ARTIFICIAL GROUND FREEZING TO ENSURE A STABLE AND WATER-TIGHT SOIL BODY SHOWN AT THE EXAMPLE OF "FŐVÁM TÉR STATION"

Ralf Schmand, Rolf Heninger

Linde AG, Unterschleißheim, Carl-von-Linde-Str. 25, 85716, Germany

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INTRODUCTION

Safety in underground construction is an enduring challenge. As several accidents in the recent past indicate the pursuit of even more safety is not always successful. In such events methods for safeguarding the underground had been chosen in all conscience. Potentially they failed nonetheless since there was no way to validate if the measures had fully worked out.

Artificial Ground Freezing as a safeguarding method does not only provide a distinguished level of safety: more than that it offers the opportunity to validate the success of the method by direct measurement. Therefore Ground Freezing has become an established technology especially for groundwater tight excavation in tunnelling.
Of course, economical considerations have to be taken into account. Considering all aspects like time, risk and running costs Ground Freezing can be as competitive as any other soil improvement method (Itoh, 2005).
As the method can be used even for complex projects, it should be considered along with other soil improvement methods from the beginning.

Basics on Ground Freezing with liquid nitrogen

Ground Freezing is based on the withdrawal of heat from the surrounding soil with the target of creating water tight and load carrying frozen soil bodies. Two variants of Artificial Ground Freezing exist: brine freezing and freezing with liquid nitrogen (LIN). Both follow the same principle whereas this article focuses on liquid nitrogen only.

Ground Freezing with liquid nitrogen is an environmentally friendly application leaving no residuals like grouting material or diaphragm walls in the affected soil.

Liquid nitrogen (-196 °C) is produced in air separation plants by cooling and liquefying ambient air. The transport of liquid nitrogen is done by trucks and trailers in vacuum insulated vessels with a total weight of up to 40 tons.
From the trailer the liquid nitrogen is pumped into a storage tank (1) at the construction site (above ground level, see Figure 1). A main supply line (3) takes the nitrogen to manifolds (6) from where it is distributed over a set of individually controlled freeze lances (11).

A freeze lance works like an indirect heat exchanger and consists of two tubes: an inject pipe (10) is connected to the nitrogen supply. Liquid nitrogen is pumped through the inject pipe and leaves it at its open end. The nitrogen then flows in reverse direction through an outer pipe (11) which is embedded in the surrounding soil.

The nitrogen absorbs heat from surrounding soil, vaporizes and leaves the pipe in gaseous state whilst the moisture in the soil cools down and finally freezes to ice. Over the time, a solid circular body of frozen soil grows around the freeze lance. Several lances are placed in an appropriate pattern. Finally the circular ice bodies around each individual lance merge and a temporary closed wall of frozen soil is created.

The gaseous nitrogen exiting each individual lance is collected in an open exhaust system above ground and is finally released into the ambient air.
Freeze lances can be installed both horizontally and vertically, even bottom-up is possible. Lengths of more than 30 m can be realized.

The time required to achieve a closed wall depends on the heat conductivity of the soil and potential flow of ground water. Typically are one or two weeks.
Due to cryogenic temperatures of LIN ground water speeds of up to 10 m/day can be handled. This is a big advantage compared to freezing with brine which can barely compensate more than 2 m/day.

After a first phase of freezing up the frost body the LIN supply is throttled until the frost body reaches an equilibrium state and doesn't grow anymore. This is controlled by numerous temperature sensors placed in the underground (several per freeze lance). A second indicator is the temperature of the vaporized nitrogen exiting each freeze lance.

During this second phase the construction work can finally be carried out. Even after shut down of the nitrogen supply the soil remains frozen for several days and still allows safe construction work.

