Geotechnik im Bauwesen
Geotechnical Engineering
Univ.-Prof. Dr.-Ing. Martin Ziegler

RWTH AACHEN UNIVERSITY

# Short Report

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Research topic: „Energy saving potential of artificial ground freezing applications for the construction of complicated basement stories“

Lemma: „Energy saving potential of artificial ground freezing applications”

Research institution: Chair of Geotechnical Engineering – RWTH Aachen University
Mies-van-der-Rohe-Str. 1
52074 Aachen

Project manager: Univ.-Prof. Dr.-Ing. Martin Ziegler

Project team member: Dipl.-Ing. Rebecca Schüller

Further involved institutions:

Geophysica Beratungsgesellschaft mbH
Lütticher Str. 32
52064 Aachen

Supporting institution:

Wayss & Freytag Ingenieurbau AG
Bereich Mitte
Wiesenstraße 21 A II
40549 Düsseldorf

Züblin Spezialtiefbau GmbH
Bereich Nord
Bessemerstraße 42b
12103 Berlin

Deilmann-Haniel Shaft Sinking GmbH
Haustenbecke 1
44319 Dortmund

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The author is responsible for the content of the report.

## 1 Aim of the research project

The artificial ground freezing method in general represents a construction method for the creation of frost zones for constructions under complicated geological and hydrological conditions. The artificially frozen soil provides both an increased static load-bearing capacity and an increased impermeability. Furthermore, not only the flexibility and reversibility of the method but also the reliable realization and monitoring constitute competitive advantages. Due to its technical and environmentally relevant advantages the artificial ground freezing method with brine has been recently applied in a number of construction projects, such as tunnelling and the construction of excavation pits. However, the energy consumption and the related costs are often assessed inaccurately and expected to be excessively high.

The aim of this research project was to optimize ground freezing applications in its entirety. This requires not only the consideration of the freezing time but also the consideration of the energy consumption. For a realistic consideration of the energy consumption respectively the refrigeration capacity not only the freezing phase but also the operating phase needs to be analyzed. The operating phase essentially determines the total energy consumption. The freezing plant is selected due to the required peak refrigeration capacity in the freezing phase. However, the required refrigeration capacity in the operating phase is significant for the prediction of the entire energy consumption. As a result of the research project artificial ground freezing applications shall be optimized with regard to the freezing time and the energy consumption in the run-up to the construction.

## 2 Realization of the research project

For the estimation of the refrigeration capacity during the freezing and the operating phase a status quo analysis has been carried out at first. Thereby the existing reference values and calculation approaches for the estimation of the refrigeration capacity have been summarized. Furthermore, this analysis has been complemented by an evaluation of actual construction projects that also result in rough reference values for the required refrigeration capacity.

For a realistic determination of the refrigeration capacity during the freezing and the operating phase the program SHEMAT has been extended. Both a simplified and a detailed numerical model for the determination of the refrigeration capacity has been developed and implemented in the program code SHEMAT. The detailed model has been developed in cooperation with the Geophysica Beratungsgesellschaft mbH. Furthermore, both numerical models have been extended to simulate different operating modes, such as the intermittent mode, during the operating phase. To verify both numerical models a laboratory model test carried out at ETH Zurich as well as a real construction project, the construction of a crosscut at the Statentunnel in Rotterdam, have been simulated.

Based on this, the decisive influencing parameters on the freezing time and the refrigeration capacity have been identified in the course of a parameter study. Furthermore, optimization systems for an artificial ground freezing application of an excavation pit have been simulated determining the refrigeration capacity for the freezing and the operating phase. In this context different operating modes during the operating phase have been examined and evaluated with regard to saving of the refrigeration capacity. Finally, the optimization systems during freezing and operating phase have been evaluated within a simplified economic efficiency analysis.

# 3 Summary of the results

In the following a brief summary of the results is presented. A detailed description of all investigations and results can be found in the comprehensive final report.

## 3.1 Status quo – refrigeration capacity of artificial ground freezing applications

The refrigeration capacity depends on many influencing parameters such as the thermal and physical soil properties, the used refrigerant and the groundwater conditions. In literature different reference values and calculation approaches for the refrigeration capacity, mainly from shaft constructions, are documented. Table 3.1 summarizes some reference values for the refrigeration capacity.

