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"Case studies of artificial ground freezing simulations for urban tunnels"

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Case studies of artificial ground freezing simulations for urban tunnels

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Summary

We present and quantitatively analyse results from the monitoring of three highly demanding applications of artificial ground freezing in urban underground construction projects. The interpretation of the field measurements is based upon coupled thermo-hydraulic numerical simulations using the finite element code FREEZE. The first case study concerns the construction of a twin tunnel for the Fürth subway in Germany in soft ground with significant seepage flow. The emphasis of this study was on a realistic simulation of the overall project situation during the frozen body growth stage. The second case study relates to a platform tunnel in a station of the Naples metro and aims to determine missing but relevant material parameters via back analysis and to make comparisons of model predictions with field measurements. In the third case, that of a tunnel beneath the Limmat river in Zurich, considerable construction delays occurred due to the inability to create a completely closed frozen body. The numerical simulations indicate that this problem was caused by a number of big deviations in the boreholes, in combination with seepage flow.

Keywords: Artificial ground freezing, urban tunnels, numerical simulations, field measurements

1. Introduction

Improvements in transport networks often create a need for underground construction projects in urban areas. The selection of the tunneling method often depends on geological conditions. In water bearing soft ground, auxiliary measures such as grouting or artificial ground freezing (AGF [1]) are often indispensable for maintaining face stability and preventing groundwater drainage. The potential problems of AGF include surface heaves (due to expansion of the frozen soil) or settlements (due to consolidation in the thawing phase). Furthermore, high seepage flow velocities may prevent the closure of the freezing body. Hardly any systematic experimental investigations have been conducted in respect of these topics. In order to investigate the effects of seepage flow on the growth of a frozen body, the 3D numerical code FREEZE for simulating coupled thermo-hydraulic processes was developed at the ETH Zurich [2] and verified against the results of large scale model tests [3]. The aim of the present paper is to illustrate the possibilities, limitations and practical usefulness of numerical simulations of AGF by means of three case studies.

The first case study concerns the construction of a 56 m long tunnel for the subway network of the German town of Fürth. The groundwater flows perpendicularly to the tunnel with a velocity of 1.25 m/day. The second case involves the Naples subway and concerns a 50 m long platform tunnel for the Università metro station. The third study concerns the application of AGF in the undercrossing of the Limmat River in Zurich by a double track tunnel. The emphasis varies in these three case studies. In the first case, all of the relevant data was available. This made it possible to simulate the entire freezing operation as a thermo-hydraulic process, to make class A predictions and to compare them with the monitoring results. In the second case, the FREEZE code was used to back-calculate the thermal conductivity of the ground based upon field measurements. In the third case the main technical problem encountered during the freezing process was the incomplete closure of the frozen body. The simulations have been performed in order to trace back its cause.

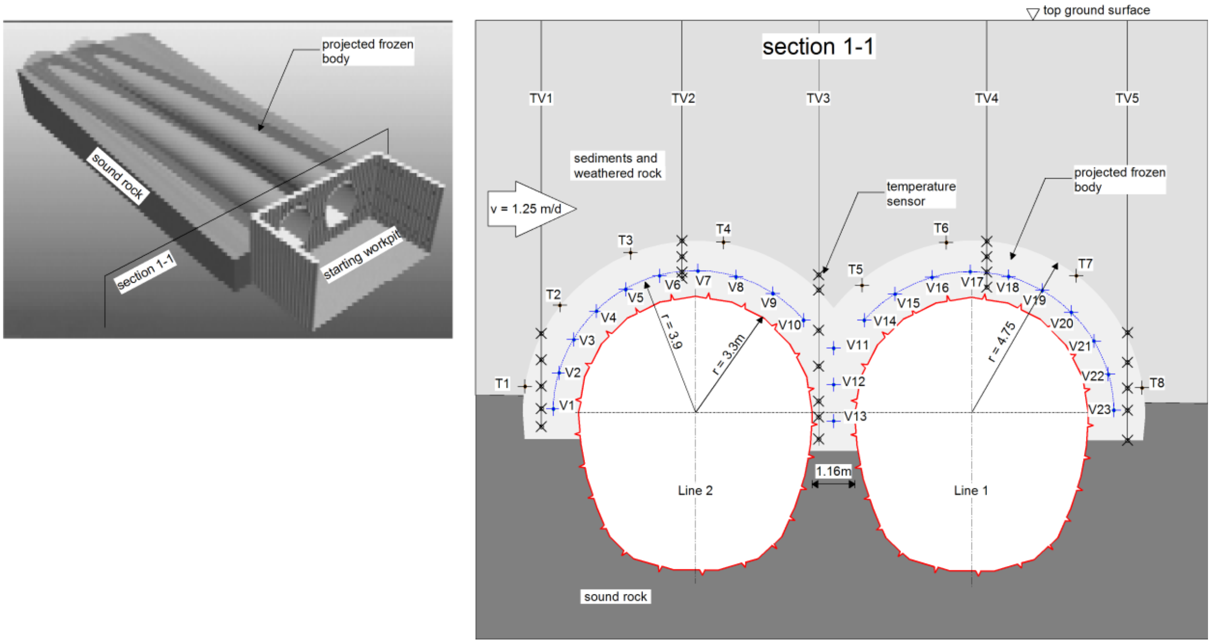
In all case studies the first stage of the AGF operation, i.e. the formation of the frozen body prior to the tunnel excavation, was modelled. Table 1 gives an overview of the thermal parameters.