Pos	Description / Link
1	LIN-Tank
2	Evaporator
3	Main LIN-Supply Line
4	Main LIN Valve
5	Safety Valve
6	LIN Manifold
7	Solenoid Valve
8	LIN lines
9	Freeze Head
10	Inject Pipe
11	Freeze lance
12	Exhaust Hose
13	Exhaust Collector
14	Exhaust Line
15	Exhaust Heater
16	Temperature Lance
17	Thermo cables
18	Wiring for solenoid valves
19	Junction Box
20	Control unit

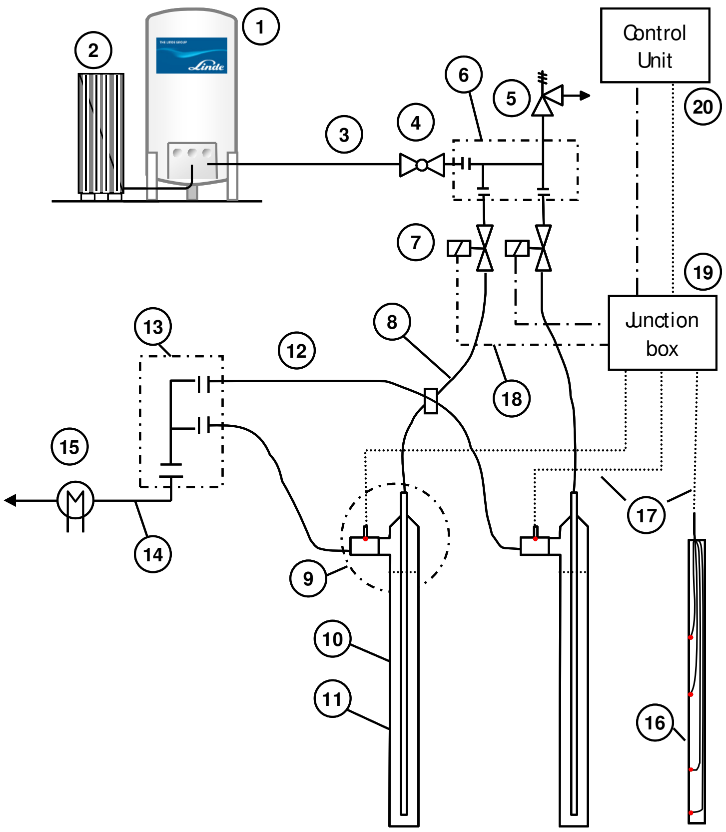

Fig. 1: Flow Diagramm

GROUND FREEZING AT FÖVÁM TÉR STATION

An example for numerous projects which have been successfully completed during the last years was the Ground Freezing at Fővám tér Station in Budapest.

The Budapest Metro is the world's second oldest Metro line after the London Subway. To cope with the task of transporting 1.3 billion passengers per year in the district of Budapest, the new Metro line 4 is being constructed. Metro 4 is built in 3 sections with the first section starting operation until 2014. This section has a length of 7.4km and will contain 10 stations. The second section has an additional length of 3.2km and 4 stations. Another 2 stations will be added in the third section of 2.1km length.

