15, Rosenheim, pile foundation for a stayed cable bridge in soft soils with high sensibility, “Geotechnical consultancy, including planning and supervision of additional subsoil investigations and pile loading tests, numerical simulations of the behavior of the bridge foundation and recommendations for construction”
2016	Dominion Diamond Corporation, Canada, DDMI, Diavik cutt-off-wall, Geotechnical Consultancy for the control of the relative density after vibro-compaction.
2016	Sylvensteinspeicher / water dam, “geotechnical consultancy for the rebuild and adaptation of the main outlet”
2016-2017	Ingolstadt, IN-Tower, High-rise building, geotechnical consultancy for the design and the settlement calculation of a piled raft foundation

2017	Lawsuit Sand- und Kieswerk Rauscheröd Ulrich Alex GmbH ./. Jakob Reiter Az: 4 O 436/15, “expert opinion for the law court”
Since 2017	Stuttgart 21, Main Railway Station, “Geotechnical consultancy for the construction of the main station. Planning, supervision and interpretation of pile loading tests, 3D-FE-Element calculations of the main station, including soil-structure-foundation-interaction”
2017	U-Bahnhof Max-Weber-Platz, München, “Geotechnical consultancy for the stability of the top slab of the Metro station Max-Weber-Platz“
Since 2017	U9-Spange, Giselastraße, “Geotechnical consultancy for the preliminary evaluation of the geological and hydrogeological conditions on the basis of existing data for the metro station Giselastraße”
2017	U-Bahnlinie 5-West der Stadt München, “seepage model for the determination of the influence of the metro tunnel on the ground water table of the quaternary aquifer”
Since 2017	Kramertunnel – “Geotechnical and tunneling consultancy for the tender design”
2017	Industrial zone Göldern-Ost, Reichenau (Lidl- und dm-Market), “Geotechnical consultancy for a pile foundation with micropiles in soft soil regarding the safety against buckling”
2017	Railway overpass „Tumblingerstraße“, “Determination of the groundwater table for the construction time and for the time after finishing construction using measured and historical groundwater data and statistical methods”
Since 2017	Tunnel Auberg, “Geotechnical and tunnelling consultancy for the tender design”
Since 2017	Tunnel Bertoldshofen, “Geotechnical and tunnelling consultancy for the tender design”
2018	DB Verkehrsstation Lindau-Reutin, “geotechnical assessment of foundation alternatives for the railway station”
2018	DB Knoten Lindau, Gleisdreieck am Lotzbeckweg / Aeschacher Ufer, geotechnical assessment of construction alternatives for a railway overpass
Since 2018	Hofer, Zweigniederlassung Loosdorf, “Investigation of the cause of

	unexpected foundation settlement that occurred during construction”
Since 2018	BA 49/13, Einrichtungshaus (XXXLutz und Mömax) in Kempten, “Geotechnical assessment of the soil parameters and the earth pressure acting on the building, development of a monitoring concept”
Since 2018	DB railway overpass BW 8.2, Rosenheim, “Geotechnical independent checking of the foundation and excavation design as well as the construction method”
Since 2018	Bhf Pasing für die U-Bahnlinie U5 der Stadt München: Erstellung des Geotechnischen Berichts
Since 2018	Metro Gran Paris Express, Paris, “Geotechnical Assessment and optimization of the Metro Stations Santory, Saint Quentin and Versailles Chantiers, new metro Line 18”, Societé de Grand Paris
2019	Metro Gran Paris Express, Paris, “Geotechnical Assessment and optimization of the Metro Stations Santory, Saint Quentin and Versailles Chantiers, new metro Line 15O”, Societé de Grand Paris
2019	Metro Gran Paris Express, Paris, “Numerical study of the construction of the gare hybrid”, Societé de Grand Paris
Since 2019	Metro Nord-Süd Cologne, Los Süd, “Waidmarkt Station, geotechnical checking of the design rehabilitation measures for the completion of construction of the station in the damaged excavation”
2020	Geokunststoffbewehrte Stützkonstruktionen mit Gabionenfronten, BAB A3 bei Geiselwind
Since 2020	Hangbrücke Schellenberg, B2 Donauwörth, Beurteilung des Tragverhaltens der Brückengründung und Empfehlungen für Ertüchtigungsmaßnahmen
2020	Anbindung Schleißheimertraße an A99, Variantenuntersuchung (7 Varianten) allgemeine Baugrundbeschreibung, GW mit statistischer Auswertung GW-Modell, Tunnel offene bauweise allgemeine butechnishe Geichtpunke
Since 2020	Tunnel Kauerndorf: Tunnelbautechnischer Sachverständiger für einen 700 m langen Straßentunnel inklusive Portalbaugruben und Rettungsstollen
Since 2020	Wanktunnel: Tunnelbautechnischer Sachverständiger für einen 3,2

	km langen Straßentunnelinklusive Portalbaugruben und Rettungsstollen
Since 2020	Fentbergstollen: Tunnelbautechnischer Sachverständiger für einen ca. 11 km langen Trinkwasserstollen für die Stadt München
Since 2021	Lokhöfe Baufeld 5 und 6, Rosenheim, Gründung eines Gebäudekomplexes auf strukturempfindlichen feinkörnigen Böden. Geotechnische Beratung, Gründungskonzept und Prüfung der Gründung
Since 2021	Schadensfall ATC Aldenhoven, Gutachterliche Beurteilung der Rissbildung in der Asphaltbefestigung und Ausführung der Schutzplanken in den Steilkurven.
Since 2020	Schadensfall B 33 Tunnel Waldsiedlung, gutachtliche Beurteilung der Ursache von unplanmäßigen Verbauverformungen
Since 2021	Neubau U9-Entlastungsspange München, geotechnischer Bericht, geotechnische Beratung für 10,5 km U-Bahn-Strecke.

Geotechnik Schweiz Frühjahrstagung 2019

Vereisungsmassnahmen in der Geotechnik

Neubau der U5 in Berlin - Errichtung der Bahnsteighalle im Schutz einer Baugrundvereisung

Referent:

Torsten Brenner, Teilprojektleiter Museumsinsel,

Ingenieurbüro Brenner

Co-Autoren

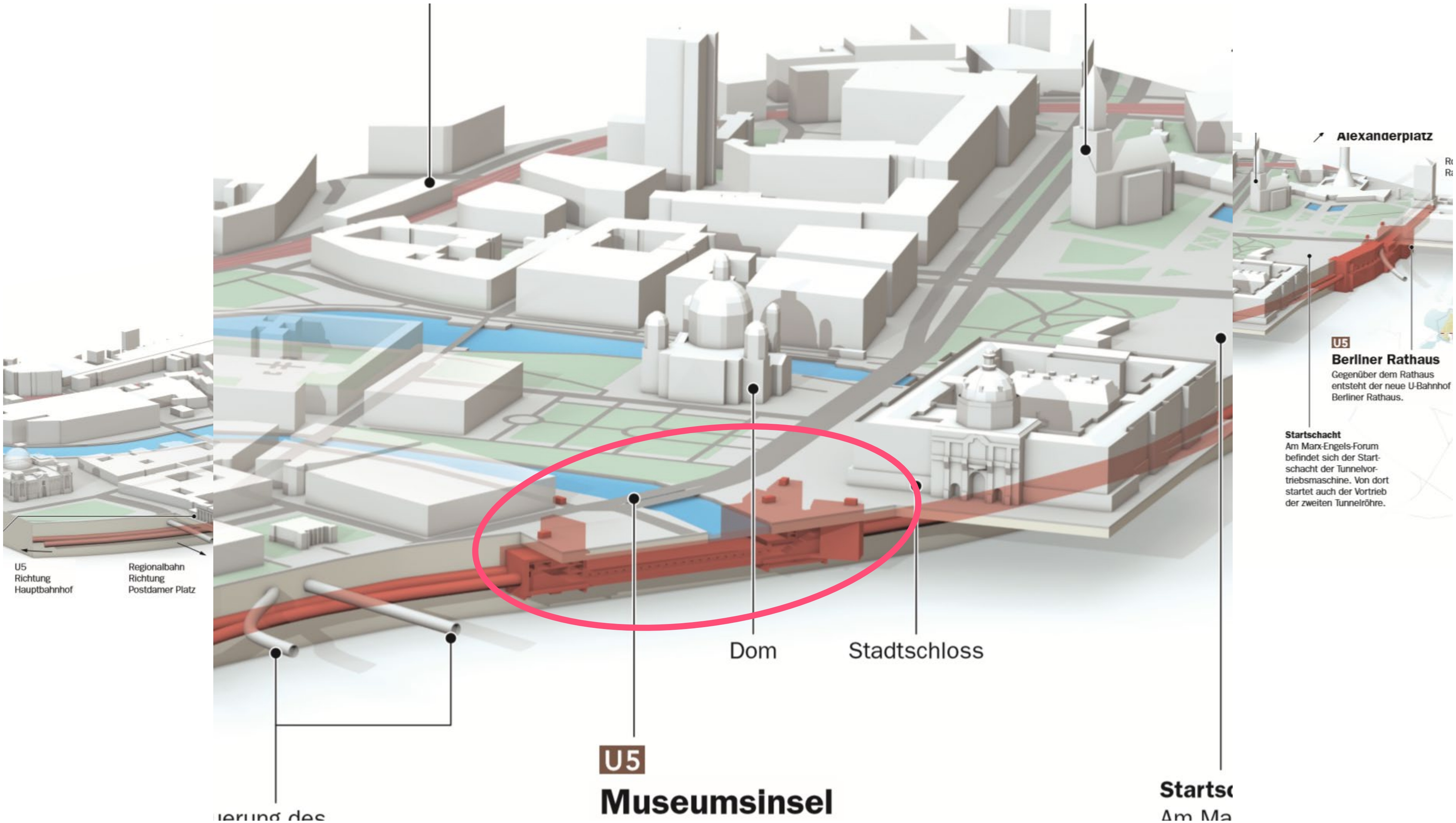
Jörg Seegers, Projektrealisierungs GmbH U5

Ralf Hebecker, Gruner AG

PROJEKT U5

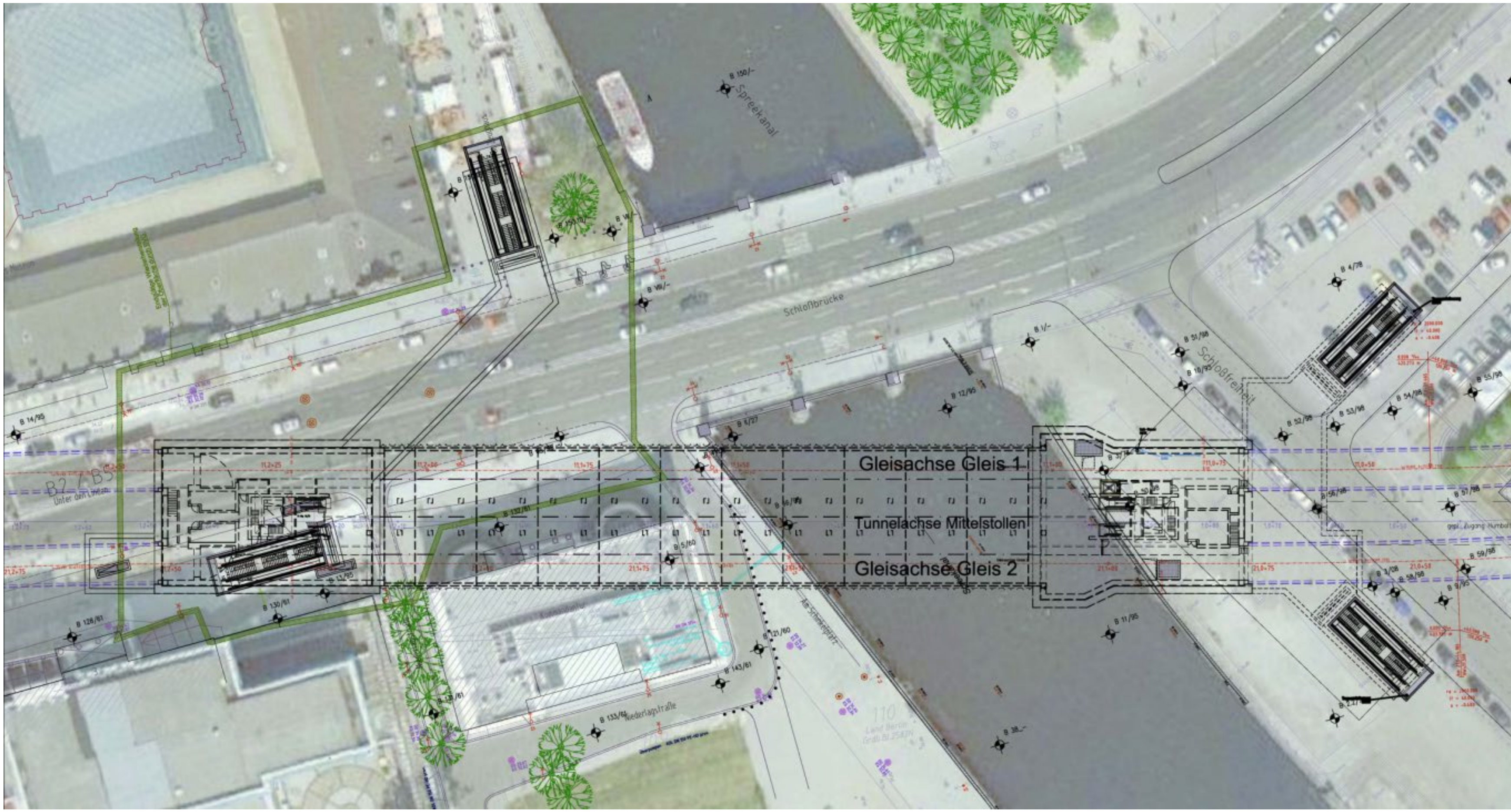
Projektrealisierungs GmbH U5

Der Bahnhof „Museumsinsel“ (MUI) liegt teilweise unterhalb des Spreekanals.