Table 1 Material properties

Material	γ_d (kN/m^3)	k_f (m/s)	$k_{unfrozen}$ (W/mK)	k_{frozen} (W/mK)	$c_{v\ unfrozen}$ (MJ/m^{3}K)	$c_{v\ frozen}$ (MJ/m^{3}K)	α (%)	β (-)
Fürth project								
Soil	17	10^{-4}	2.20	3.40	2.78	2.03	1.5	-0.700
Rock	20	10^{-14}	2.00	2.16	2.40	1.95	-	-
Naples project								
Tuff	12	10^{-5}	0.49	1.11	3.23	2.03	1.5	-0.700
Zurich project								
Compacted gravel	17	10^{-4}	2.10	2.80	2.50	1.80	0.8	-0.727
Young gravel	16	6×10^{-4}	2.40	3.00	2.40	1.60	0.8	-0.727
Old gravel	15	10^{-4}	2.30	3.00	2.30	1.70	0.8	-0.727
Lake deposits	19	8×10^{-5}	1.60	2.80	2.80	2.10	3.0	-0.574
Glacial till	18	10^{-5}	1.70	2.90	2.70	1.90	1.5	-0.699
Molasse	26	10^{-12}	2.30	3.00	2.50	2.00	-	-

2. Subway Fürth - Line U1

The extension of the U1 subway line in the German town of Fürth, connecting the Stadthalle and Klinikum stations, involved the construction of a 1300 m long tunnel [4]. We focus here on the first, 56 m long stretch of the tunnel, which passes beneath a block of settlement-sensitive historical buildings and crosses quaternary sandy deposits and weathered rock. The competent rock beneath this layer consists of sandstone from the middle Keuper formation. At the border of the valley the bedrock ascends steeply. The sand deposits and the weathered rock are aquiferous, while the underlying competent bedrock is less permeable. The groundwater flows perpendicularly to the tunnel with a velocity of 1.25 m/day. The alignment has a slight horizontal and vertical curvature.



(a) **(b)**

Fig. 1 Subway Fürth. (a) Perspective view [4] and (b) cross section

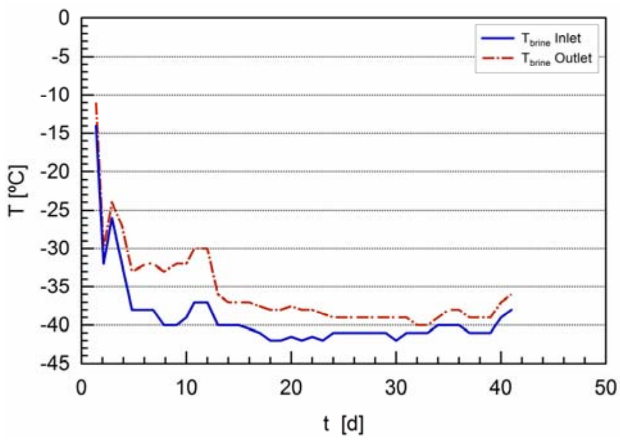


Fig. 2 History of the freeze pipe temperature

Artificial ground freezing was chosen as an auxiliary measure for the two single track tunnels (Fig. 1). Since only the aquifer had to be frozen, the freeze pipes (V1 to V23 in Fig. 1b) were located only in the upper part of the tunnels, starting from the competent rock (V1, V13 and V23). In order to limit deviations to a maximum of 25 cm at any point in the projected freeze pipes, the boreholes (which follow the curved alignment) were bored with horizontal directional drilling equipment. Safety during construction demands a frozen body thickness of at least 1 m at each point. To control the size and the temperature of the frozen body during freezing, 23 additional boreholes with temperature sensors were drilled (T1 to T8 and TV1 to TV5 in Fig. 1b). The freezing plant consisted of two two-stage freezing aggregates, each with a cooling performance of 465 kW. Calcium chloride brine cooled down to -40 °C was used as a refrigerant.

The numerical analyses consider a 14.5 m x 62.6 m x 26.8 m large domain. The weathered rock layer was assumed to have the same properties as the quaternary soil deposits. The calculations were carried out with the material constants of the design documents [6], i.e. the dry density γ_d, the hydraulic conductivity k_f, the thermal conductivities $k_{unfrozen}$ and k_{frozen}, and the volumetric heat capacities $c_{v\ unfrozen}$ and $c_{v\ frozen}$ (Table 1).