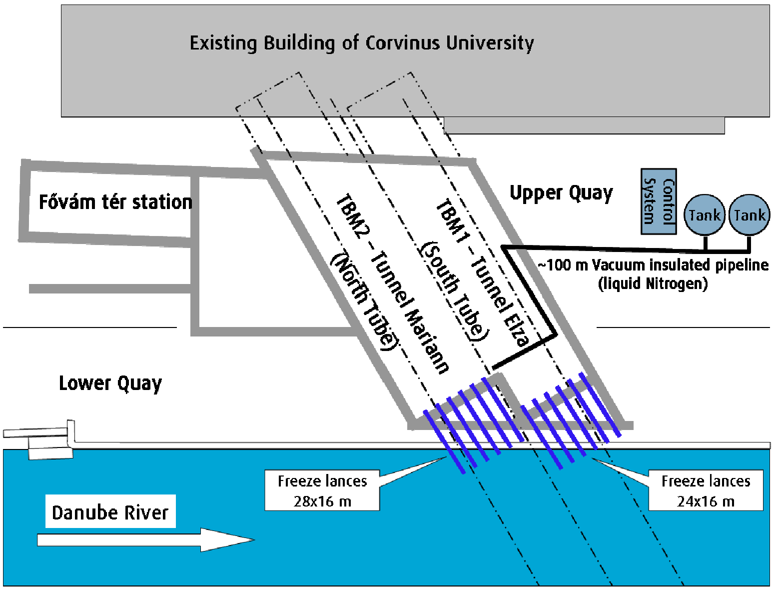

Fig.2: top view on scheme of construction site

Figure 2 shows a top view of the crossing of Metro line 4 and the Danube River: Two tunnel tubes between Szent Gellért tér station and Fővám tér station connect the districts Buda and Pest underneath the Danube. The Fővám tér station is located at the east side of the Danube river (downtown of Pest) between the building of the Corvinus University and the embankment. Coming from Szent Gellért tér station from underneath the Danube, the tunnel tubes were driven through a fault zone with several fractures comprising tertiary Törökbálint sandstone and Kiscell clay into the Fővám tér station. The minimum cover of the tertiary soils above the tunnel crown is about 8m plus an overlay of about 2m by quaternary gravel.

At Fővám tér station two platform tunnels extend the station to allow the train to stop within the station with its full length. Due to the close proximity to the Danube River there was a potential risk of water inrush which made additional protection of the platform tunnel necessary. In an earlier planning phase the platform tunnels should have reached 40m under the Danube. This solution had been rejected and the platform tunnel was moved 20m to Kálvin Square leaving only 20m of the platform tunnel under the Danube.

Construction sequence

The tunnel roof had already been equipped with a steel pipe umbrella which was nonetheless not sufficient to minimize the risks to a level which was accepted by parties involved. Therefore it was decided to combine the steel pipe umbrella with Ground Freezing.

In total 52 freeze lances of about 16 m length each were installed: 24 lances for tunnel Elza, 28 lances for the tunnel Mariann. Both tunnels have a diameter of 10.9m.
Since the freeze lance system followed the umbrella shape of the steel pipes the distance between the individual lances increased from 0.6m (tunnel mouth) to 1.2m (far end of the umbrella).

These distances were comparably small but from a time and cost perspective it should be avoided that too big gaps between the lances delayed the closure of the frost body. For the same reason it was of high importance to know the exact location and gradient of the drillings and the correlating maximum distance of the freeze lances. Critical gaps had to be monitored by additional temperature sensors.

Fig.3: tanks and container

The installation started on 05.01.2009. Above ground level two tanks of each 30 tons capacity were installed. To minimize thermal losses a vacuum insulated tube was used as main supply pipe. It was manufactured on site with a total length of 100 meter. At its end the main supply pipe was split into two extensions to feed the freezing systems at both tunnels.

Manifolds were installed to connect each single freeze lance with the supply pipe. Solenoid valves controlled the flow of liquid nitrogen to each individual freeze lance. The gas outlets of the freeze lances were connected to an exhaust pipe of 250 mm diameter.

Above ground level a container with the control system was placed close to the LIN storage tanks. All measurements from the temperature sensors, the safety system and other control signals were monitored and processed in this container. The control and the freeze systems were linked via a bus cable which ended at junction boxes at the tunnel walls. Each freeze lance was individually controlled by temperature sensors which were connected to junction boxes as well as the 24 V supply lines for the solenoid valves.