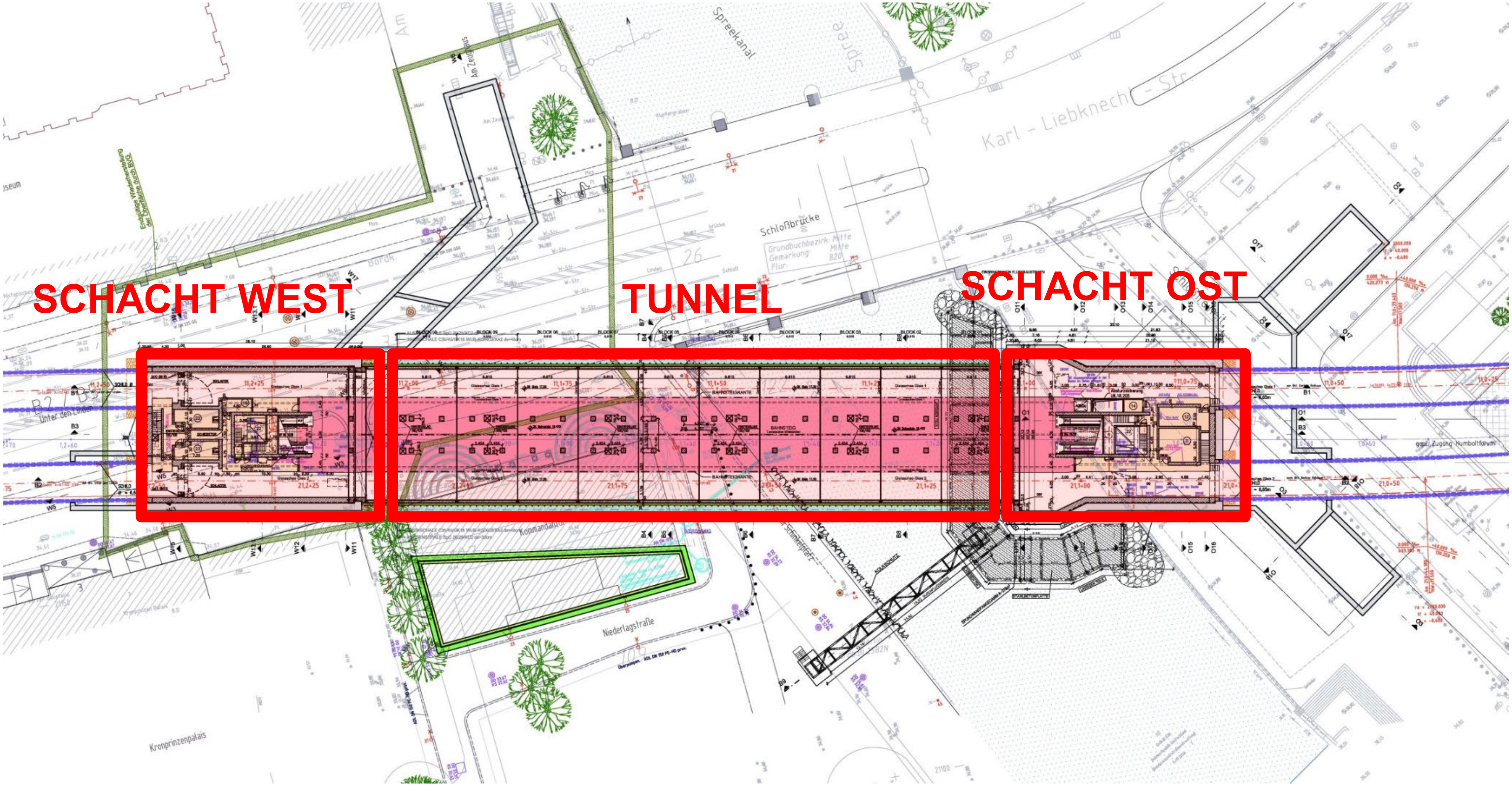
PROJEKT U5
Projektrealisierungs GmbH U5

U-Bahnhof Museumsinsel (MUI) – die Lage



PROJEKT U5
Projektrealisierungs GmbH U5

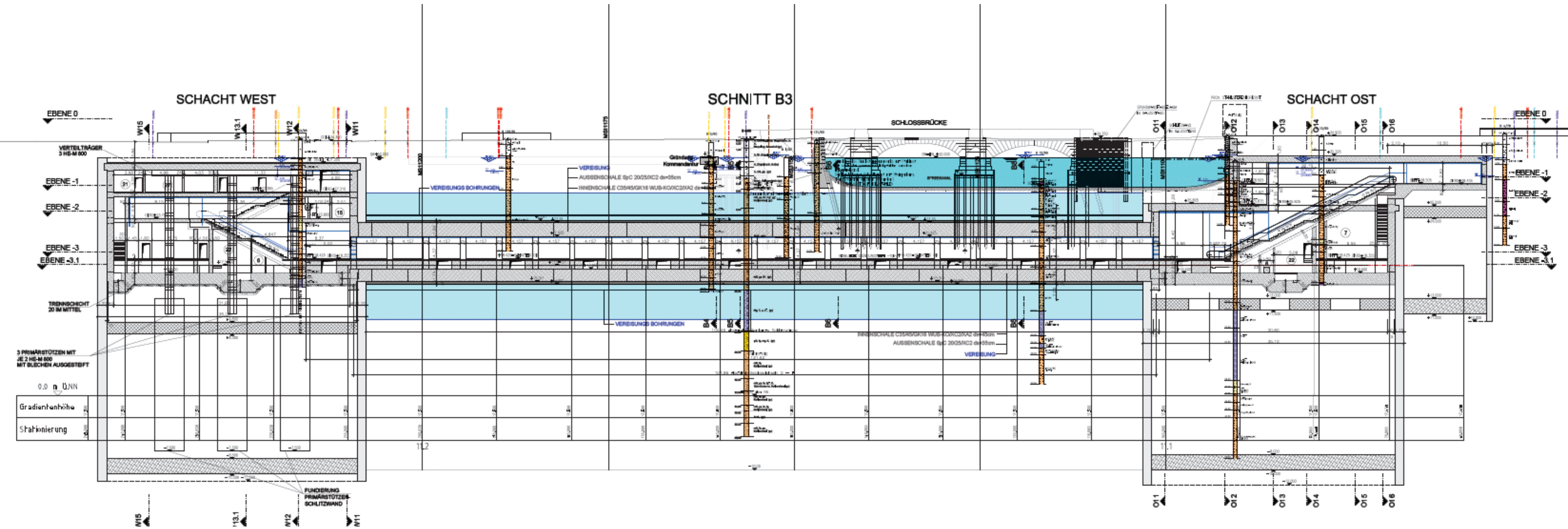
U-Bahnhof Museumsinsel (MUI) – strukturelle Draufsicht