**Table 3.1 summary of reference values for the required refrigeration capacity**

| Reference | Brine temperature [°C] | Refrigeration capacity per meter freeze pipe [kW/m] | Refrigeration capacity per freeze pipe surface [kW/m²] |
|---|---|---|---|
| Ständer (1967) | -25 | 0,116 – 0,186 | |
| Braun et al. (1979) | -23 | ~ 0,065 (Ø 10,8 cm)<br>up to ~0,13 | at least 0,192<br>up to 0,384 |
| Andersland & Ladanyi (2004) | -30 | 0,1 – 0,23 | |
| Harris (1995) | -30 | 0,464 | |

The reference values negelct the majority of the mentioned influencing factors and show a large variation between 0,065 kW/m and 0,464 kW/m. It becomes clear that the reference values of the first three authors, which refer to shaft constructions, are significantly lower than the reference value from Harris (1995) for tunneling. Consequently, the reference values from shaft constructions cannot be applied to ground freezing applications in civil engineering.

The evaluation of actual construction projects has not shown a clear dependency of specific parameters such as soil type or groundwater flow either. Figure 3.1 presents the results of the average refrigeration capacity during the freezing phase in summary. The evaluation is based on an arithmetic averaging without special weighting regarding different construction times. The average refrigeration capacity is 0,29 kW/m.

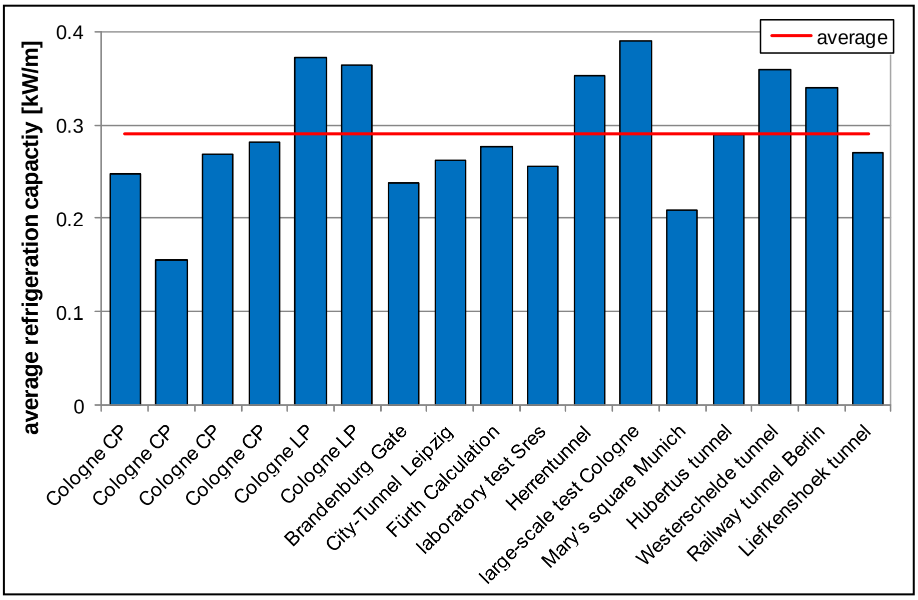


**Figure 3.1** **Comparison of average required refrigeration capacity in freezing phase**

## 3.2 Numerical solution models for the determination of the refrigeration capacity

The Finite-Difference Program SHEMAT (Simulator for Heat and Mass Transport) had been developed by a group of Prof. Clauser at the chair of Applied Geophysics of RWTH Aachen University for the simulation of geothermal processes in porous rocks (Clauser 2003). Adaptations of Mottaghy and Rath (2006) and Baier (2009) allow the realistic determination of the freezing process for ground freezing applications with the so called “freezing”-module.

For a realistic determination of the required refrigeration capacity during the freezing and the operating phase two numerical models have been developed and implemented in the program SHEMAT. First, a simplified determination of the refrigeration capacity has been implemented in the “freezing”-module. This simplified determination includes the summation of all heat flows entering the freeze pipe cells. In this case the freeze pipes are defined as Dirichlet boundary conditions with a specified temperature.