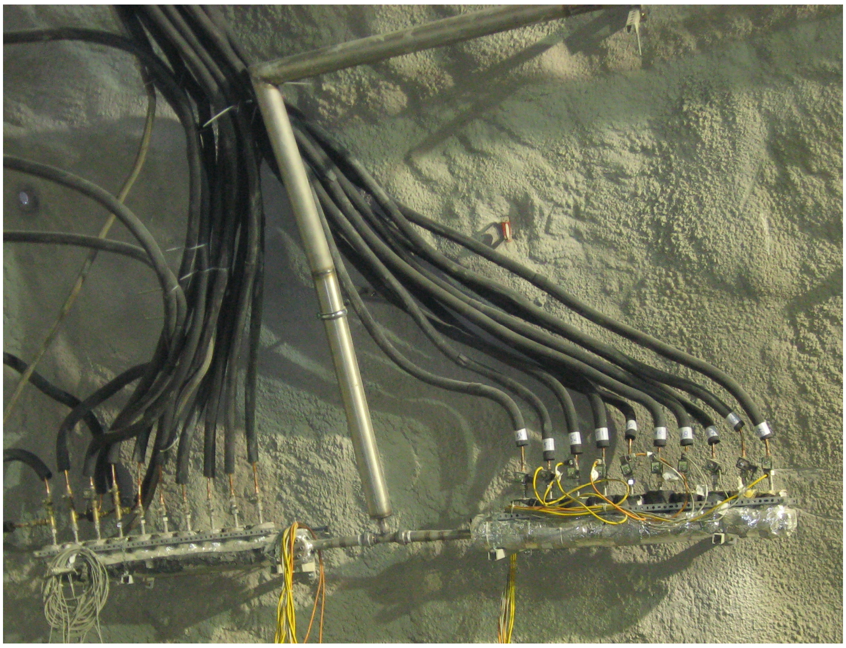

Fig.4: LIN manifold

A system of temperature sensors was installed in the soil using special temperature lances. It allowed monitoring the growth of the freeze body. Eight lances comprising 38 sensors were installed for the South Tunnel, five lances with 25 sensors for the North Tunnel.
To ensure a maximum safety level regarding oxygen each tunnel was equipped with oxygen level sensors. In case of low oxygen content an alarm would have been raised and the main LIN valve would have shut off the LIN supply. The shut valve was located in the main supply line close to the tank. Two alarm poles with optical and acoustic alarms were installed and equipped with additional emergency stop buttons.

To ensure best workflow, the work on both tunnels was timely shifted. The North tunnel TBM had been scheduled to arrive few weeks later than the South tunnel TBM, accordingly the Ground Freezing installation started in the South tunnel.

Control system

The control system was operated in automatic mode. The operator could access all relevant data via computer in the control container or via remote control from outside. All data like temperatures, oxygen content in the tunnel, tank level and switching status of the solenoid valves were stored and visualized in the system. Additionally all data were filed on spread sheets and provided to the site management on a regular basis.

Freezing

The first freezing started at 23.01.2009 at the south tunnel and was completed by 28.03.2009. The freezing at the north tunnel started at 14.02.2009.
The frost body was designed to a thickness of up to 1.5 m. For both tunnels it took about 17 days to achieve this dimension.
During the freeze up phase the temperature of the exiting gaseous nitrogen ranged from -100 to -130 °C. In the maintaining phase it increased to -40 and -90 °C.
Figure 5 shows the south platform tunnel with the freezing umbrella in operation. All equipment was installed away from the work area for excavation.