Abmessungen des Bahnhofes: 215 m x 26 m

U-Bahnhof Museumsinsel (MUI) – Längsschnitt

Errichtung der 105 m langen Bahnsteighalle in geschlossener Bauweise



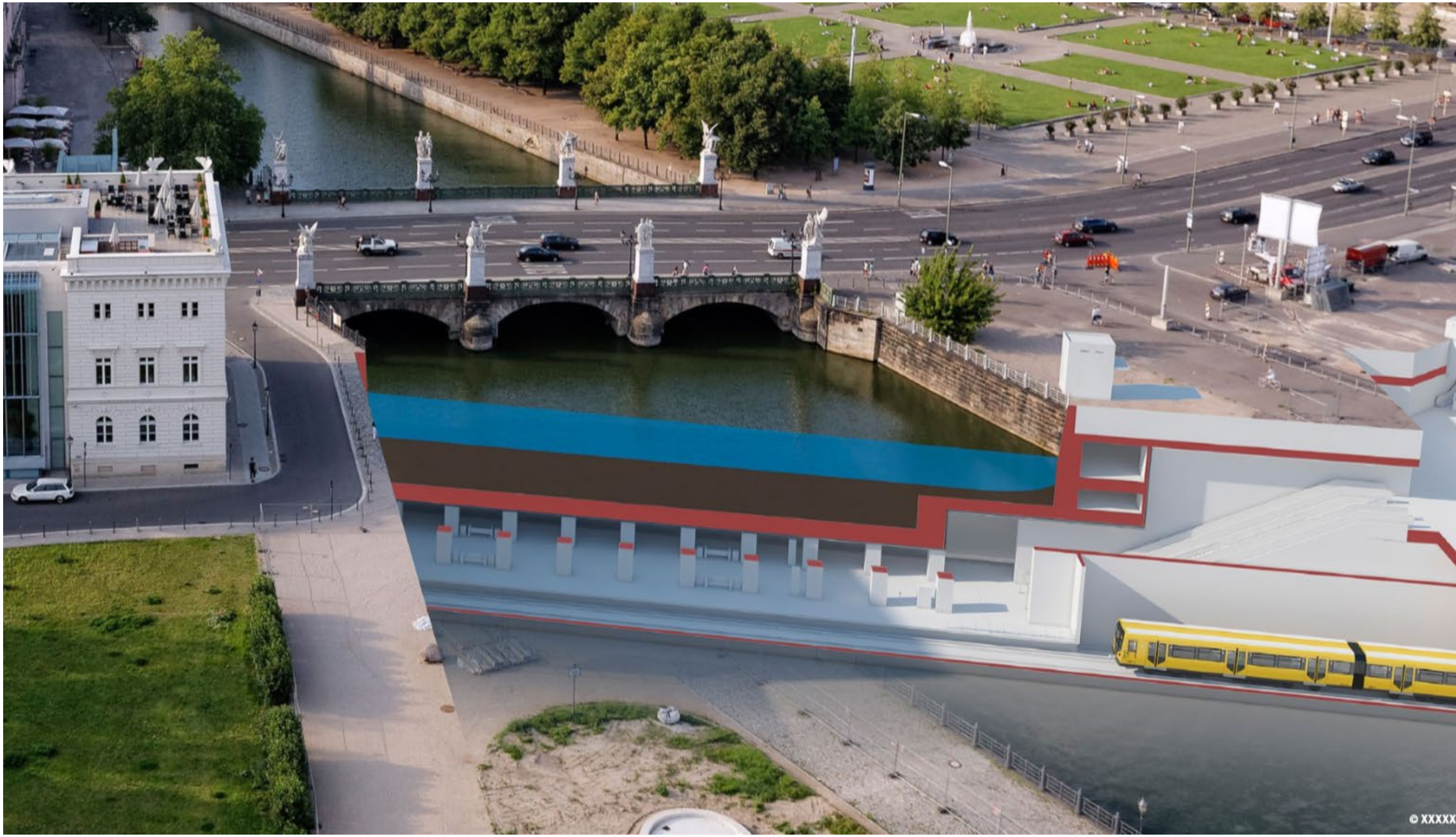
SCHACHT WEST | TUNNEL | SCHACHT OST

Schlitzwände bis 44 m unter Terrain

Schachtsohlen bei 22 m unter Terrain

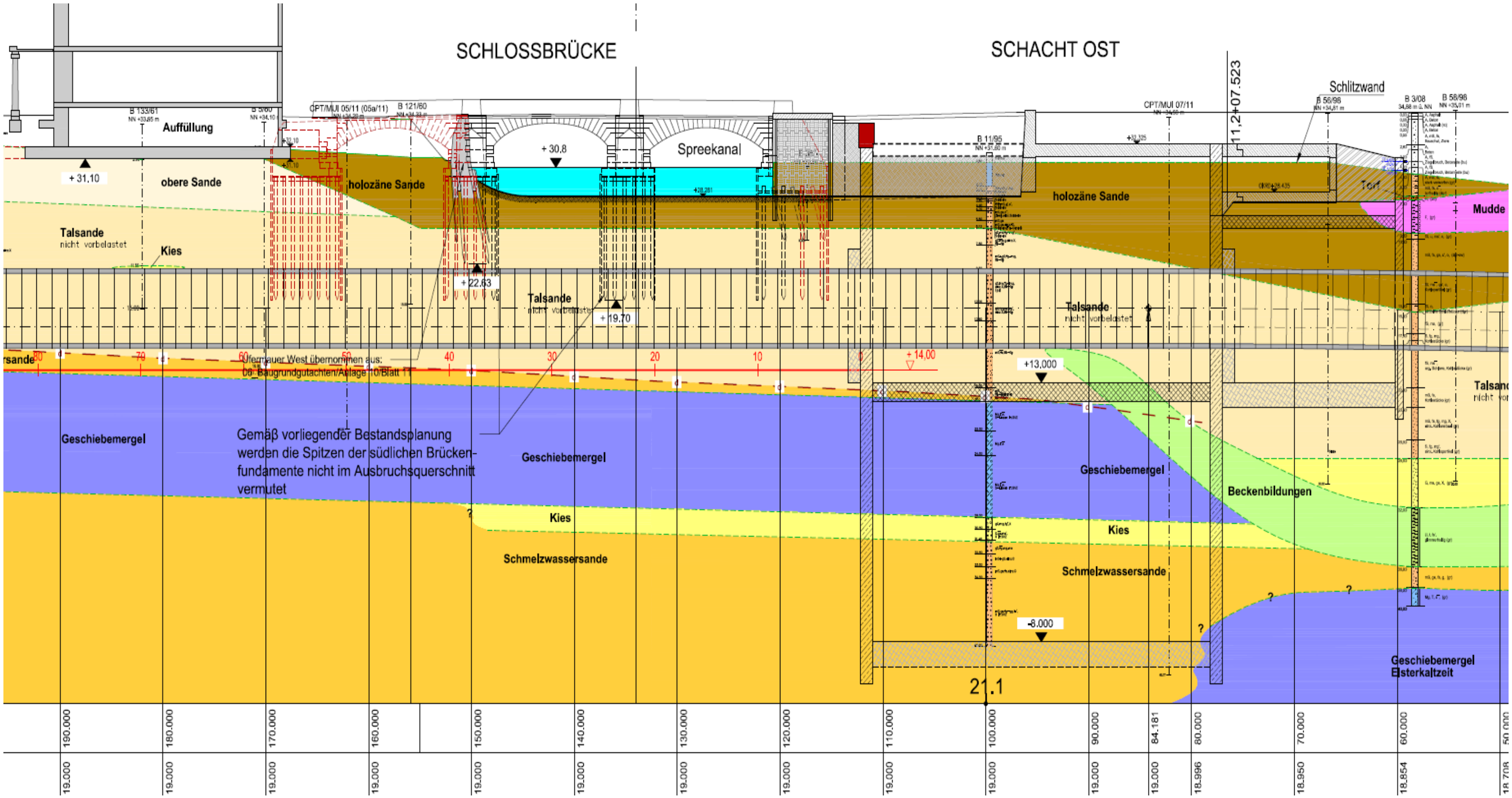
Überdeckung im Spreekanal maximal 5 m

U-Bahnhof Museumsinsel (MUI) - Vereisung des Baugrundes zur Herstellung der Bahnsteighalle



PROJEKT U5
Projektrealisierungs GmbH U5

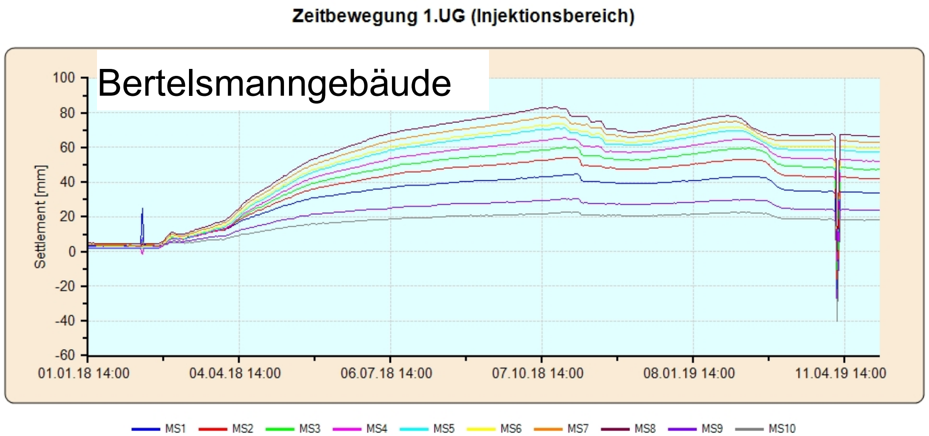
Geologie / Baugrund

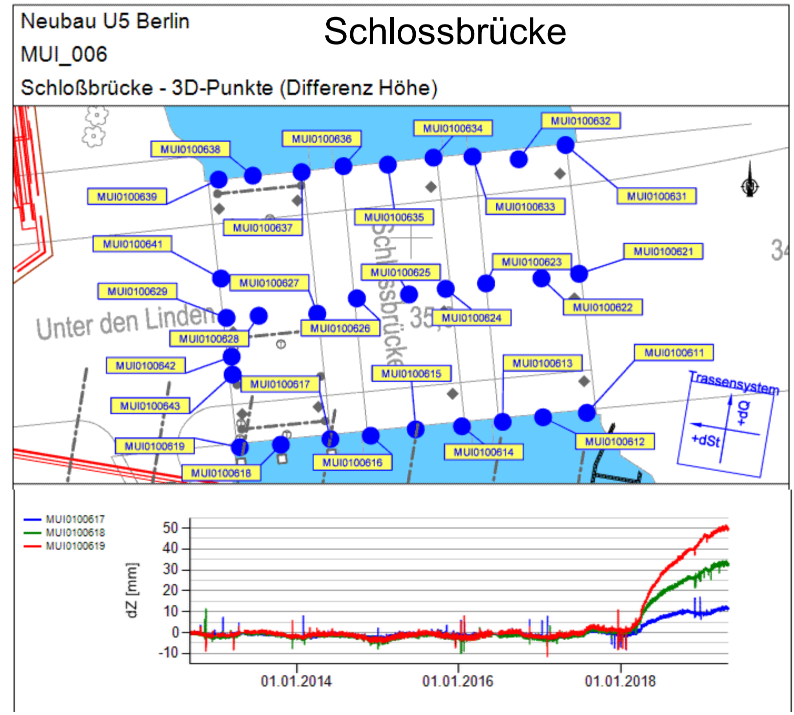


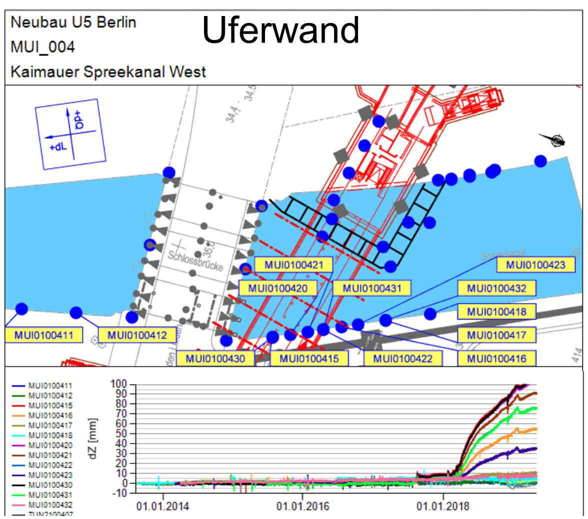
Talsande, darunter erodierte Sand- und Geschiebemergelschichten und weichselkaltzeitlicher Geschiebemergel in stark schwankender Mächtigkeit, Grobgeschiebelagen, einzelne Blöcke und Steine

PROJEKT U5
Projektrealisierungs GmbH U5

Besonderheiten Großräumige Hebungen







Großräumige Hebungen bis 105 mm.

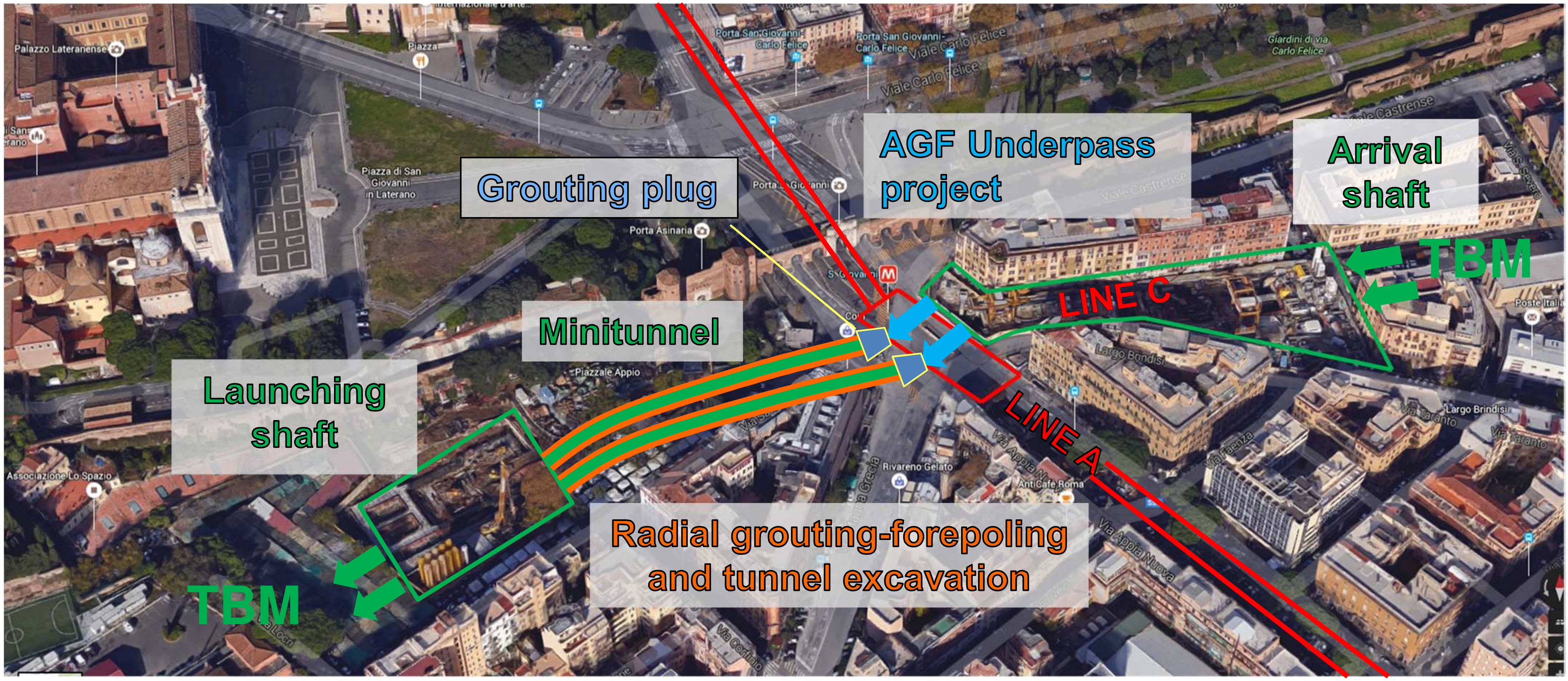
Artificial Ground Freezing – An application for the Underpass of an existing Metro Station in Rome

Bern 16/05/2019

TREVIGroup

Eng. Luca Pingue
Senior Technical Advisor
Design, Research and Development dept.