To ensure a realistic determination of the refrigeration capacity of ground freezing applications the freeze pipe has to be modelled in detail in numerical simulations. This implies the consideration of the so far neglected flow conditions and heat transfer within the freeze pipe itself. To avoid a very fine discretization which causes long computing times a separate “freezrefcap”-module for the calculation of the heat transfer processes within the freeze pipe has been developed in cooperation with Geophysica Beratungsgesellschaft mbH. Based on the Kelvin line source theory the freeze pipes are modeled as one-dimensional line sources. The horizontal heat transfer within the freeze pipes is determined using the concept of thermal resistances (Hellström 1991). There are two interfaces between the “freezrefcap“-module and SHEMAT (s. Figure 3.2). The soil temperature calculated in SHEMAT is passed to the “freezrefcap”-module as a Dirichlet boundary condition. In turn, a cooling generation calculated with “freezrefcap”-module is returned to SHEMAT and leads to a change of soil temperature.

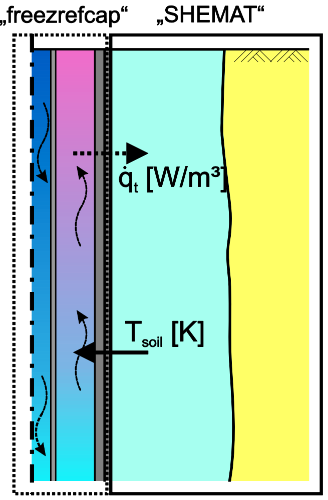


**Figure 3.2** **Interfaces between „freezrefcap“-module and SHEMAT**

The refrigeration capacity is finally determined from the temperature difference between inlet and outlet temperature of the refrigerant ($T_{inlet}$ - $T_{outlet}$), the pump rate $Q_F$ and the temperature dependent volumetric heat capacity of the refrigerant $c_{v,F}$.

$$P = c_{v,F} \cdot Q_F \cdot (T_{inlet} - T_{outlet}) \tag{3-1}$$

Additional, the extension of both numerical models for the simulation of different operating modes, such as the temperature controlled intermittent mode, during the operating phase has been realized.

## 3.3 Verification of the numerical models

For the verification of the numerical models a laboratory model test carried out at ETH Zurich has been simulated. In the test three freeze pipes have been installed in a watertight and thermally isolated PVC tub. Within the model test different groundwater flow velocities have been adjusted (Sres 2010).

The results of the numerical simulation of two tests, one with and another one without groundwater flow, have shown a good agreement with the measured temperatures in the soil. The results of the refrigeration capacity are displayed in Figure 3.3 for a test without groundwater flow. The measured values (red) are compared with both the results of the simplified refrigeration capacity determination with the “freezing”-module (blue) and the results of the detailed determination with the “freezrefcap”-module (green). The results of the simulation with the „freezrefcap“-module are nearly equal to the measured values. However, the refrigeration capacity resulted from the simulation with the „freezing”-module underestimates the measured values by an almost constant difference. The reason for the underestimation respectively the difference between both modules can be seen in the negligence of the heat transfer processes within the freeze pipe.

Consequently, the freezing process in the soil can be depicted realistically and the refrigeration capacity can be determined with sufficient precision with both modules.