The temperature-dependent unfrozen water content was described by a power law [5] with the parameters α and β according to Table 1. The sub-horizontal contact between the two layers, as well as the exact position of the freeze pipes, were incorporated into the model based upon the in-situ measurements. Average constant boundary conditions were considered as follows: seepage flow velocity of 1.25 m/day perpendicularly to the tunnel axis, a ground temperature of 12.9 ºC at the beginning of the simulation and a groundwater inflow temperature of 12.9 ºC.

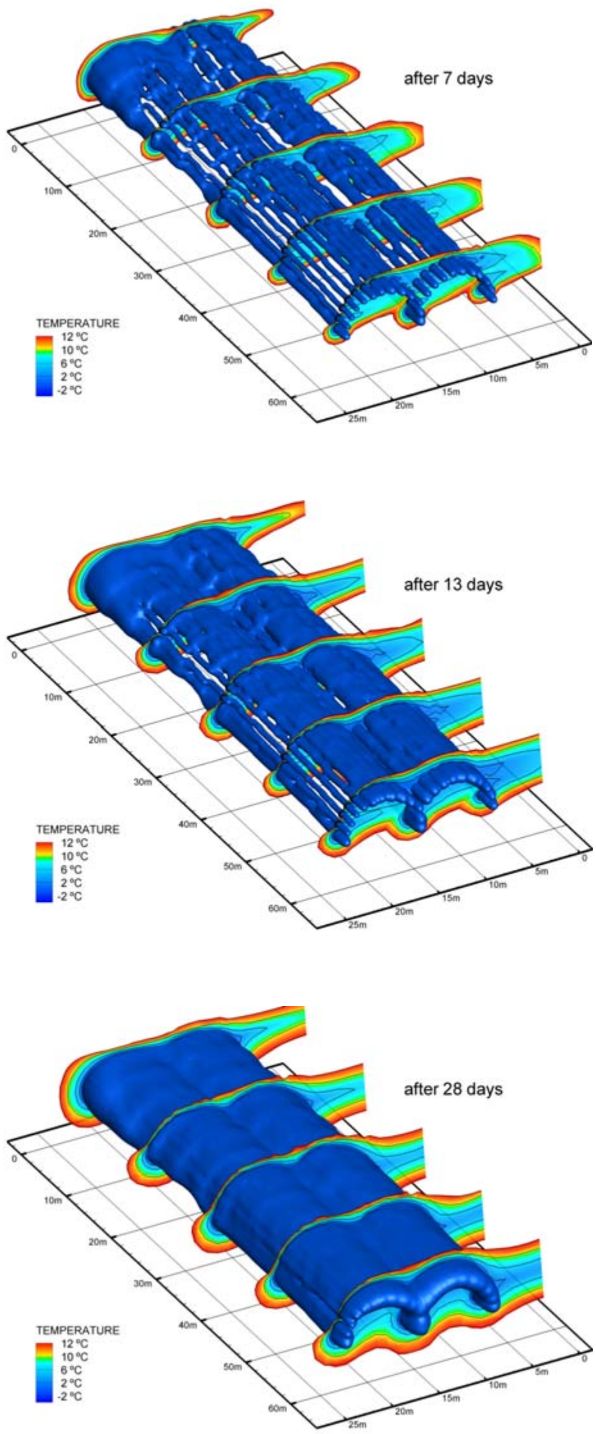


Fig. 3 Simulation results: longitudinal isothermal contour at -0 ºC (frozen body) and isothermal lines at 5 cross sections

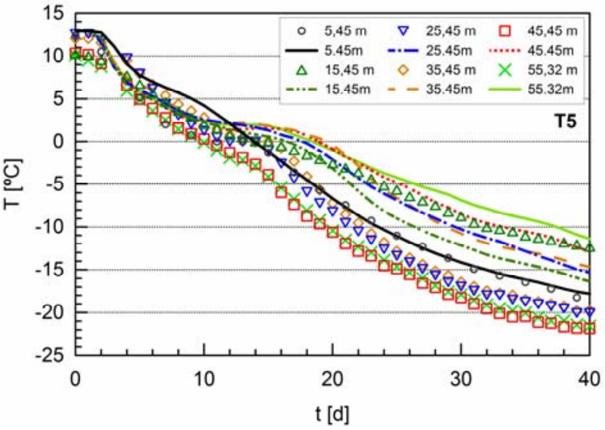


Fig. 4 Cooling history along the temperature sensor chain T5, positions measured from the working pit (symbols = measurements, lines = simulation results)

The freeze pipes were also discretisized by finite elements in order to take account of spatial and temporal temperature variations. The measured inlet and outlet brine temperature were adopted for the elements on the bottom and at the head of the freeze pipes respectively. For all the other elements forming the freeze pipes, the temperature was linearly interpolated between these two values. The temperature history is shown in Figure 2. The time steps were taken to 3600 s.

Fig. 3 presents the top view of the predicted extent of the frozen body (isotherm line 0 ºC), as well as the temperature distribution in 5 cross-sections after 7, 13 and 28 days. Due to the non-horizontal contact between rock and soil, the frozen body at the bottom of the pipes grows faster than the zones with a thicker soil layer. The required closure time for the frozen body of about 4 weeks correlates well with the measured time of less than 1 month.