PROJECT OVERVIEW

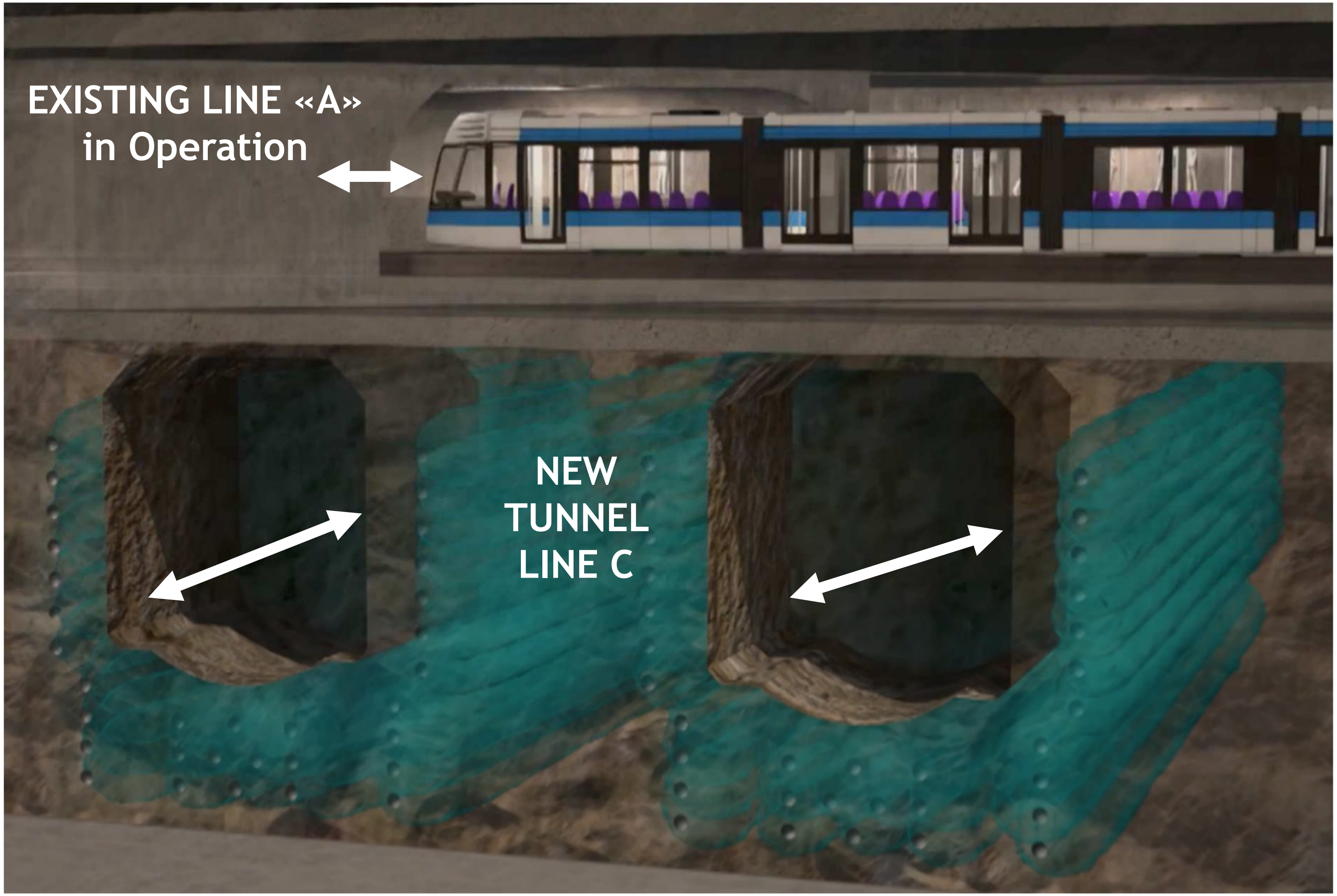


For completing the remaining portion of the tunnels (i.e. from the East side of the ne station and the launching shaft), two different methods were adopted. The section below the existing station was performed by mined excavation under the protection of AGF walls and a grouting plug.

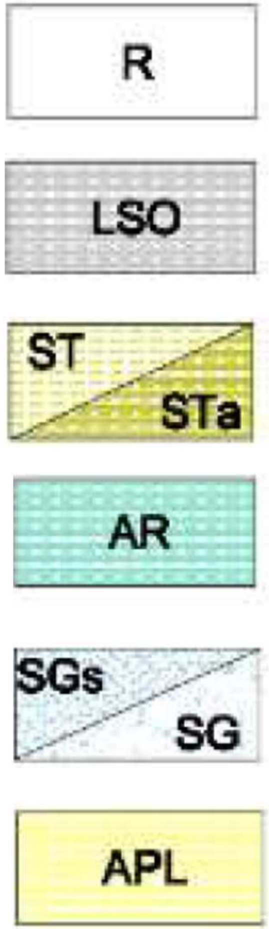
While the section between the launching shaft and the grouting plug was performed by mechanized boring of two mini-tunnels successively enlarged to the required section under the protection of radial grouting and forepoling.

PROJECT OVERVIEW

AGF application to create a structural and waterproof temporary cut off to allow the excavation with conventional mining method of the two new tunnels, while keeping trains running in the safest possible condition.



PROJECT OVERVIEW



Made Ground

Alluvial silty clay and silty sand

Sandy silt and clayey silt

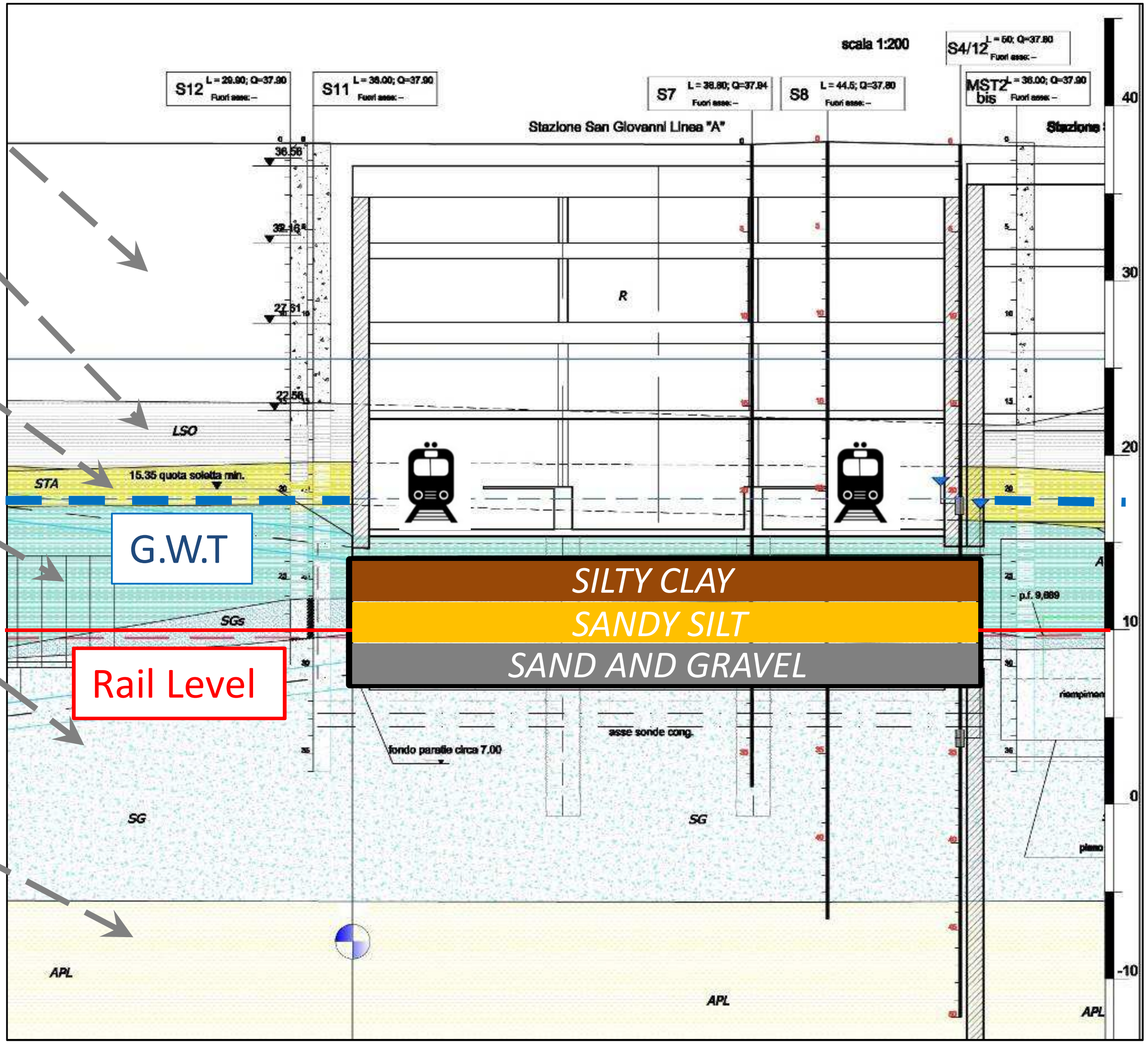
Clayey silt and Silty Clay

Sand and gravel

Silty Clay

Unconfined Water Table at an absolute elevation of 18 m…

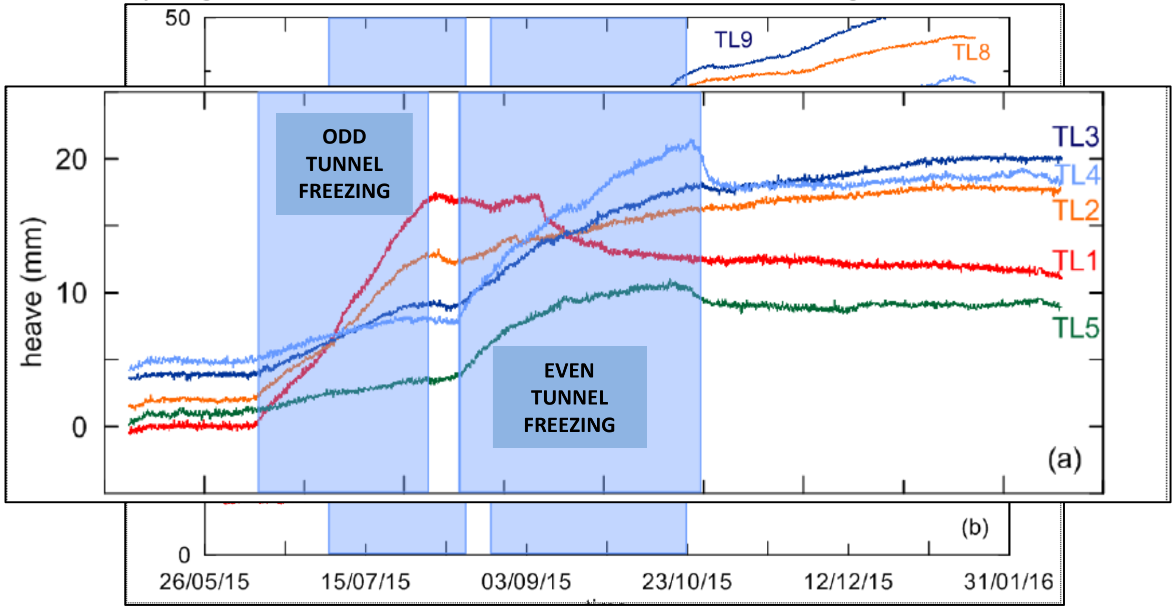
…Confined Water Table in sand and gravel layer

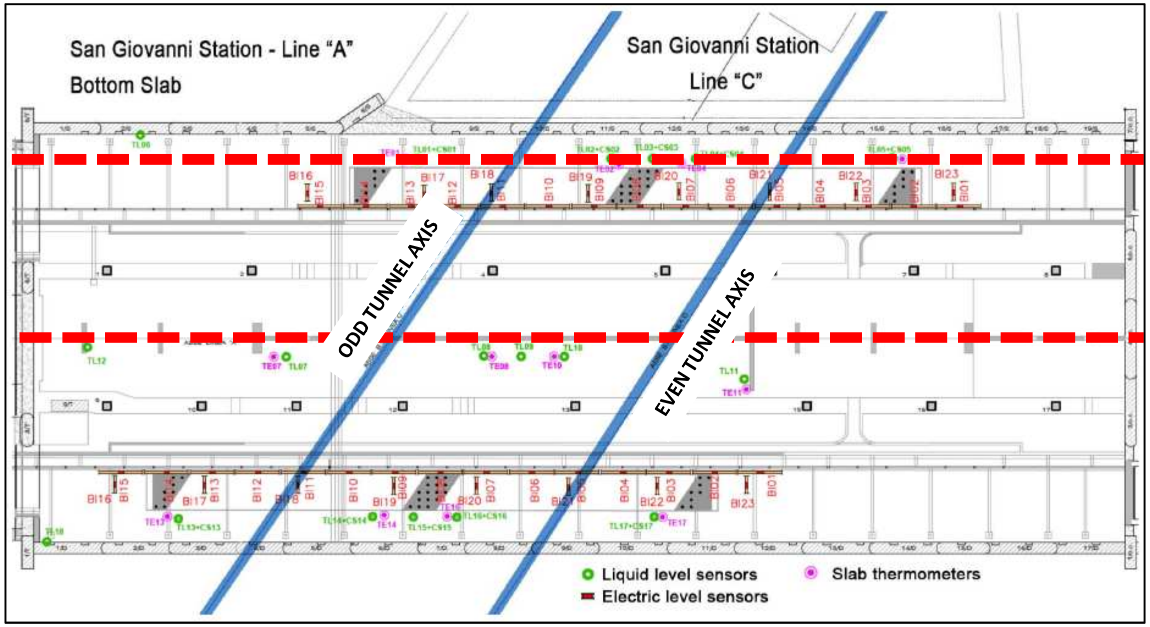


MESURES AND MONITORING SYSTEM

Bottom slab of the overlaying Line “A” deformation monitoring:

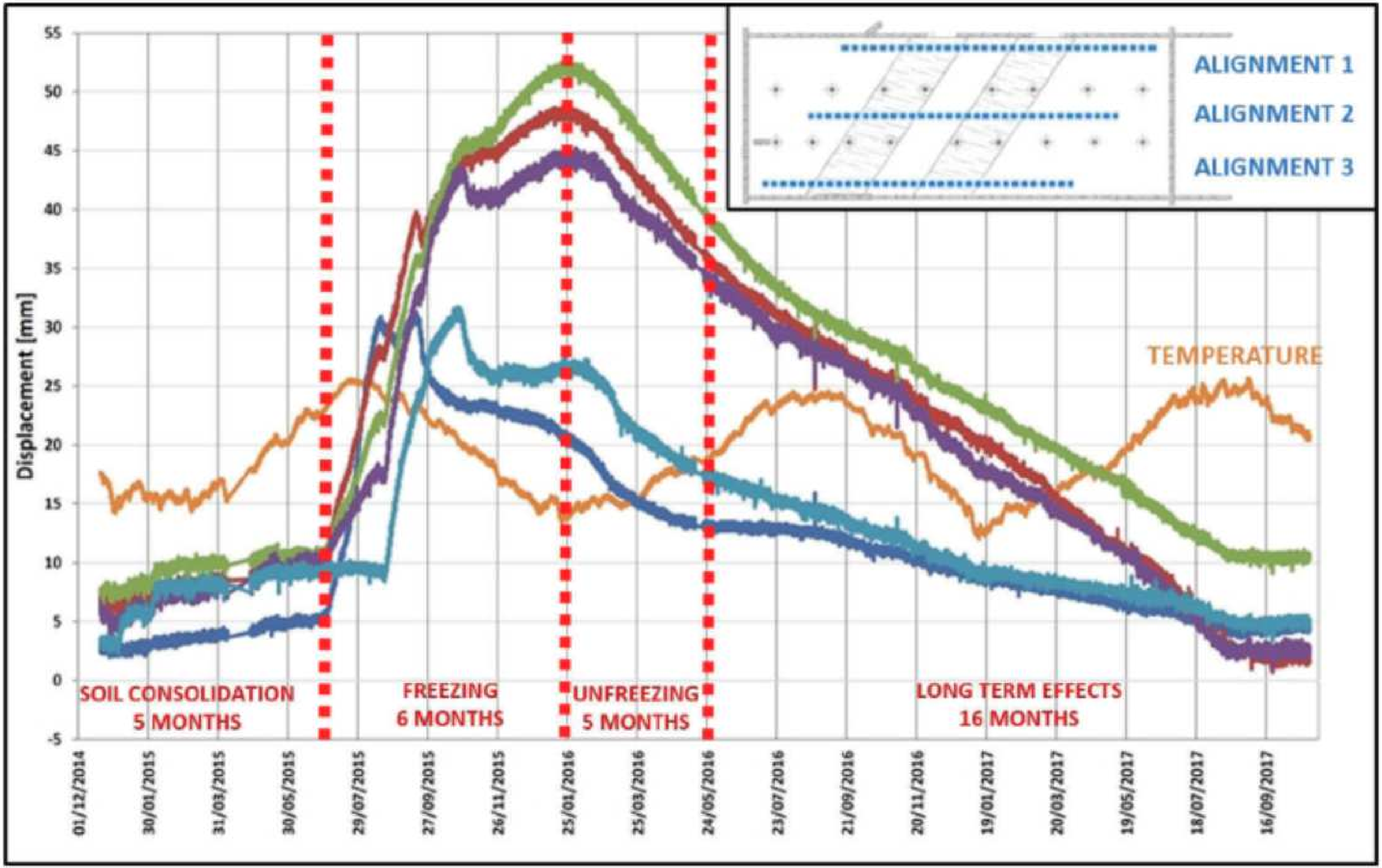
The initial vertical displacements of some of the points are not zero as some heave was caused by the preliminary cement and chemical grout injection

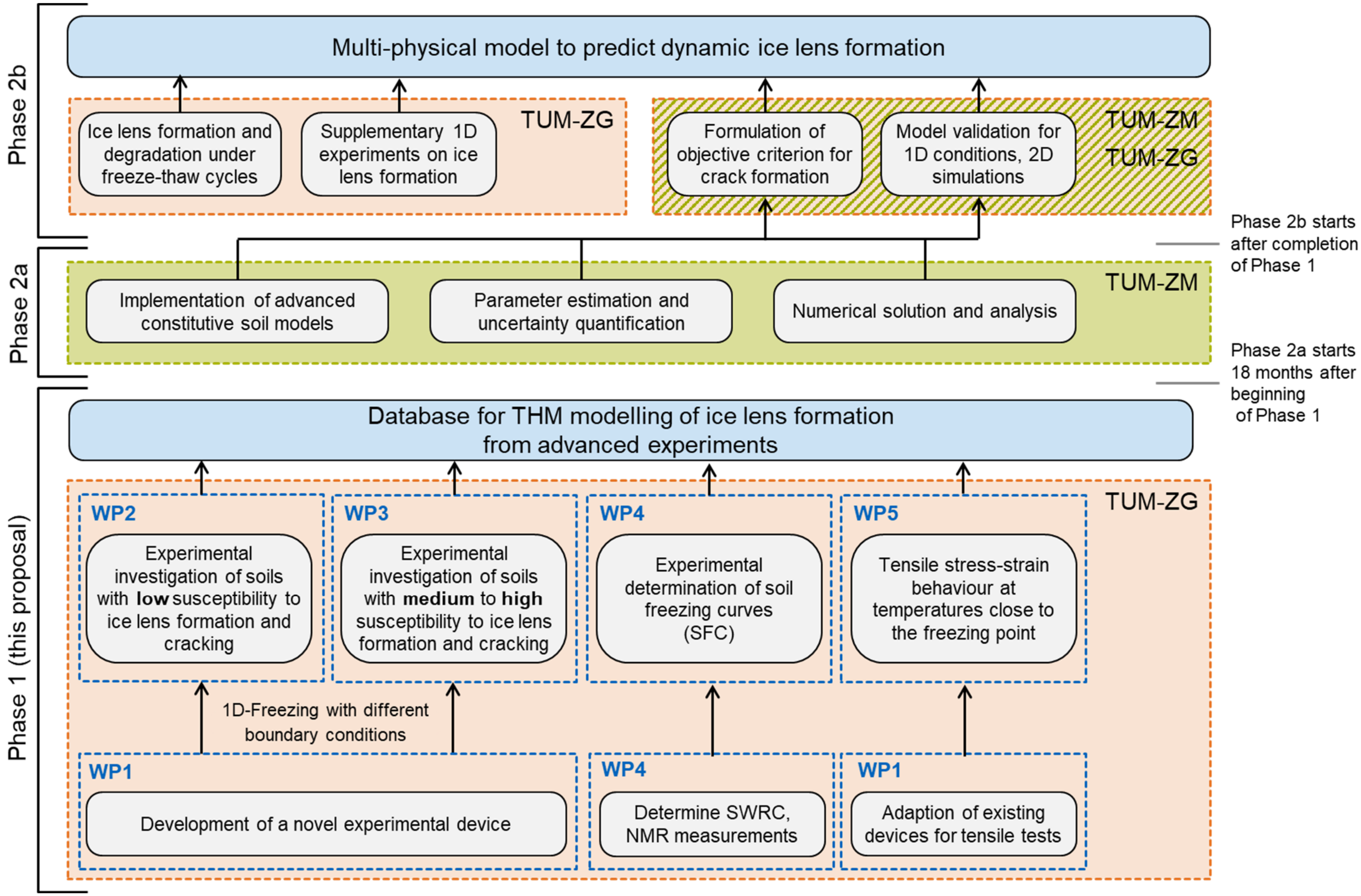




MESURES AND MONITORING SYSTEM

Bottom slab of the overlaying Line “A” deformation monitoring:





Technische Universität München

Technische Universität München

Stand: Beginn Sommersemester 2021

Beschäftigung in Wochenstunden	wissenschaftliche Hilfskraft	Studierende/r mit wiss. Hilfstätigkeiten	Studierende/r mit wiss. Hilfstätigkeiten
	Master Universität Diplom Universität Master FH/HAW	Bachelor Universität Diplom FH/HAW Bachelor FH/HAW	ohne Hochschulabschluss
	18,50 €	**13,60 €**	**11,70 €**
1,00	80 €	59 €	51 €
1,50	121 €	89 €	76 €
2,00	161 €	118 €	102 €
2,50	201 €	148 €	127 €
3,00	241 €	177 €	153 €
3,50	282 €	207 €	178 €
4,00	322 €	237 €	203 €
4,50	362 €	266 €	229 €
5,00	**402 €**	296 €	254 €
5,50	442 €	325 €	280 €
6,00	483 €	355 €	305 €
6,50	523 €	384 €	331 €
7,00	563 €	**414 €**	356 €
7,50	603 €	443 €	382 €
8,00	644 €	473 €	**407 €**
8,50	684 €	503 €	432 €
9,00	724 €	532 €	458 €
9,50	764 €	562 €	483 €
10,00	804 €	591 €	509 €
10,50	845 €	621 €	534 €
11,00	885 €	650 €	560 €
11,50	925 €	680 €	585 €
12,00	965 €	710 €	610 €
12,50	1.005 €	739 €	636 €
13,00	1.046 €	769 €	661 €
13,50	1.086 €	798 €	687 €
14,00	1.126 €	828 €	712 €
14,50	1.166 €	857 €	738 €
15,00	1.207 €	887 €	763 €
15,50	1.247 €	917 €	789 €
16,00	1.287 €	946 €	814 €
16,50	1.327 €	976 €	839 €
17,00	1.367 €	1.005 €	865 €
17,50	1.408 €	1.035 €	890 €
18,00	1.448 €	1.064 €	916 €
18,50	1.488 €	1.094 €	941 €
19,00	1.528 €	1.124 €	967 €
19,50	1.569 €	1.153 €	992 €
20,00	1.609 €	1.183 €	1.017 €

Hinweis: Die drei fett markierten Beträgen kennzeichnen die jeweilige 450 €-Grenze unter Berücksichtigung der zustehenden Sonderzahlung. Diese Angabe erfolgt ohne Gewähr, Abweichungen sind im Einzelfall möglich. Verbindliche Auskünfte zur Sozialversicherungspflicht erteilt das Landesamt für Finanzen.

GEOTECHNIK

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Prüfamt für Grundbau, Bodenmechanik, Felsmechanik
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Baumbachstraße 7
81245 München

Angebot 19600763

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Durchwahl: +49 551 30752 116
Fax: +49 551 30752 20
E-Mail: twille@wille-geotechnik.com
Web: www.wille-geotechnik.com

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Telefon: +49 89 289 27144
Fax: +49 89 28927 189

Datum: 30.10.2019
gültig bis: 29.12.2019

Sehr geehrter Herr Schindler,

vielen Dank für Ihre Anfrage. Im Folgenden erhalten Sie unser Angebot über einen elektromechanischen Lastrahmen bis 60 kN Axiallast vom Typ UL60 mit digitalem Wegsensor, Kraftsensor und servopneumatischer Drucksteuerung

Bei Fragen stehen wir Ihnen gerne zur Verfügung.