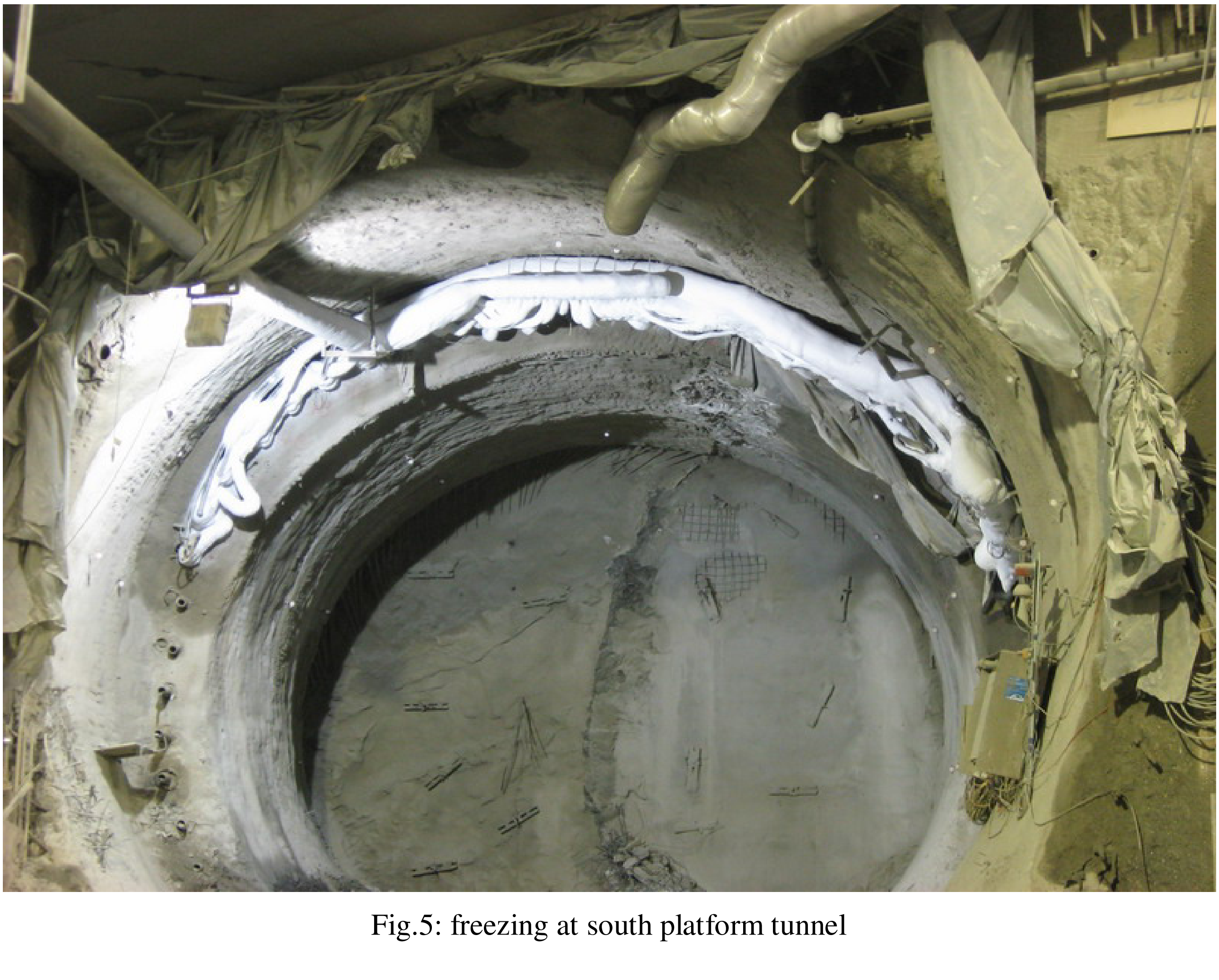

Fig.5: freezing at south platform tunnel

The arrival of the TBM at the station platform was on 29.06.2009 (South tunnel) and on 06.08.2009 (North tunnel). Both platform tunnels had reached the degree of completion suitable to receive the TBMs ahead of time.

The site had also been prepared for extending the Ground Freezing system in the placed steel pipe umbrella to the tunnel sides in case of eventual lateral water inrush.
But manual excavation showed that the frozen tunnel roof was sufficient and no additional freezing of the side walls was necessary.

Ground Freezing with LIN aims for an average temperature of the frost body between -10 to -20°C.