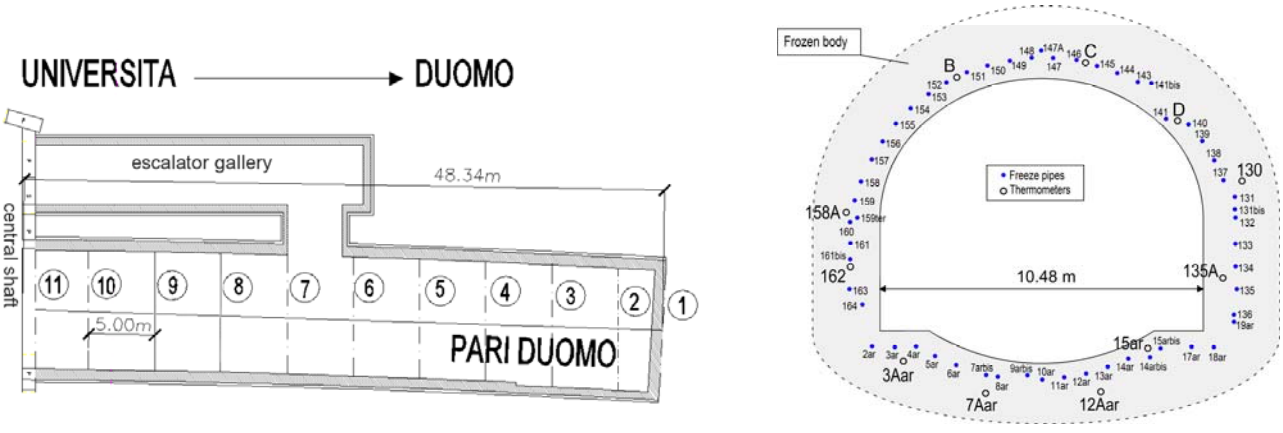
Figure 4 compares the measured cooling history along the temperature sensor chain T5 with the simulation results. The simulation results show a consistent behaviour and a good agreement especially with the measured values during the first week. After that and for the next 10 days the simulated temperatures fall more slowly than the in-situ values until reaching freezing point (0 ºC). Afterwards the temperature fall is similar or somewhat slower for most of the simulated sensors.

The possible reasons for these moderate discrepancies are: slight overestimation of the seepage velocity; constant ground temperature prior to freezing of 12.9 ºC (sensors 45.45 m and 55.32 m in Fig. 4 show 10 ºC); no dissemination between the weathered rock and the soil; slight underestimation of the thermal conductivity of the frozen soil; slight overestimation of the porosity, i.e. of the amount of latent heat.

In conclusion, using the three-dimensional thermo-hydraulic coupled numerical model (FREEZE) a highly demanding AGF measure can be simulated realistically. It must be pointed out that no calibrations were carried out in respect of the material constants or other model adjustments. Compared to previous simulations with constant freeze pipe temperatures, [5] an enhancement of the simulation results could be achieved by taking account of the temperature gradient along the freeze pipes, as well as the time-dependent temperature of the brine.

3. Subway Naples - Università Station of Line 1

The Università station consists of a rectangular central shaft, 4 platform tunnels with a length of approximately 50 m each and 4 escalator galleries connecting the platform level with the first slab above the rails [6]. It is located at a distance of about 230 m from the coastline. As the water table is close to the surface and the shaft has a depth of more than 30 m, significant piezometric heads were expected. The ground consists mainly of tuff and occasionally, in the upper part, pozzolana. The platform and escalator tunnels were driven through the yellow tuff of Naples, a material exhibiting an increased secondary permeability due to the presence of an irregular pattern of vertical cracks, which make excavation difficult without prior waterproofing [6]. The AGF method in a horizontal direction was employed as the most suitable method for ensuring stability and waterproofing of the platform and escalator tunnels. Figure 5a shows part of the Pari-Duomo platform tunnel in the Università station.



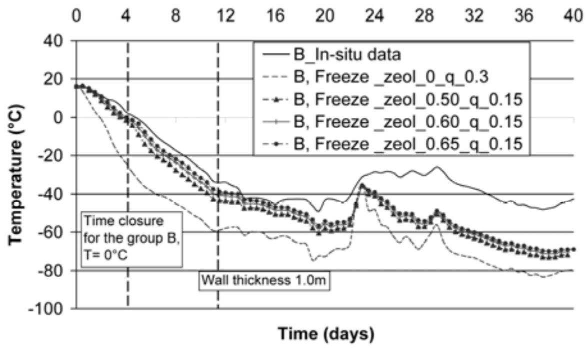
(a) **(b)**

Fig. 5 (a) Plan view of the Pari Duomo platform tunnel and, (b), cross section 11 with freeze pipes and thermometers chains