Mit freundlichen Grüßen

i. A. Carsten Fette
Ihr Ansprechpartner APS

Pos	Artikelnummer/Bezeichnung/Spezifikation	Menge	Einzelpreis	Nettopreis
1	00101-A4-001	1 Stk.	15.850,00	15.850,00

Microprozessorgesteuerte Präzisions- Universalprüfpresse UL 60
mit integrierter Kraft-, Lage- und Geschwindigkeitsregelung
sowie integrierter Messdatenerfassung

- Geeignet zur Durchführung von jeder Art von Kompressionsversuchen mit geregelten, konstanten Geschwindigkeiten oder lastunabhängigen Lagen (kostanste Höhe), nach internem oder externem Wegsensor, konstante, incrementale Lasten (Lastregelung) sowie alle Arten von Lastrampen mit Be- und Entlastung nach internen oder externen Kraft- oder Drucksensoren
- Sollwertüberwachung durch geschlossenen Regelkreis bis zu 1000 Mal pro Sekunde
- präzise feinstregulierbare Steuerung über hochgenauen, elektromechanischen Präzisionsantrieb mit vorgespannter und gelagerter Kugelumlaufspindel
- Extrem robuste Industriesteuerung von SIEMENS mit menügeführter Versuchsdurchführung und serieller sowie Ethernet-Schnittstelle
- Integrierte Messdatenerfassung mit A/DWandlung für alle angeschlossenen Sensoren mit 4-20 mA oder 0-10 V bis zu 6

Pos	Artikelnummer/Bezeichnung/Spezifikation	Menge	Einzelpreis	Nettopreis

Sensoren

- Optimale Meßbereichswahl durch austauschbare Kraftsensoren mit automatischer Sensorerkennung (wahlweise z.B. 0.5, 2, 5, 10, 20 oder 60 kN)
- Direkte, menügeführte vollautomatische Ansteuerung über PC mit Steuerssoftware oder halbautomatisch über das integrierte Bedientableau mit Folientastatur
- 2-Säulen Standmodell mit stabilem geschweißtem, pulverbeschichtetem Stahlblechgehäuse (auch als Tischmodell UL 60/T)
- Ausbaufähige, robuste und kompakte Konstruktion
- Geeignet für unterschiedlichste Prüfeinsätze wie Triaxialzellen bis 150er Probendurchmesser, Ödometerzellen, Kompressionseinsätze, Scherprüfungen, CBR-Versuche, etc.
- Erweiterbar durch Steuerungsmodule für verschiedene Versuchsarten
- Softwaregestützter Festspeicher für die Sensorkalibrierung, bedienbar über Folientastatur

Technische Daten:

- Maximalkraft: 60 kN (Lieferung ohne Kraftsensor)
- Spindelhub: 100 mm
- Vorschubgeschw. (stufenlos): 60-0.00001 mm/min
- Lichte Prüfraumhöhe: ca. 1000 mm
- Prüfraumweite: 360mm
- Maße (H*B*T): 2200*600*600 mm
- Versorgungsspannung: 220 V
- Integrierte Zusatzeingänge: 4 (optional 0-10 V, 4-20 mA)
- Serielle oder Ethernet-Schnittstelle

Notwendiges Zubehör:

- Kraftsensor (0.5,2,5,10,20 oder 60 kN)
- Wegmeßgeber beliebiger Länge (siehe Optionen)

Optionen:

- Adapter für beliebige Applikationen bzw. Versuche nach Versuchsart
- PC und Softwaremodule für verschiedene Triaxialversuche oder andere Applikationen
- Verschiedene Steuer- und Regelungssoftware für verschiedenen bodenmechanische Versuche Adapter für beliebige Applikationen bzw. Versuche nach Versuchsart
- PC und Softwaremodule für verschiedene Triaxialversuche oder andere Applikationen
- Verschiedene Steuer- und Regelungssoftware für verschiedenen bodenmechanische Versuche
- Automatische Hebevorrichtung für Triaxialzellen

Pos	Artikelnummer	Menge	Einzelpreis	Nettopreis
2	00401-A1-007	1 Stk.	1.140,00	1.140,00

APS Antriebs-, Prüf- und Steuertechnik GmbH
Götzenbreite 12, D-37124 Rosdorf
Geschäftsführer Thorsten Wille

Commerzbank Göttingen
IBAN DE19 2604 0030 0627 9269 00
BIC COBADEFF260

Volksbank Solling eG
IBAN DE67 2626 1693 0700 9291 00
BIC GENODEF1HDG

Gerichtsstand Göttingen
HRB Göttingen 4129
UST-ID DE 162 092 653
St.-Nr. 20 200 14631

Pos	Artikelnummer/Bezeichnung/Spezifikation	Menge	Einzelpreis	Nettopreis

Kraftsensor 60 kN mit Messverstärker

Hauptbestandteile:

- DMS-Präzisionskraftsensor zur Messung mit integriertem Meßverstärker
- Einfaches Wechseln des Sensors ohne Neukalibrierung und automatischer Sensorerkennung an den Prüfmaschinen
- Zum Anschluß an Triaxialprüfanlagen, Kompressionsgeräte, Prüfpressen, Datalogger oder elektronisches Display der Wille Geotechnik

Technische Daten:

- Meßbereich: 60 kN
- Genauigkeitsklasse: 0.1 %.
  mit Meßverstärker: 0.2 %
- Normsignalausgang: 0-10 V

Pos	Artikelnummer/Bezeichnung/Spezifikation	Menge	Einzelpreis	Nettopreis
3	00403-A7-001	1 Stk.	1.380,00	1.380,00

Typ. DIT30.91

Wegaufnehmer, inkremental, Messbereich 30mm

Digitaler Präzisions-Wegaufnehmer, 30 mm, Auflösung 0.025 µm mit Kabelkonfektionierung zum Anschluß an eine WILLE GEOTECHNIK Prüfpresse

Technische Daten:

- Meßbereich: 0 - 30 mm
- Auflösung: 0,025 µm
- Max. Verfahrgeschwindigkeit: 0,225 m/s
- Einspannschaft: Ø 8 mm
- Schutzart: IP 64

Pos	Artikelnummer/Bezeichnung/Spezifikation	Menge	Einzelpreis	Nettopreis
4	AN-1000	1 Stk.	8.450,00	8.450,00

Mikroprozessorgesteuerte Druckregelapparatur "APC-3/XX " mit 3 Druckausgängen mit kundenspezifischen Druckbereichen

- Vollautomatischer, elektropneumatischer Regelkreis zur Erzeugung von hydrostatischen Drücken (z.B. Zell- und Sättigungsdruck)
- Vollautomatische Regelung des Drucks über integrierten Mikroprozessor
- Meßwertkontrolle und Steuerung über 3 integrierte Präzisions-Druckregler
- Hochgenaue, kontinuierliche Nachregelung der vorgegebenen Drücke (Spannungen) durch Soll/Ist Vergleich
- Direkte, menügeführte Ansteuerung über PC oder über das integrierte Bedientableau mit Folientastatur
- Leichte Handhabung
- Kompakte, platzsparende Bauform
- z.B. geeignet für Durchlässigkeitsprüfanlagen, Triaxialscheranlagen, pneumatische Oedometer, etc.

Technische Daten:

- Regelbereich: kundenspezifisch
- Auflösung: 0.1 KPa
- Anschluß: 230 V

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Pos	Artikelnummer/Bezeichnung/Spezifikation	Menge	Einzelpreis	Nettopreis
	• Druckausgänge: 3 Ausgang 1: 500kPa Ausgang 2: 300kPa Ausgang 3: 300kPa • Versorgungsdruck: nach Druckbereich Sinnvolles Zubehör: • Medientrenner (z.B. LT 25000) • Analoge Zusatzeingänge zur Regelung über externe Sensoren			
5	90601-A1-001 Fracht und Verpackung (national) Fracht und Verpackungskosten für alle Angebotsartikel	1 Stk.	895,00	895,00

Netto	27.715,00
19% MWSt	5.265,85
Gesamtbetrag	**32.980,85 €**

Lieferzeit:
- Lieferzeit: nach Absprache

Zahlungsbedingungen:
- 50% netto Anzahlung nach Auftragserteilung, 50% 30 Tage netto nach Lieferung

Angebot:
- freibleibend und unverbindlich.
- Es gelten unsere Allgemeinen Geschäftsbedingungen.
- Diese finden Sie auf unserer Internetseite unter www.wille-geotechnik.com.

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Angebot

Polytec GmbH • Polytec-Platz 1-7 • 76337 Waldbronn • Germany

TU München
Zentrum Geotechnik
Herr MSc. Ulrich Schindler
Franz-Langinger-Straße 10
81245 München

Angebotsnummer:	**P5005198**
Angebotsdatum:	**10.01.2022**
Versions Nr.:	4
Gültig bis:	08.02.2022
Ihr Zeichen:	
Kundennummer:	1000178
Kundenanfragenummer:	
Ansprechpartner:	Dr.-Ing. Daniel Kaufmann
Disponent:	Katja Wilhelm +49 7243 604-1540 k.wilhelm@polytec.de

Sehr geehrter Herr Schindler,

wir danken Ihnen für Ihre Anfrage und bieten freibleibend (Vertragsabschluss erst nach Auftragsbestätigung durch Polytec) folgende Produkte gemäß unseren allgemeinen Verkaufs- und Lieferbedingungen (AVL) & allgemeinen Geschäftsbedingungen für Software (AGB) an:

Pos	Unsere Artikel Nr.: Beschreibung	Verkaufsmenge Einheit	Preis EUR	Nettobetrag EUR
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2	410523 Spleißgerät OFS-95S inkl. Faserbrechgerät OFC-10	1 Stk.	2.700,00	2.700,00
3	853191 Software zur Erzeugung von Faserkodierungen für akademische Kunden	1 Stk.	12.000,00	12.000,00

Gesamtnetto		**122.580,00**
MwSt.	**19 %**	**23.290,20**
Gesamtbrutto		**145.870,20**

Bitte beachten Sie die "Technischen Details" auf Seite 3.

Lieferbedingungen:	Ab Werk (Incoterms 2020)
Zahlungsbedingungen:	15 Tage netto
Lieferzeit:	ca. 4 - 6 Wochen nach Auftragseingang
Gewährleistung:	12 Monate ab Rechnungsdatum
Dollaranpassung:	Unsere Preise basieren auf einem Dollarkurs von 0,90 / 1 US$ und werden bei Kursschwankungen entsprechend dem Dollarkurs (EZB Referenzkurs) am Tag der Rechnungsstellung angepasst.

Sollten Sie nach Durchsicht des Angebotes noch Rückfragen haben, dann steht Ihnen Dr. Daniel Kaufmann gerne unter der Telefonnummer 07243/ 604-1740 zur Verfügung.

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Sparkasse Karlsruhe (EUR)	DE26 6605 0101 0001 0577 77 / KARSDE66XXX	Dr. Dietmar Gnaß, Dipl.-Wirt. Ing. (FH) Alfred Link
HSBC Trinkaus & Burkhardt AG (EUR)	DE91 3003 0880 0500 2880 19 / TUBDDEDDXXX	Handelsregister Mannheim: HRB 360938
HSBC Trinkaus & Burkhardt AG (USD)	DE68 3003 0880 4500 2880 06 / TUBDDEDDXXX	VAT-Nr.: DE811165398
Deutsche Bank Karlsruhe AG (EUR, USD)	DE35 6607 0004 0082 0431 00 / DEUTDESM660	WEEE-Reg.-Nr.: DE 35692877

Angebot

Angebotsnummer:	Angebotsdatum:	Versions Nr.:	Ansprechpartner:	Disponent:	
P5005198	**10.01.2022**	**4**	**Dr.-Ing. Daniel Kaufmann**	**Katja Wilhelm**	**+49 7243 604-1540**

Wir machen besonders darauf aufmerksam, dass wir ausschließlich zu unseren allgemeinen Verkaufs- und Lieferbedingungen (AVL) GmbH mit AGB Software, Stand 18. März 2020 liefern, die Sie unter folgender Adresse anfordern können: https://www.polytec.com/de/agb/. Für Hardware-Produkte der Polytec GmbH, die Software-Bestandteile beinhalten sowie für Software, gelten unsere allgemeinen Lizenzbedingungen (EULA) für Software-Produkte der Polytec GmbH, Stand 18. März 2020, die Sie ebenfalls unter der Adresse https://www.polytec.com/de/agb/ anfordern können. Wir weisen ausdrücklich darauf hin, dass unsere Haftung auf maximal den Auftragswert begrenzt ist.

Mit freundlichen Grüßen

POLYTEC GMBH
Geschäftsbereich Photonik

i.V.

Dr. Dirk Samiec
Geschäftsfeldleiter

Mit freundlichen Grüßen

POLYTEC GMBH
Geschäftsbereich Photonik

i.A.

Dr.-Ing. Daniel Kaufmann
Vertrieb Optische Technologien

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Technische Details:

Pos.: 1 853161-ODiSI 6104 Faseroptisches Auslesesystem, 4 Kanäle, Standard System (upgradefähig)
ODiSI 6104 Faseroptisches Auslesesystem basierend auf C-OFDR Technologie, 4 Kanäle, Standard System,
aufrüstbar bis max. 8 Kanäle
Messmodi für Faserlängen bis 20 m
Inklusive Laptop, Software (vorinstalliert), Hartschalenkoffer,
4 HD Standard-Remote-Module und 50 m Zuleitungen auf Kabeltrommel

Pos.: 2 410523-Spleißgerät OFS-95S inkl. Faserbrechgerät OFC-10
Optical Fusion Splicer OFS-95S
Dimension: 125W×125D×135H mm, Weight: 1.7kg (with battery)
Applicable fibers: SMF(ITU-T G.652), MMF(ITU-T G.651), DSF(ITU-T G.653), NZDSF(ITU-T G.655),BIF(ITU-T G.657), EDF.
Actual average splice loss: SM:0.02dB; MM:0.01dB; others:0.04dB;
Splice time:Typical 9sec. with standard SM fiber; Tube heat time:Typical 25sec.
With Interchangeable 4in1 holder (250µm/900µm/3mm/indoor cable compatible).
Six-motors, 5" touch screen, Core alignment With 1pc of Fiber Cleaver OFC-10

Pos.: 3 853191-Software zur Erzeugung von Faserkodierungen für akademische Kunden
Unbegrenzte Anzahl von Keys

Polytec GmbH
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Polytec

Ulrich Schindler, M.Sc.
Technische Universität München
Zentrum Geotechnik
Baumbachstr. 7
81245 München

Ihre Nachricht	Ihre Zeichen	Unsere Zeichen	Tag
		DKA/KAW	10.01.2022

Alleinstellungsmerkmal ODiSI 6

Sehr geehrter Herr Schindler,

die faseroptischen Messsysteme von Luna Inc. sind nach unserem Kenntnisstand die einzigen weltweit, die Temperatur- und Dehnungsprofile entlang einer Glasfaser mit sehr hoher räumlicher Auflösung im Millimeterbereich messen können. Dabei kann die Länge der Sensorfaser bis zu 50 m betragen. Bei gleichzeitiger Verwendung mehrerer Messkanäle können mehr als 300.000 Messpunkte gleichzeitig ausgelesen werden. Dadurch ist es möglich, Linienprofile oder auch flächenhafte oder räumliche Verteilungen vollständig aufzunehmen.