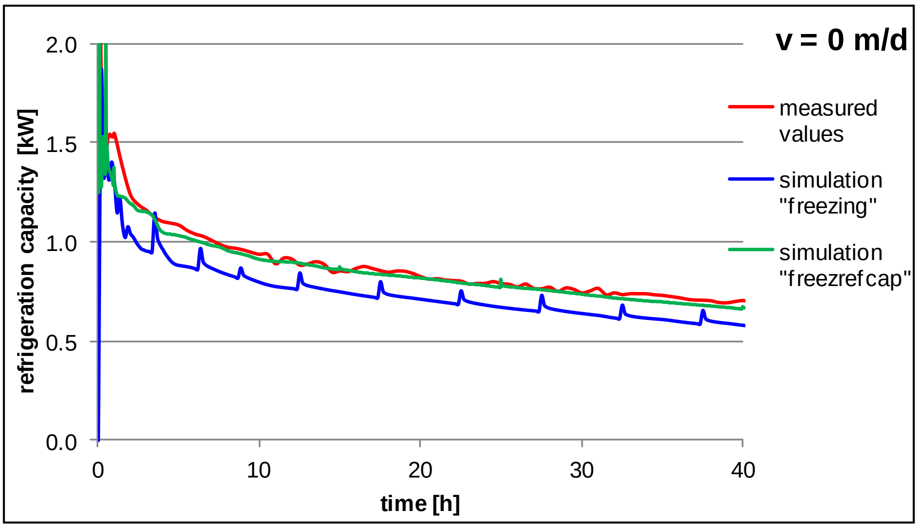


**Figure 3.3 Comparison of measured and simulated refrigeration capacity (v = 0 m/d)**

It was also attempted to simulate the freezing of a crosscut at the Statentunnel in Rotterdam with the detailed “freezrefcap”-module. The results indicated further optimization potential for the “freezrefcap”-module. The module needs to provide the possibility to define different freeze pipe length. Furthermore the modeling of inclined freeze pipes, which represent the normal case in practice, needs to be implemented.

## 3.4 Parameter study of an excavation pit

Within the scope of the research project a parameter study for the determination of the decisive influencing parameters on freezing time and refrigeration capacity especially was carried out. The “freezrefcap”-module enabled the variation of the relevant soil parameters as well as the properties of the freeze pipe and the refrigeration circuit. For this example, the freezing of an excavation pit with 5 freeze pipes was simulated. The variation of soil properties consisted of the pore content, the content of quartz, the groundwater temperature and the groundwater flow velocity. Additionally, the thermal conductivity of the riser pipe as well as the length and the geometry of the freeze pipe have been modified. Furthermore, the supply temperature of the refrigerant, the used brine respectively the concentration of calcium chloride and the pump rate was varied.

The numerical simulations have shown that the groundwater flow velocity is the major influencing parameter for both the freezing process and the refrigeration capacity. In general all soil properties have shown a significant influence on freezing time and refrigeration capacity. It should be noted that the soil properties cannot be changed in practice, but they need to be determined correctly to enable a realistic planning of the ground freezing application. The freezing time and refrigeration capacity is less affected by properties of the freeze pipe and the refrigerant circuit. In contrast to the soil properties these properties can be actively controlled and nevertheless offer good saving potentials. The major savings can be achieved by choosing the supply temperature and the pump rate properly.

## 3.5 Energetic optimization of artificial ground freezing applications

The results of the parameter study showed the major influence of groundwater flow on the freezing time and the refrigeration capacity. Former investigations indicated a significant reduction of freezing time by flow adapted freeze pipe arrangements. Within this research project the required refrigeration capacity during freezing phase of these decisive optimizations systems (Ziegler et al. 2010) has been examined. Furthermore, the investigations have been expanded to the operating phase. In this context different operating modes and their impact on the refrigeration capacity have been examined.

The basic system of an excavation pit with 9 freeze pipes at a distance of 0,8 m is presented in Figure 3.4.

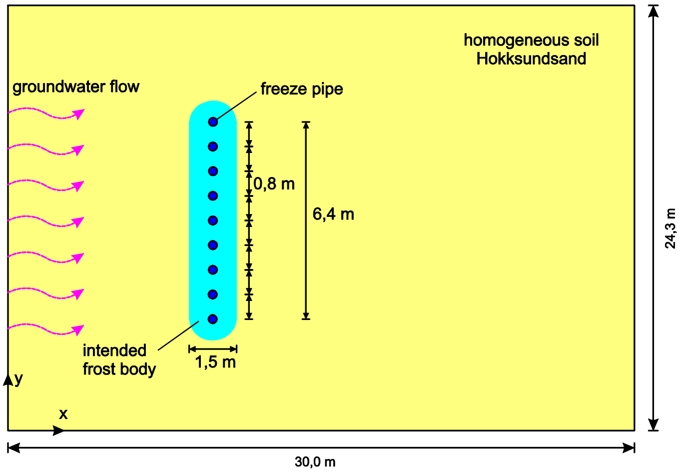


**Figure 3.4** **Basic system (excavation pit) for optimizing the refrigeration capacity**

First, the refrigeration capacity during the freezing phase of the most effective optimization system for groundwater flow adapted freeze pipe arrangements, the precooling of groundwater, has been investigated. Thereby significant reductions of the freezing time correlating with the number of additional freeze pipes in the upstream could be achieved. With regard to the refrigeration capacity no clear correlation is obvious, so that system-specific numerical simulations are always necessary. An increase of additional freeze pipes does not result in a reduction of the required refrigeration capacity for all systems.