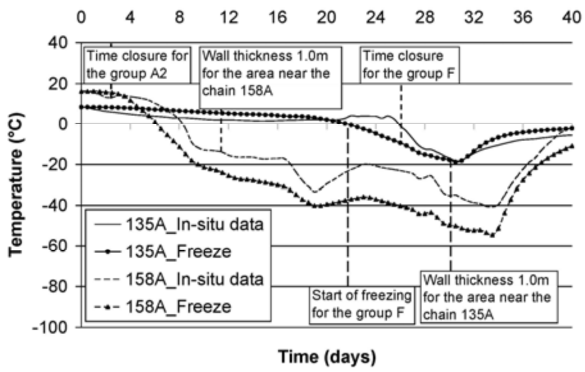
The first stage of the AGF operation was applied with liquid nitrogen. For this purpose 36 freeze pipes with a length of 50 m and an outer diameter of 76 mm were installed in a horizontal direction in the upper part of the planned tunnel and 19 freeze pipes were installed underneath the invert. The orientation of the boreholes was controlled by the horizontal directional drilling method. The growth of the frozen body was monitored by temperature sensors located along chains parallel to the freeze pipes. Seven thermometer chains were installed in the area around the planned tunnel and above the invert and 4 thermometer chains underneath the invert. Each chain has 50 m length and consists of a set of thermometers located at intervals of 5 m. The temperature was automatically recorded every 30 minutes. Figure 5b shows the location of the freeze pipes and the thermometer chains at the first cross section (section 11 in Fig. 5a).

Due to the absence of groundwater flow, only thermal analyses were considered. Uncertainties concerning the stratigraphy of the ground, and the absence of temperature measurements for the freeze pipes underneath the tunnel invert do not justify complex 3-D analysis. Therefore the numerical calculations were carried out in 2-D, taking account of a homogeneous material (tuff), i.e. only sections 11 and 8 (Fig. 5a) were studied. The computational domain is a 18.1 m x 16.7 m large rectangular region around the tunnel. For section 11, the locations of the freeze pipes were taken according to the cross section shown in Fig. 5b, while for section 8 the deviations from their initial location in section 11 were taken into account. It should be noted that neither the project documents nor the literature [6] include information about the thermal properties of the ground. The properties must therefore be estimated or determined by means of a back analysis. Most of the minerals have a thermal conductivity of about 2 W/mK.

In the tuff, the abnormal minerals in respect of heat transport are quartz and zeolite with a thermal conductivity of 7.7 W/mK and 0.12 W/mK respectively, which means that thermal conductivity can vary considerably, depending on the mineral composition. The thermal conductivity can be calculated using the approach of [7] for each different mineral composition. The given tuff values in Table 2 apply to a zeolite content of 0.65 and a quartz content of 0.15. As discussed later in this paper, these mineral contents produce the best match between the theoretical predictions and the temperatures monitored *in situ* above the invert. The outlet temperature of the nitrogen gas was measured (Section 11 in Fig. 5a). The inlet temperature of the liquid nitrogen was assumed to be -196 ºC (Section 1 in Fig. 5a), while the freeze pipe temperatures in the other sections were linearly interpolated between both values. The time steps were taken to 3600 s.



(a)



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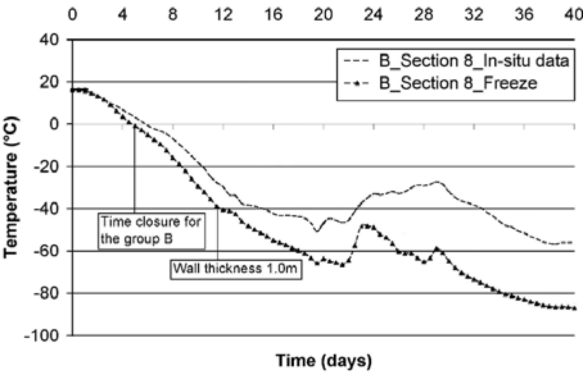


(c)

Fig. 6 Measured temperature history of the thermometer chain B at section 11, as well as calculated histories for different mineralogical compositions; (b) Temperature histories for thermometer chains 158A and 135A at section 11; (c) Temperature histories for thermometer chain B at section 8.

As indicated above, the thermal conductivity of the tuff was determined by means of back analysis, namely using only the temperature history of thermometer chain B at cross section 11 and varying the mineral content. Figure 6a shows this temperature history as well as the calculated temperature for four different mineral compositions. The best match was achieved for a zeolite content n_z=65% and a quartz content n_q=15%. Based on the back-calculated thermal conductivity, predictions were made for the other thermometer chains and cross sections.

The calculated temperature of thermometer 158A differs systematically by about 7 – 10 °C from the measurement data (Fig. 6b). Closure time is 2.5 days for the group of pipes ranging from pipe 158 to pipe 160, close to thermometer chain 158A.