Das zugrundeliegende Messprinzip liest die Rayleigh-Rückstreuung aus kommerziell verfügbaren Standardglasfasern aus und berechnet daraus die lokalen Temperatur- und Dehnungsänderungen. Es werden also keine Spezialfasern oder Faser Bragg Gitter benötigt, was einen erheblichen Kostenvorteil bei gleichzeitig drastisch reduziertem Installations- und Wartungsaufwand und deutlich mehr Flexibilität bei der Anwendung mit sich bringt.

Wie uns der Hersteller Luna mitgeteilt hat, wird dieses Messprinzip exklusiv in seinen Produkten der ODISI- und OBR-Reihe benutzt und ist durch folgende Patente geschützt, die nicht unterlizensiert sind.

US 8.400.620
US 7.440.087

Gerne bestätigen wir, dass die Fa. Polytec GmbH, Waldbronn, für die Geräte der ODiSI-Reihe exklusiver Vertriebs- und Servicepartner der Fa. Luna Inc., Blacksburg, USA in D, A, CH und NL ist.

Für Fragen stehen wir Ihnen gerne unter Telefon 07243/604-1540 zur Verfügung.

Mit freundlichen Grüßen

Polytec GmbH
Geschäftsbereich Photonik

i. A. D. Kaufmann

Dr.-Ing. Daniel Kaufmann
Optische Technologien
Vertrieb Photonik

ALLEINSTELLUNGSMERKMAL_OD6_TU_MUENCHEN_GEOTECHNIK

Polytec GmbH
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Angebot

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POLYTEC GMBH
Geschäftsbereich Photonik

i.V. D. Samiec

Dr. Dirk Samiec
Geschäftsfeldleiter

Mit freundlichen Grüßen

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i.A. Daniel Kaufmann

Dr.-Ing. Daniel Kaufmann
Vertrieb Optische Technologien

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Dr. Daniel Kaufmann
Polytec GmbH
Geschäftsbereich Photonik
Polytec-Platz 1-7
76337 Waldbronn

Waldbronn, 05.01.2022

Ulrich Schindler, M.Sc.
Technische Universität München
Zentrum Geotechnik
Baumbachstr. 7
81245 München

Key-Generator Software ODiSI

Sehr geehrte Damen und Herren,

wesentlicher Bestandteil eines verteilt messenden Sensorsystems ist ein ortsauflösendes Reflektometer. Für die Rayleigh-Sensorik mit dem ODiSI-System wird dies mittels Frequenzbereichsreflektometrie (OFDR) erreicht. Wird eine handelsübliche Glasfaser mittels OFDR abgetastet, zeigt sich ein fluktuierender Intensitätsverlauf der Rayleigh-Streuung entlang der Faser. Dieser Verlauf ist stabil und stellt einen charakteristischen „Fingerabdruck“ der Faser dar. Bei fertig konfektionierten Sensorfasern wird dieses charakteristische Rückstreumuster in Form einer Datei mitgeliefert. Mit der Key-Generator Software ist es möglich, diese Datei selbst zu erstellen und bietet daher die Möglichkeit, Sensorfasern gezielt für bestimmte Applikationen zu erstellen (Flexibilität in Faserlänge und Beschaffenheit).

Mit freundlichen Grüßen

D. Kaufmann

Dr. Daniel Kaufmann

Electrolux RI16R1G 1-TÜR(GLAS)-EINFAHR-KÜHL.SCHR. 1600L CNS (Code 726869)

Listenpreis: ~~€8,435.70~~ Angebot: -15%

€7,170.34

zzgl. 19% USt., zzgl. Versand

- 1 + IN DEN WARENKORB

Produkt | Technik | Lieferstatus

Electrolux RI16R1G Produkt beschreibung

Innen und außen aus CNS 1.4301. 75 mm dicke Isolierung. Glastür mit Rechtsanschlag und beheiztem Rahmen. Eingebaute Kälteeinheit, Umluftkühlung, digitale Steuerung, automatische Abtauung, digitales Temperaturdisplay. Innenbeleuchtung. Betriebstemperatur +2/+10°C. Für Umgebungstemperatur bis +32 °C. FKW und FCKW frei. Kältemittel R134a. Gas in der Ausschäumung: Cyclopentan. Kaufen Sie Electrolux 1-TÜR(GLAS)-EINFAHR-KÜHL.SCHR. 1600L CNS RI16R1G (Code 726869) online zu einem günstigen Preis (pris, prijs, cena, hinta).

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Electrolux EDVP20VR1G

Electrolux RI27R2F

Electrolux RI075R1FL

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EZRT

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ein Bereich des
Fraunhofer-Instituts für Integrierte Schaltungen IIS

Institutsleiter
Prof. Dr. Albert Heuberger (geschäftsführend)
Dr. Bernhard Grill
Prof. Dr. Alexander Martin
Bereichsleiter EZRT
Prof. Dr.-Ing. Randolf Hanke

Dr. Daniel Haddad
Fraunhofer EZRT
Magnetresonanz- und Röntgen-Bildgebung
Am Hubland
97074 Würzburg

Telefon: 0931 / 31 - 83062 | Fax - 84680
E-Mail: daniel.haddad@iis.fraunhofer.de
Internet: www.ezrt.de | www.iis.fraunhofer.de

Fraunhofer EZRT | Am Hubland | 97074 Würzburg

Ulrich Schindler M.Sc.
Technische Universität München
Zentrum Geotechnik
Franz-Langinger-Str. 10
81245 München

Würzburg, 30. September 2020

Angebot Nr. 044/18530/240

Sehr geehrter Herr Schindler,

wir bedanken uns für Ihr Interesse an unseren Forschungs- und Entwicklungsleistungen und geben hiermit auf der Grundlage unserer Allgemeinen Bedingungen für die Durchführung von Forschungs- und Entwicklungsaufträgen in der Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. (Fassung 2002/II) folgendes Angebot ab:

1 Gegenstand, Verantwortlichkeiten

Unterstützung bei der Durchführung des Forschungsvorhabens:

»Untersuchungen der Bildung von Eislinsen in gefrorenen Böden«

Im Rahmen des von Ihnen beantragten DFG-Projekts sollen am EZRT NMR-Untersuchungen an Bodenproben durchgeführt werden. Die Messungen sollen im Temperaturbereich von +20°C bis -20°C erfolgen. Die Bodenproben inkl. Isolationsbehälter und Thermostat werden vom Auftraggeber für die Messungen zur Verfügung gestellt. Die Proben inkl. Isolationsbehälter besitzen eine zylindrische Geometrie mit einem Durchmesser von max. 60 mm und einer Höhe von 40 mm. Etwaige verwendete Kühlmittel dürfen kein NMR-Signal liefern.

Das EZRT führt in Absprache mit dem Auftraggeber T_2-Messungen und kombinierte T_1-T_2-Messungen bei verschiedenen Probentemperaturen durch. Dabei wird das Signal des nicht-gefrorenen Wassers als globales Signal gemessen. Die Messdaten werden als nicht-prozessierte Rohdaten per Download zur Verfügung gestellt. Das EZRT behält eine Kopie der Messdaten und darf diese für eigene Forschungsvorhaben zur Verbesserung der NMR-Methodik verwenden.

Im Vorfeld der eigentlichen Messungen werden vom EZRT der NMR-Detektor für die Messungen angepasst bzw. neu aufgebaut und zusätzliche NMR-Messungen zur Parameteranpassung an die Bodenproben durchgeführt.

2 Vorgesehene Dauer

Der genaue zeitliche Rahmen und die einzelnen Termine für die Messungen werden nach Bewilligung des DFG-Projekts in Abhängigkeit freier Kapazitäten gemeinsam festgelegt.

3 Vergütung

Vorarbeiten inkl. Anpassung/Neuaufbau des NMR-Detektors und Parameteranpassung,
pauschal EUR 3.200,00 zzgl. gesetzl. USt.

10 NMR-Messtage (inkl. je 8 Stunden Messzeit und Personalaufwand für die Durchführung der Messungen und Bereitstellung der Messdaten zu je EUR 1.960,00 zzgl. gesetzl. USt),
EUR 19.600,00 zzgl. gesetzl. USt.

4 Zahlungsplan

Rechnungsstellung erfolgt halbjährlich für die jeweils durchgeführten Messungen.

Vollständige Zahlung ohne Abzüge innerhalb von 20 Tagen nach Rechnungsstellung.

5 Angebotsbestandteile

Die beiliegenden »Allgemeine Bedingungen für die Durchführung von Forschungs- und Entwicklungsaufträgen in der Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. (FhG), Fassung 2002/II« (Anlage) sind Bestandteil dieses Angebots.

Ergänzende Regelungen:
Der Auftraggeber stellt dem Auftragnehmer von sämtlichen Ansprüchen Dritter im Zusammenhang mit den Arbeiten nach diesem Angebot frei.

6 Beachtung von möglichen Beschränkungen durch Exportvorschriften

Soweit die Erfüllung von vertraglichen Verpflichtungen der Fraunhofer-Gesellschaft aufgrund der nationalen, europäischen, US-amerikanischen oder internationalen Vorschriften des Außenwirtschaftsrechts einschließlich Embargos (und/oder sonstigen Sanktionen) einer Genehmigung bedarf, steht die Vertragserfüllung unter dem Vorbehalt der Erteilung einer Genehmigung durch die zuständigen Behörden; bei Nichterteilung der Genehmigung liegt seitens der Fraunhofer-Gesellschaft keine Vertrags- oder Pflichtverletzung vor. Entsprechendes gilt, wenn die Erfüllung des Vertrages aufgrund der genannten Vorschriften verboten sein sollte.

Eine Schadensersatzpflicht aufgrund von Verzögerungen oder Leistungshindernissen im Hinblick auf nationale, europäische, US-amerikanische oder internationale Vorschriften des Außenwirtschaftsrechts einschließlich Embargos (und/oder sonstigen Sanktionen) ist ausgeschlossen. Gleiches gilt für sonstige Ansprüche (wie bspw. Rückzahlungs- oder Garantieansprüche aufgrund von Anzahlungsbürgschaften oder Anzahlungsgarantien etc.).

Ist der Auftraggeber aufgrund der vertraglichen Regelungen im Einzelfall berechtigt, an den Forschungs- und Entwicklungsergebnissen auch Lizenzen außerhalb von Deutschland zu vergeben, so wird der Auftraggeber alle nationalen, europäischen, US-amerikanischen oder internationale Vorschriften des Außenwirtschaftsrechts einschließlich Embargos (und/oder sonstigen Sanktionen) einhalten.

7 Individuelle Regelungen

In Abweichung von Ziffer 7.2 der geltenden und beigefügten »Allgemeinen Bedingungen für die Durchführung von Forschungs- und Entwicklungsaufträgen in der Fraunhofer Gesellschaft (FhG)«, haftet der Auftragnehmer nur in Fällen von Vorsatz und grober Fahrlässigkeit. In Fällen von grober Fahrlässigkeit ist die Haftung auf die Höhe der Auftragssumme beschränkt. Eine Haftung für mittelbare Schäden und Folgeschäden ist - außer im Fall von Vorsatz - ausgeschlossen.

Der Auftraggeber ist verpflichtet, dem Auftragnehmer die zu untersuchenden Bodenproben rechtzeitig, in aus-reichender Menge und für die Testungen in geeigneter Beschaffenheit zur Verfügung zu stellen. Die erhaltenen Bodenproben wird der Auftragnehmer nach Durchführung der NMR-Untersuchungen an den Auftraggeber zurückgeben.

8 Bindefrist

An dieses Angebot halten wir uns ab dem heutigen Datum für 6 Wochen gebunden.

Wir erwarten gerne Ihren Auftrag. Sofern Sie weitere Informationen benötigen, setzen Sie sich bitte mit uns in Verbindung.

