Numerical simulation of artificial ground freezing applications for tunnel excavations

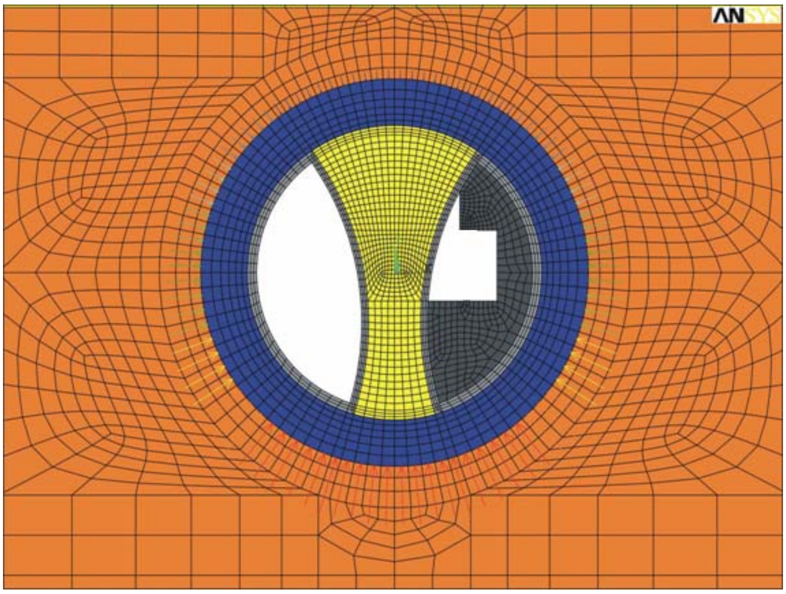
Problem and objective

The freezing method aims to provide artificially frozen soil that can be used temporarily as a support structure for tunneling or mining applications. It is a versatile technique that increases the strength of the ground and makes it impervious to water seepage. Excavation can proceed safely inside the frozen ground structure until construction of the final lining provides permanent support. In contrast to grouting works the freezing method is completely reversible and has no environmental impact. Ground freezing is not limited by adverse ground conditions and may be used in any soil formation, regardless of structure, grain size, permeability or moderate groundwater flow. Due to the time- and temperature dependent behaviour of frozen soil the analytical approaches so far known for the design of frozen support structures can only inadequately assess the complex phenomena occuring at different construction stages. They are therefore restricted to simple design cases only.

The objectie of this research work is to provide a practicable numerical analysis tool, which allows a more realiable and safe prediction of the freezing process and the structural behaviour of frozen ground support structures. Based on this prediction and on-site measured data an optimization of the freezing process should be permitted by adjusting the output of the refrigeration plant during the construction sequence.

Solution approaches

The complexity of artificial ground freezing applications requires the use of numerical analysis tools to describe and solve the specific boundary value problem. The model to be developed should be capable of predicting the structural as well as the thermal processes involved in the freezing application. Since frost propagation during freezing is characterised by moving isothermes transient computations are necessary. Beyond that, a numerical model allows the identification of the most decisive parameters on the freezing process for a particular engineering design and the amount of energy to be supplied by the refrigeration plant for successive construction stages.

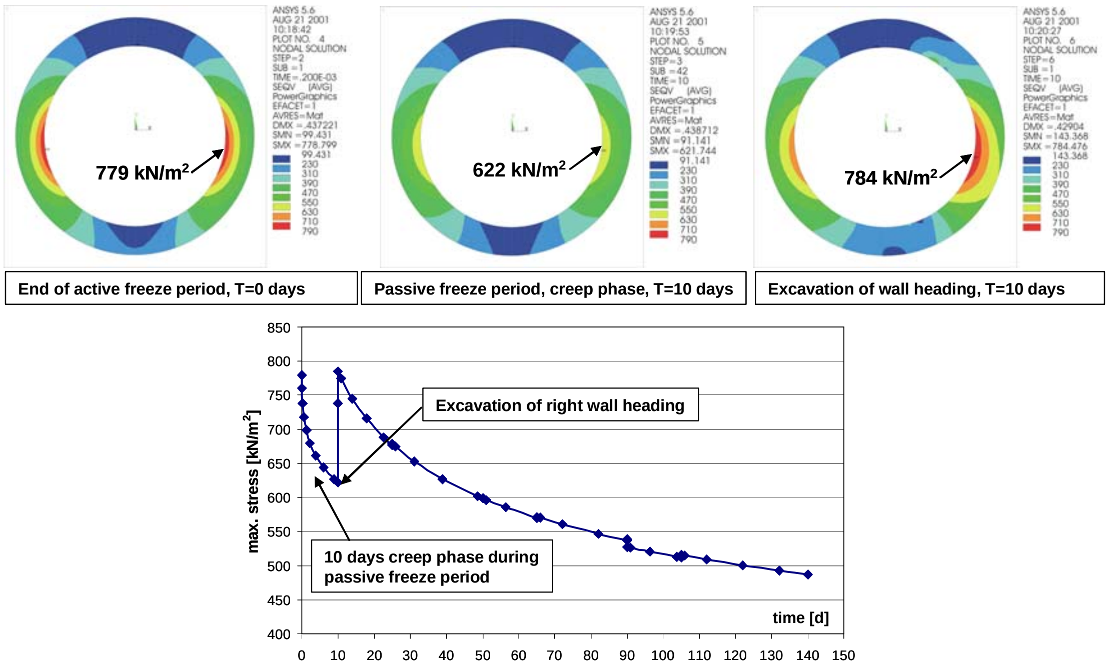


Finite Element (FE)-Grid for simulating the excavation of a cross passage inside a circular frozen support structure (see [1])