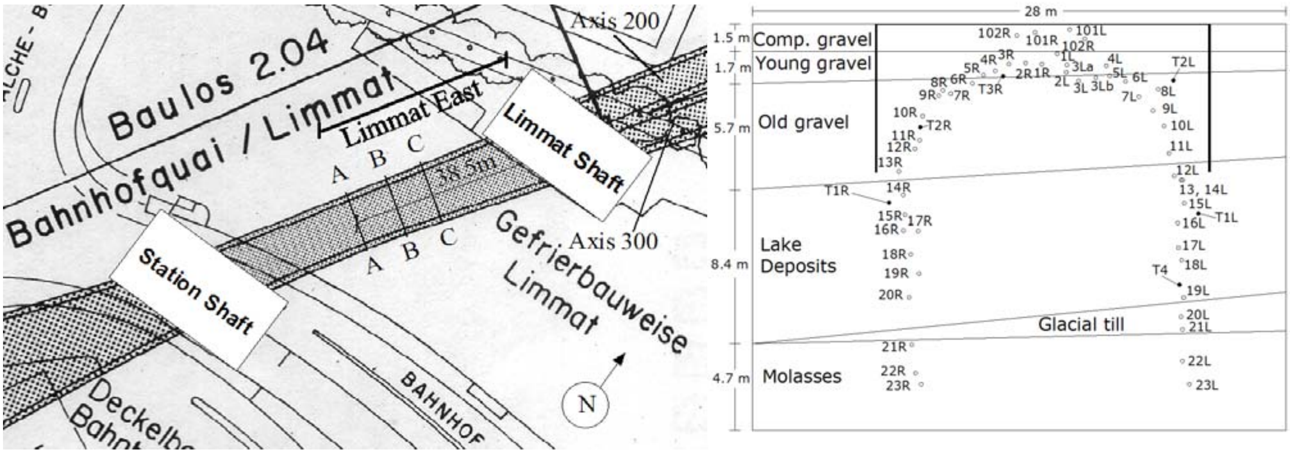
A good agreement (for the entire freezing time period) can also be observed in the case of thermometer chain 135A (Fig. 6b). Closure time is 4 days (from day 3 to day 7) for the group of pipes 131, 131bis, 132, 137 and 138 near thermometer chain 130, and also 4 days (from day 22 to day 26) for pipes 133, 134 and 135 near thermometer chain 135A.

At cross section 8, a considerable difference develops over time between the numerical results and the values measured by thermometer chain B (about 15 °C, Fig. 6c). A possible explanation for this is that the temperatures of the freeze pipes are different from those determined by linear interpolation between the entrance and the outlet temperature of the liquid nitrogen.

In conclusion, the thermal conductivity of the ground is a key parameter in modeling artificial ground freezing and can be estimated reasonably well by a numerical back analysis when it is not known.

4. Under-crossing of the river Limmat in Zurich

The Limmat under-crossing by a double track tunnel was constructed in 1986. The AGF method with brine was applied as an auxiliary measure to stabilize and seal the ground. After [8] the length of the under-crossing did not allow AGF to be applied in a single phase. For the purposes of AGF, the tunnel was divided into three stretches starting from two shafts, which were also used for drilling the boreholes for the freeze pipes (Fig. 7a). The present study concerns only the AGF applied in the Limmat East stretch. The ground consists of an upper gravel layer, followed by lake deposits, glacial till and sedimentary rock (Molasse) (Fig. 7b).



(a)

(b)

Fig. 7 (a) Plan view of Limmat under-crossing [8] and, (b), cross section A-A with actual location of the freeze pipes and auxiliary measures

The area above the tunnel crown was identified as a problematic zone when applying the AGF method due to the high permeability of the gravel layer surrounding it and its proximity to the river bed. Auxiliary measures were therefore taken to improve the ground in this area (compaction of the upper 1.1 m gravel, thermal insulation of the river bed, piling of two sheet piles on both sides of the planned tunnel and an additional row of freeze pipes in the crown area, see Fig. 7b).

For applying the AGF method with brine, 53 freeze pipes with a length of 38.5 m and an outer diameter of 101.6 mm were installed in a horizontal direction, parallel to the planned tunnel (Limmat East), and were supplied by a freezing plant with a cooling power of 81.4 kW. The distance between adjacent freeze pipes should be 0.8 - 0.9 m. As a rule, the longer the borehole, the bigger the deviation. At project time (1986) the horizontal directional drilling technique was not available, with the result that deviations from the planned position as large as 2.0 m were measured at the bottom of the holes. The actual geometry of all the boreholes was measured before installation of the freeze pipes.

It should be noted that the actual refrigeration time was considerably longer than the expected period of 60 days, with the result that grouting was necessary around the problematic regions after the detection of holes in the frozen body by ultra-sound measurements. In order to trace back the cause of the incomplete frozen body after the long refrigeration time, a 2-D model at the cross-section A-A (Fig. 7a) was used. The computational domain consists of a rectangular region of 28.1 x 22.0 m^2 around the tunnel.