Mit freundlichen Grüßen

Dr. Karl-Heinz Hiller

PD Dr. Simon Zabler

Anlage

»Allgemeine Bedingungen für die Durchführung von Forschungs- und Entwicklungsaufträgen in der Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. (FhG), Fassung 2002/II«

Veröffentlichungen:

- P. Mörchel, M. Hildenbrand, *„Identifiziert Polymere, Mobiler Polymer-Profiler für Labor und Produktion“*, K-Zeitung, Qualitätssicherung, Ausgabe 12, Giesel Verlag, 23. Juni 2017
- „Handbuch zur industriellen Bildverarbeitung“, ISBN 978-3-8396-1226-2, Fraunhofer Verlag, 2017
- Philipp Mörchel, Markus Hildenbrand, Karl-Heinz Hiller, *„Großes Potential, Magnetresonanz ist Zukunftstechnologie in der Materialforschung“*, QZ Qualität und Zuverlässigkeit, Carl Hanser Verlag, 11/2017
- Markus Hildenbrand, Philipp Mörchel, „Non-destructive testing with Magnetic Resonance”, IEEE, Print ISBN: 978-3-8007-4683-5, (16 August 2018)
- Karl-Heinz Hiller, Markus Hildenbrand, Philipp Mörchel, *„Magnetresonanz”*, Fraunhofer Vision, Leitfaden zur Bildverarbeitung in der zerstörungsfreien Prüfung, ISBN: 978-3-8396-1380-1, Fraunhofer Verlag, 2018
- Daniel Haddad, Philipp Mörchel, Markus Hildenbrand, Karl-Heinz Hiller, *„Selected Magnetic Resonance applications for non-destructive material testing”*, https://doi.org/10.1515/teme-2019-0149, tm - Technisches Messen, 2020

Vorträge:

- P. Mörchel, *“NMR-Imaging for NDT”*, World Federation of NDE Centers (WFNDEC), Boise, Idaho, USA, 2014
- P. Mörchel, *„Zerstörungsfreie Untersuchung von Kunststoffen mit Magnetresonanz“*, ZfP- Zerstörungsfreie Prüfmethoden in der Kunststoffindustrie. Würzburg (SKZ) 2016
- P. Mörchel, M. Hildenbrand, K.-H. Hiller, *„Magnetic Resonance Imaging and Relaxometry”*, Sensoren und Messsysteme, 19. ITG/GMA-Fachtagung, Nürnberg, Germany, 2018

METER

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Baumbachstraße 7
81245 München

Ihr Ansprechpartner: Thomas Keller
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Angebot

Angebots-Nr. : 012887
Datum : 12.03.2019
Seite : 1 von 2

Angefragt durch : Frau Elissavet Barka

Versandadresse
Technische Universität München
Zentrum Geotechnik
Baumbachstraße 7
81245 München
Deutschland

Pos	Stk.	Bezeichnung	Grundpreis	Rabatt	Einzelpreis	Gesamtpreis
1.0	2	Best.-Nr.: 140101 Tensiometerlogger DL6-te 6-Kanal-Datenlogger für Tensiometer T4, T4e, T5 Autarker Betrieb mit 6 x AA Batterien, Lieferbar so lange Vorrat reicht! Zusätzliche Kanäle: 1 x Zähler, 1 x Temperatur, 1 x Alarmausgang, 16.000 Messwertespeicher, Messintervall ereignissteuerbar, freilandtauglich IP 67. Inkl. Konfigurations-Software und RS232-Datenübertragungskabel, PC ohne RS232 benötigen zusätzl. USB-RS232 Adapter Gewicht: 1,3 kg Ursprungsland: DE Stat. Waren-Nr: 84718000 Zusätzliche Kanäle: 1 x Zähler, 1 x Temperatur, 1 x Alarmausgang, 16.000 Messwertespeicher, Messintervall ereignissteuerbar, freilandtauglich IP 67. Inkl. Konfigurations-Software und RS232-Datenübertragungskabel, PC ohne RS232 benötigen zusätzl. USB-RS232 Adapter	1.235,00		1.235,00	2.470,00
2.0	12	Best.-Nr.: 015010 UMS Mini-Tensiometer T5, freie Schaftlänge 10 cm Gewicht: 0,3 kg Ursprungsland: DE Stat. Waren-Nr: 90278017 Schaftlänge: 10 cm	456,00		456,00	5.472,00
3.0	3	Best.-Nr.: 015007 UMS Mini-Tensiometer T5, freie Schaftlänge 7 cm Gewicht: 0,3 kg Ursprungsland: DE Stat. Waren-Nr: 90278017 Schaftlänge: 7 cm	456,00		456,00	1.368,00

Übertrag/ EUR **9.310,00**

METER

Angebots-Nr.: 012887 **Angebotsdatum:** 12.03.2019

Pos	Stk.	Bezeichnung	Grundpreis	Rabatt	Einzelpreis	Gesamtpreis
Übertrag/ EUR						**9.310,00**
4.0	12	Best.-Nr.: 5124500 UMS Verlängerungskabel EC-4/5 Länge 5 m, 4-polig Stecker/Buchse M12. Geeignet für z.B. T4, T5, Echo, Th3-s Gewicht: 0,3 kg Ursprungsland: DE Stat. Waren-Nr: 85444290	37,50		37,50	450,00
5.0	10	Best.-Nr.: 0162 Befülladapter für T5 Tensiometer Gewicht: 0,01 kg Ursprungsland: DE Stat. Waren-Nr: 90279050	29,80		29,80	298,00
6.0	1	Best.-Nr.: 0151 UMS Anzeigegerät INFIELD7 Handanzeigegerät mit Grafikdisplay Auslesen und Konfigurieren von Tensiometern, Watermark, SISC8, Th2f & Th2t Temperatursonden, Echo- und Thetaprobe, Speicher für 220 Messwerte, für 4-Pol und 8-Pol Stecker M12/IP67, inkl. Tragekoffer Gewicht: 0,76 kg Ursprungsland: DE Stat. Waren-Nr: 90303900	787,00		787,00	787,00

Gültigkeit	:	26.11.2018
Versandart	:	DPD CLASSIC
Lieferkondition	:	inklusive Verpackung und Versand
Zahlungskonditionen	:	30 Tage netto
Gewährleistung	:	12 Monate auf Eigenprodukte

Warenwert	EUR	10.845,00
+ Versand	EUR	20,00
+ 19.0 % MwSt	EUR	2.064,35
Gesamtsumme	EUR	**12.929,35**

Es gelten ferner die allgemeinen Lieferbedingungen für Erzeugnisse und Leistungen der Elektroindustrie in der aktuellen Fassung zum Angebotszeitpunkt.

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Technische Universität München
Zentrum Geotechnik
Herr Ulrich Schindler
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ANGEBOT

Nummer	:	**6141328**
Datum	:	08.04.2019
Kunden-Nr.	:	2506000
Ihre USt-Id-Nr.	:	DE213277530
Unsere USt-Id-Nr.	:	DE 129490229
Steuer-Nr.	:	143/191/30161
Seite	:	1

Ansprechpartner: Frau Sarah Weitzbrich
Telefon: +49 / 89 / 451023-24
Email: weitzbrich.sarah@wagnermunz.com

Anfrage - Umwälzthermostat, vom 07.04.2019, Herr Schindler per E-Mail

Sehr geehrter Herr Schindler ,
wir danken für Ihre Anfrage und bieten nachfolgend die gewünschten Produkte freibleibend an:

Pos	Artikelbezeichnung	Menge	ME	Preis/Eh.		Gesamt
001	**9999999** PP15R-40 15 Liter Ref. Umwälzthermostat, -40° 4,3"-SmartTouch-Touchscreen, -40° bis 200° - Selbstverstauende LidDock® Gefäßabdeckung - Isolierende, chemikalienbeständige DuraTop™ Abdeckung - Tankablass - Abwaschbarer Luftfilter - OpenMode-Zeit-/Temperaturprogrammierung (ohne Beschränkung der Programm- oder Schrittzahl) - Intuitives 4,3-Zoll (10,9-cm)-SmartTouch™ Display - 11 Sprachen: Französisch, Deutsch, Spanisch, Chinesisch, Portugiesisch, Russisch, Hindi, Arabisch, Italienisch, Koreanisch, Englisch - Pumpe mit variabler Geschwindigkeit und externer Umwälzfähigkeit im offenen und geschlossenen Regelkreis - Rotierendes Temperaturdisplay Swivel 180™ - Integrierte Konnektivität: USB-A UND B, Ethernet, RS232/485, Remote-Ein/Aus und externe Temperatursonde - Ereignisplanung (Uhrzeit und Datum) mit Echtzeituhr - Prüfung von Temperaturtrends für bis zu 10 Tage - Mehrere wählbare Home-Bildschirme - Bildschirmhilfe - Automatische und/oder vom Benutzer einstellbare Leistungsoptimierung - 10-Punkt-Kalibrierbarkeit - Beinhaltet Enhanced-Performance-Hardware und Software-Paket (Pt100-Temperatursonde, USB-Flashdrive zur Datenprotokollierung, Edelstahlanschlussteile und -leitungsadapter, PolyScience LabVIEW™ Virtual Instrument, iPhone® App-Download)	2,00	Stück	4.755,28	netto	9.510,56 € [b)] (4.755,28 €/Eh.)

Übertrag **9.510,56 €**

+49/89/289-27189

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ANGEBOT

Nummer	:	**6141328**
Datum	:	08.04.2019
Kunden-Nr.	:	2506000
Ihre USt-Id-Nr.	:	DE213277530
Unsere USt-Id-Nr.	:	DE 129490229
Steuer-Nr.	:	143/191/30161
Seite	:	2

Übertrag **9.510,56 €**

Pos	Artikelbezeichnung	Menge	ME	Preis/Eh.	Gesamt
	- Mit DeviceNet/CANbus-, Modbus- und Profibus-Optionen erhältlich Lieferzeit: Momentan ca. 5 Wochen				

Gesamt-Betrag
9.510,56 €

Preisstellung
Die genannten Preise verstehen sich zuzüglich der gesetzlichen Mehrwertsteuer am Tag der Lieferung. Alle Preisangaben in EUR. Preise freibleibend.

Zahlungsbedingung: 30 Tage netto nach Rechnungsdatum

Lieferbedingung: Frei Haus, nur zu Inlandsbedingungen, nicht zum Weiterversand geeignet.

Bitte beachten Sie unseren Mindestbestellwert von 50,00 € netto, unter dem eine Pauschale von 15,00 € anfällt. Bei Gutschriften wird eine Bearbeitungsgebühr erhoben!

Dieses Angebot kann nur berücksichtigt werden, wenn Sie bei der Bestellung die Angebotsnummer angeben.

Es gelten unsere Allgemeinen Geschäftsbedingungen. Das UN-Kaufrecht wird ausgeschlossen.

Wir hoffen, daß Ihnen unser Angebot zusagt und würden uns über Ihren Auftrag freuen.

Mit freundlichen Grüssen

Wagner & Munz GmbH Labortechnik

i.A. Sarah Weitzbrich

a) nicht skontofähig, b) nicht bonusfähig, c) nicht skonto -und bonusfähig

Angebot Luna Key Generator

Wirtschaftlichkeitsbetrachtung TUM-ZG zu 853191-Software zur Erzeugung von Faserkodierungen für akademische Kunden (Angebot_KeyGenerator_Polytec)

Preise LUNA-Sensoren (vorgefertigte Sensoren vom Hersteller):

- 1m Sensor: 230 € (netto)
- 2m Sensor: 240 € (netto)
- 3m Sensor: 250 € (netto)
- 5m Sensor: 280 € (netto)

Preise Zubehör Eigenbaufasern (Verwendung in diesem Projekt ausschließlich geplant):

- Key-Generator Software: 12.000 € (netto)
- Spleißgerät: 3.450 € (netto)
- Pigtail (LC/APC-Stecker): 7,70 €/Stück (netto)
- Sensorfaser: 7,19 €/m (netto)
- kernlose Faser (als Terminierung): 6,50 €/m (netto)
- Spleißschutz: 0,50 €/Stück (netto)

Für einen 1m Sensor werden benötigt:

- 1 Pigtail
- 1 m Sensorfaser
- 0,1 m kernlose Faser
- 2 Spleißschutze

Für längere Sensoren wird die entsprechende Länge Sensorfaser benötigt.

Hieraus ergeben sich folgende Preise:

Länge des Sensors	Preis (Eigenbaufasern)	Ersparnis gegenüber LUNA-Sensor
1 m	16,54 €	213,46 €
2 m	23,73 €	216,27 €
3 m	30,92 €	219,08 €
5 m	45,30 €	234,70 €

Der Preis für die Key Generator Software und das Spleißgerät beträgt zusammen 15.450 € (netto). Bei der Verwendung von ausschließlich 1 m Sensoren, haben sich die Kosten nach dem 73. Sensor amortisiert (bei 5 m Sensoren nach dem 66.).

Bei Mehrfachverwendung der Pigtails können die Kosten für einen Sensor weiter gesenkt werden. Bei Messungen entlang gerader Strecken kann zum Beispiel auch eine acrylatbeschichtete Telekomfaser für etwa 0,30 €/m verwendet werden. Ein weiterer Vorteil des Key-Generators ist die Möglichkeit, Fasern speziell für die eigene Anwendung herstellen zu können, z.B. robuste, baustellentaugliche Fasern.