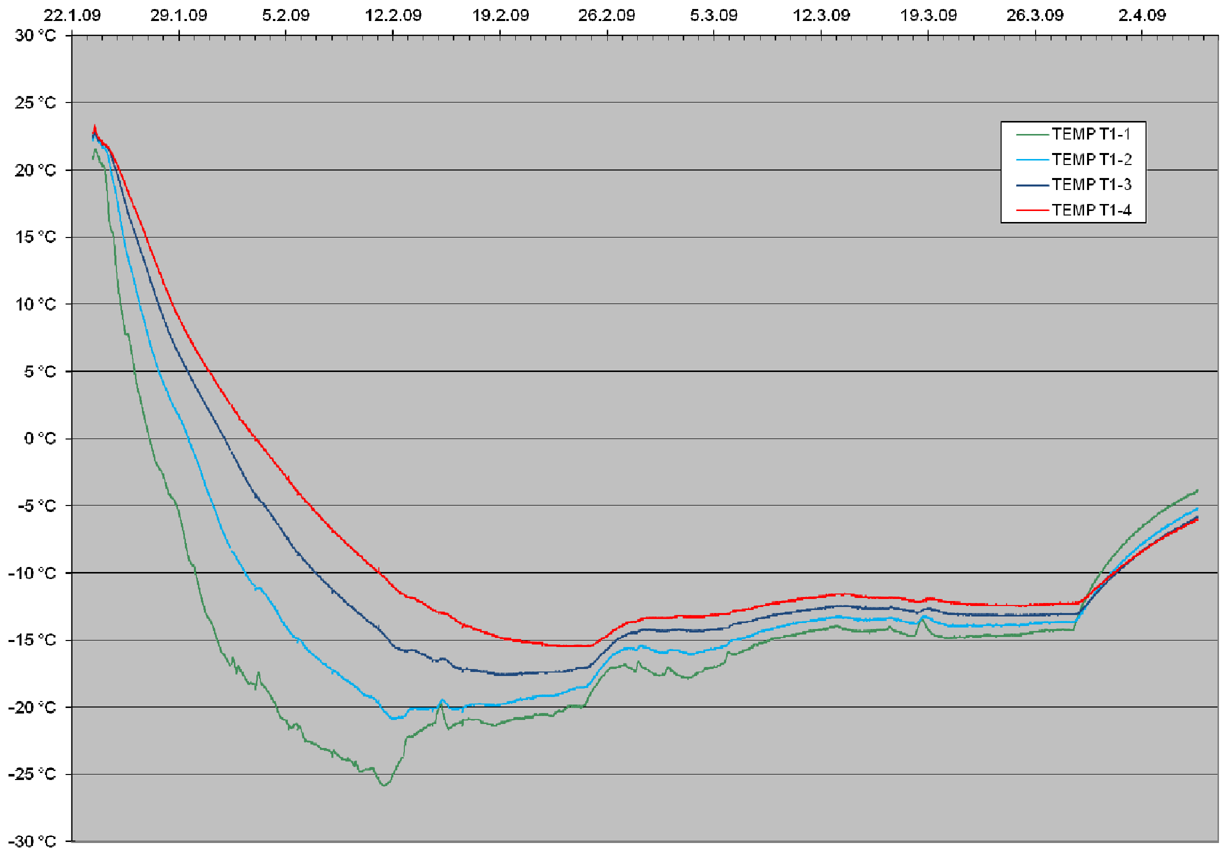

Fig.6: temperature graph of Temperature lance T1 at South tunnel

The soil temperatures are direct indicators for the size and propagation of the frozen soil body. Deviations at one of the sensors reveal the position of potential heat sources and allow countermeasures ahead of the excavation.

The graph in Figure 6 shows the temperature curve for one of the lances during the Fővám tér station project. It proofs the very stable conditions. After shut down of the freezing systems the soil remained still frozen for a considerable time.

CONCLUSIONS

The Artificial Ground Freezing project at Fővám tér station is a good example of a safe construction work. Ground Freezing helped to maximize the safety and to keep the ambiguous schedule without delay. This was despite there was little time to design and set up the Ground Freezing system.

The excavation during freezing went without any problems. Leakages which had happened at Szent Gellért before could be avoided.
The LIN consumption was lower than expected; all temperatures were well under control despite the proximity to the river. No unexpected situations occurred during the complete project time of 82 days – starting from the first day of installation until the end of freezing.
Although Artificial Ground Freezing with liquid nitrogen is often not the method of first choice: it is a safe and successful method in water bearing soil and a state of the art technology.

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