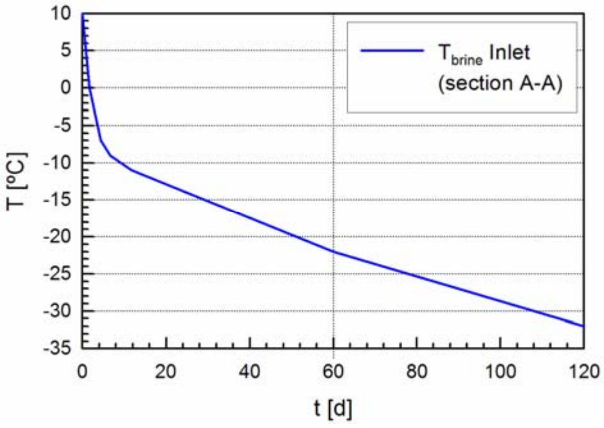


Fig. 8 History of the freeze pipe temperature

The stratigraphy (Fig. 7b), the material parameters (Table 1) and the ground temperature (which is 10 ºC for the period examined, i.e. from January to end of May) were obtained from the project documentation. The actual coordinates of the freeze pipes were taken into account (Fig. 7b). Since the cross-section A-A corresponds to the location of the bottom of the freeze pipes, their temperature was set at equal to the brine inlet temperature.

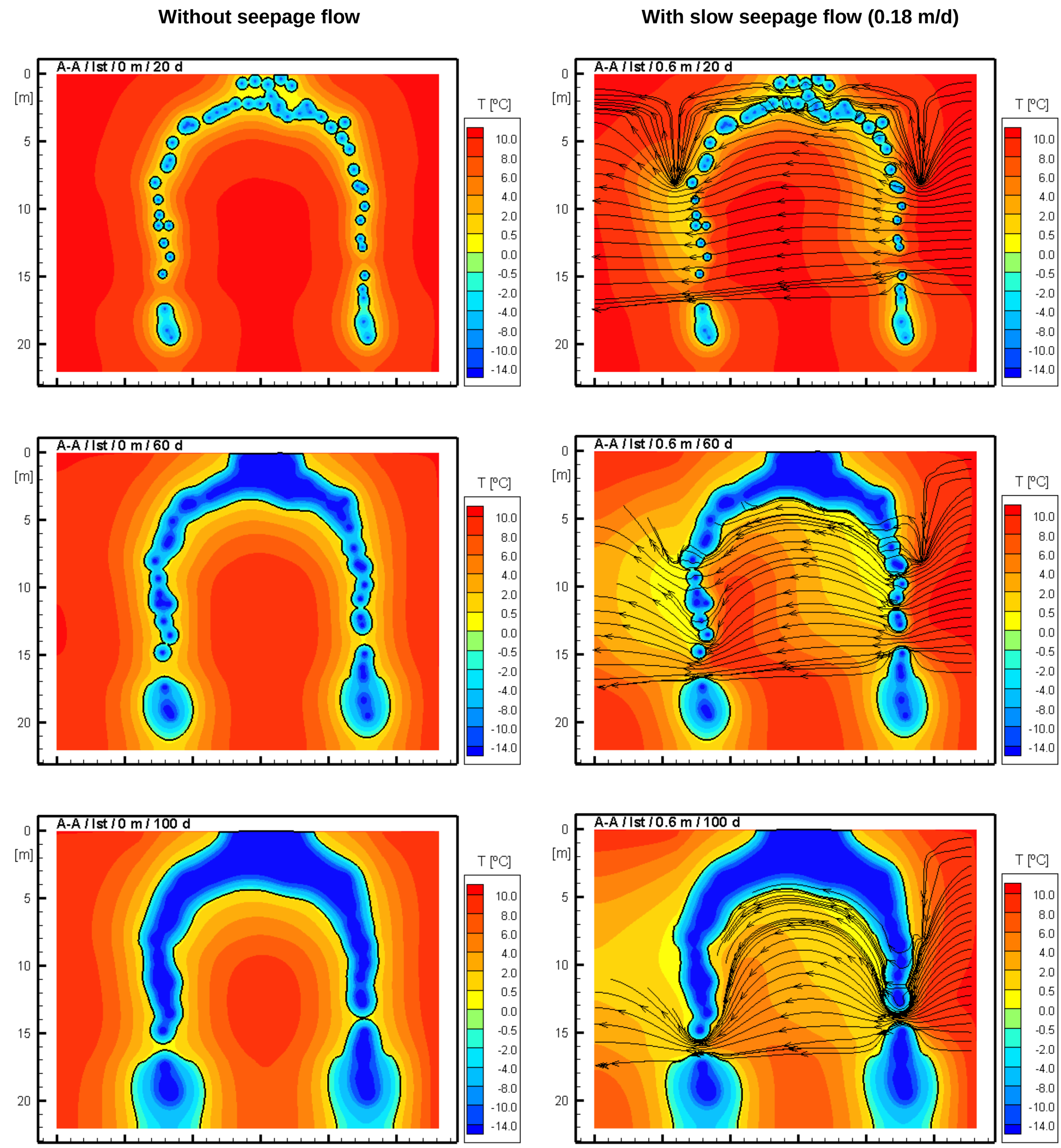


Fig. 9 Temperature distribution for the case without seepage flow (left) and with slow groundwater velocity (right) after 20, 60 and 100 days. The black contour line represents the extent of the frozen body (isotherm 0 ºC) and the arrow curves selected streamlines

Due to the lack of brine temperature measurements, the temperature history of the freeze pipes had to be estimated according to the project information. For the first two months the inlet temperature of the brine varied over time from 10 °C (first hour) to 2.5 °C (after 1 day) and down to -20 °C (after two months). After the first two months, and within the framework of remedial work to complete the closure of the frozen bodies, the cooling performance of the plant was fully utilised and the entrance temperature reached -35 °C (Fig. 8).