Present findings

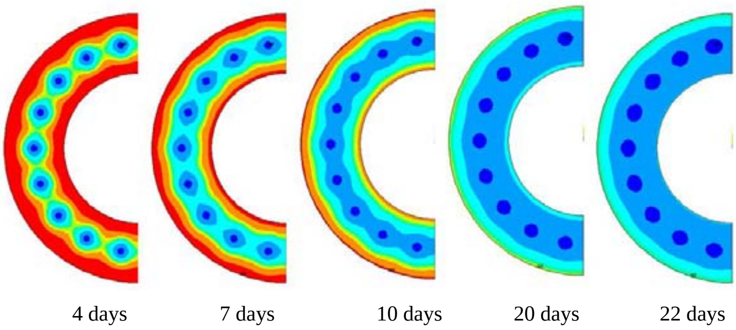
The simulations so far carried out at the Chair of Geotechnical Engineering have investigated partial aspects of the problem.

In a first step the main focus was put on the time-dependent bearing and deformation behaviour of frozen support structures, while the spatial and temporal temperature distribution in the frozen zone was considered constant. The time-dependent effects that arise due to creep and relaxation processes in the frozen soil and the resulting interaction of frozen soil and shotcrete lining could well be described by the general purpose FE-Program ANSYS. It was found out that a redistribution of stresses from the highly stressed areas in the frozen zone to the outer fiber of the shotcrete lining slightly increases the bending moment and normal force within the concrete till ring closure is obtained.



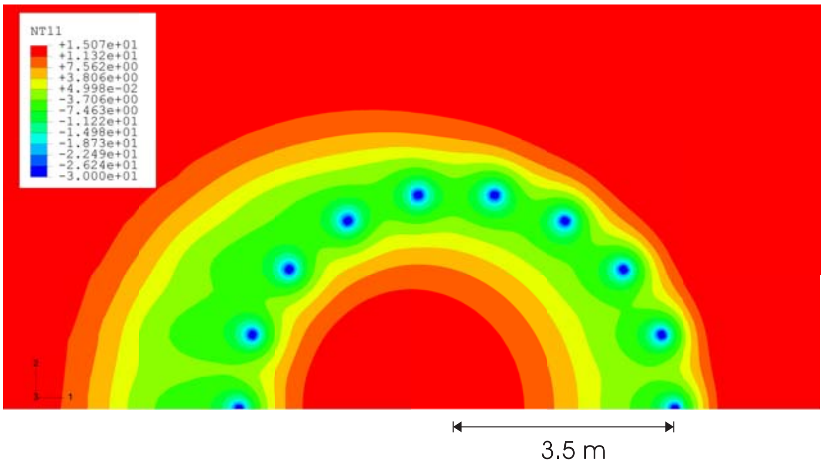
Temporal development of maximum stresses in the frozen zone (see [1])

At present, the numerical simulations aim to investigate the thermal aspects of the freezing method. The simulations account for the latent heat of fusion that is released during phase change and has to be additionally extracted from the soil. It turned out to be a very crucial parameter for the freezing time required and the overall performance of the freezing process.



Temperature development in the frozen zone during the active freezing period without consideration of groundwater flow (see [2])

Lateral groundwater flow requires additional consideration as it resembles a significant thermal load for the freeze pipes and adversely affects the refrigerative effort. If the water flow velocity is too large the freezing columns will no longer merge and leave openings in the intended frozen support structure that could result in flooding or collapse at the excavation stage. Such a steady state indicates thermal equilibrium of the heat supplied by the waterflow and the amount extracted by the freeze pipes. The consideration of existing groundwater flow is therefore vital for a safe and cost-effective freeze tube arrangement. First approaches to the simulation of groundwater flow within heat flow simulations with the general purpose FE-Program ABAQUS are promising and provide results in qualitativ agreement to field observations. Moreover, Finite Difference (FD) computations are being performed to try to achieve even better results that allow a quantitative prediction of the location of the freezing front subjected to various boundary conditions. This information seems substantial for a safe and economic freeze tube arrangement and a cost-effective operation of the refrigeration unit.



Temperature development in the frozen zone during the active freezing period with consideration of groundwater flow (see [3])

Future prospects

In the long run of the project coupled thermal-structural simulations shall be carried out. The results obtained from the numerical model shall be verified by field data measured during construction of massive frozen ground support structures at a new metro track at Cologne (Nord-Süd Stadtbahn Köln).

References

[1] Baier, Ch.: Numerische Erfassung des Tragverhaltens großflächiger Baugrundvereisungen bei der bergmännischen Herstellung von Tunnelbauwerken in wassergesättigten Lockerböden. Diplomarbeit am Lehrstuhl für Geotechnik im Bauwesen der RWTH Aachen. Aachen 2001, unveröffentlicht. In Zusammenarbeit mit der Ingenieurgesellschaft für Bautechnik Zerna, Köpper und Partner (ZKP) in Bochum.

[2] Boor, S.: Numerische Erfassung des Aufgefrierens wassergesättigter Lockerböden. Diplomarbeit am Lehrstuhl für Geotechnik im Bauwesen der RWTH Aachen. Aachen 2002, unveröffentlicht. In Zusammenarbeit mit der Ingenieurgesellschaft für Bautechnik Zerna, Köpper und Partner (ZKP) in Bochum.

[3] Beerlage, N.: Numerische Erfassung des Aufgefrierens grundwasserdurchströmter Lockerböden. Diplomarbeit am Lehrstuhl für Geotechnik im Bauwesen der RWTH Aachen. Aachen 2005, unveröffentlicht.