Due to the fact that the operating phase constitutes a large amount of the total energy consumption the operating phase has been optimized as well. The principal aim is to preserve the statically required frost body with low energy use. Moreover, a further frost body growth needs to be largely prevented to reduce detrimental frost heave. For this purpose different operating modes are used during the operating phase. On the one hand an increased supply temperature and on the other hand an intermittent mode of the refrigeration system can be choosen. The intermittent mode is characterized by an automated temperature-controlled activation respectively deactivation of defined freeze pipe groups.

The potential savings of the refrigeration capacity for the different operating modes are displayed in Figure 3.5 for the basic system (s. Figure 3.4) with regard to the operation without any adaptation during the operating phase.

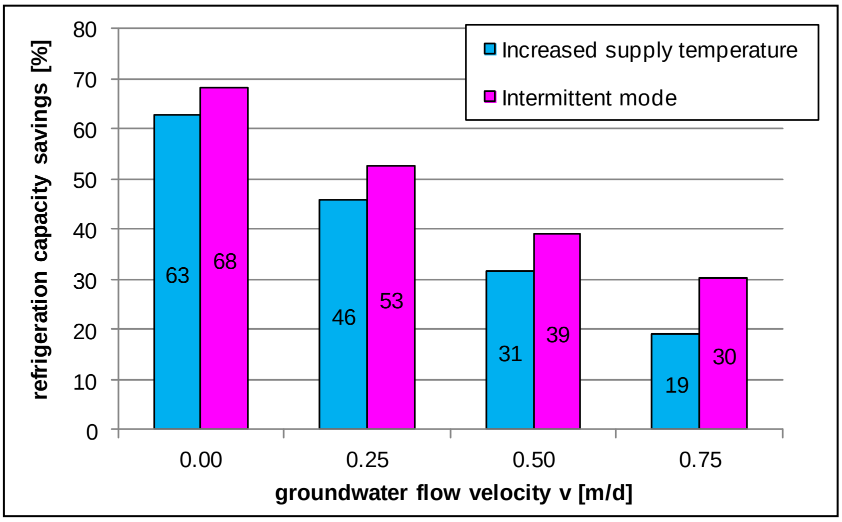


**Figure 3.5** **Energy savings for different operating modes during the operating phase for the basic system depending on the groundwater flow velocity**

The results have shown that significant savings of the refrigeration capacity can be realized. Due to the increased convective heat flow these savings decrease with an increasing groundwater flow velocity. Comparing both operating modes it becomes clear that the intermittent mode is most effective and causes further savings even for higher groundwater flow velocities. The individual control of freeze pipe groups is a main advantage of the intermittent mode. This enables the simple control of critical regions in the frost body (in this case the critical edges of the frost body). A further advantage of the intermittent mode is the effective frost body growth control.

## 4 Conclusion

The further development of the program system SHEMAT for the detailed and realistic determination of the required refrigeration capacity of artificial ground freezing applications has been verified by the simulation of a laboratory model test. Based on this, a parameter study has been carried out, that identified the groundwater flow velocity as the major influencing parameter for both freezing time and refrigeration capacity. The numerical simulations for the energetic optimization of ground freezing applications have shown that a significant reduction of freezing time and refrigeration capacity during freezing phase can be achieved by flow adapted freeze pipe arrangements. The use of adapted operating modes during the operating phase can realize further significant saving potential. In this context the intermittent mode is most effective and can lead to a saving of 2/3 of the refrigeration capacity during the operating phase depending on the groundwater flow.

In summary it can be ascertained that in principle the adapted program system enables the numerical optimization of artificial ground freezing applications prior to the construction regarding time and energetic aspects during freezing and operating phase.

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