In the project information, the presence of seepage flow is mentioned but no concrete information about velocity or direction is available. For this study two situations are considered: (i) without seepage flow; (ii) with a low seepage velocity perpendicular to the tunnel axis. The second case is simulated with a piezometric head of 0.6 m between both ends of the model, i.e. a hydraulic gradient of 0.02, which would induce velocities of 0.18 m/d or less depending on the layer permeability.

Figure 9 presents the results of the simulations for both studied cases, i.e. without seepage flow (left) and with a low seepage flow velocity (right) at different simulation times, namely after 20, 40, 60 and 100 days. The predicted extent of the frozen body (black contour line in Fig. 9), i.e. the isotherm line 0 ºC, is shown, as well as the temperature distribution. For the case with seepage flow, selected streamlines have been drawn. In the area treated with the auxiliary measures described above, i.e. down to the end of the sheet piles, both simulated cases show similar results. The frozen bodies firstly connect together in the area above the tunnel crown and then they coalesce to a frozen body within the projected refrigeration time of 60 days. This confirms the effectiveness of the auxiliary measures.

In the area beneath the biggest boreholes, deviations can be determined in the lower part of the lake deposits layer, i.e. close to the glacial till layer. Even for the case without seepage flow, no closure could be achieved in this area despite a long refrigeration time of more than 3 months. This is more pronounced where there is seepage flow velocity. It should be pointed out, that the permeability of the lake deposits is relatively high (comparable to the permeability of the gravel layers) and of course more pronounced if higher seepage flow velocities are taken into account. Furthermore, since the auxiliary measures and the frozen body in the upper part tighten the ground, the groundwater velocity increases locally in the critical zone so that it is uncertain whether a longer refrigeration time would lead to a complete closure of the frozen body at all. It therefore seems that the main reason for the incomplete closure of the frozen body was the big deviations in the boreholes, together with seepage flow. The use of a stronger refrigeration plant would be advantageous.

5. Conclusions

Three case studies involving the AGF method were presented and simulated with the thermo-hydraulical coupled code (FREEZE). In the first case, the complete first stage of the AGF method was simulated, i.e. taking into account the spatial complexity and temperature history of the freeze pipe. The highly demanding simulations show an altogether good agreement with the measured values and consistent results. In the second case study, the thermal parameters of uncommon materials were determined via back analysis and the results were corroborated with other measured values. In the last case study, a problematic application of the AGF method was analyzed and the main reasons for an incomplete closure of the frozen body were tracked back. All the three cases were performed successfully, which demonstrated that the FREEZE code is a powerful tool for planning either simple or highly demanding AGF measures, or for analysis of monitoring data if necessary.

6. Acknowledgements

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7. References

[1] ANDERSLAND O., LADANYI B., “Frozen Ground Engineering - Second Edition”, *American Society of Civil Engineering*, , John Wiley & Sons Inc., Hoboken, New Jersey, 2004.

[2] SRES A., “Theoretische und experimentelle Untersuchungen zur künstlichen Bodenvereisung im strömenden Grundwasser“, *Veröffentlichungen des Instituts für Geotechnik (IGT) an der ETH Zürich*, Volume 234, 2009.

[3] PIMENTEL E., SRES A., ANAGNOSTOU G., “3D-Modellierung der Frostkörperbildung beim Gefrierverfahren unter Berücksichtigung einer Grundwasserströmung“, *Proc. 22. Christian Veder Kolloquium*, Graz, No. 30, 2007, pp.161-176.

[4] BAYER F., “Subsoil Freezing during the Building of the Fürth Underground”, *Tunnel* 7/2002, 2002, pp. 20-28.

[5] PIMENTEL E., SCHNEIDER T., SRES A., ANAGNOSTOU G., “Modelling of artificial ground freezing of an urban tunnel”, *Proc. EURO:TUN 2009*, 2nd International Conference on Computational Methods in Tunnelling, Bochum, Vol. 1, 2009, pp. 329-336

[6] COLOMBO G, LUNARDI P., CAVAGNA B., CASSANI G., MANASSERO V., “The artificial ground freezing technique application for the Naples underground”, Proc. Word Tunnel Congress 2008, New Delhi, 2008, pp. 910-921.

[7] JOHANSEN O., “Varmeleddningsevne AV Jardarter - Thermal conductivity of soils”, *Dissertation NTH Trondheim*, 1975, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1977, Draft Translation 637.

[8] EGLI R., “Die Anwendung des Gefrierverfahrens bei der Unterquerung der Limmat durch die S-Bahn“, *Frost in der Geotechnik, Mitteilungen der Schweizerischen Gesellschaft für Boden- und Felsmechanik 141*, 2000, pp. 53-67.