Ground freezing technique with respect to tunnelling in urban areas

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1 GENERAL

Tunnel construction in water-bearing soils is possible only in conjunction with preliminary or simultaneous auxiliary work, which subsequently assumes special significance. Auxiliary work considered effective in the elimination of groundwater during the construction stage includes, for example, the following methods and the appropriate measures to be taken:

METHOD	MEASURE
Water lowering	Dewatering
Displacing of water	Compressed air Pressurized slurry
Sealing	Cut-off wall Grouting body Body of frozen ground

In general dewatering is one of the cheapest technologies. On the other hand, it could induce a transportation problem based on a huge quantity of water as well as settlements, which are not always accepted in urban areas.

The slurry shield tunnelling method with segment lining is one of the standard procedures in use today in tunnel construction. An aspect to be taken into account, however, is the investment costs required for the acquisition of a shield represented a considerable cost factor. Due to economical reasons shield tunnelling requires a minimum of tunnel length.

An alternative construction method in special cases involves driving the tunnel with shotcrete, combined with a collar of frozen ground around the tunnel. Here the frozen ground, which is present only during the construction stage, plus the shotcrete lining, which is added as the driving progresses, combine to provide the necessary support, while simultaneously serving as a barrier to the groundwater. Excavation of the tunnel itself is carried out in conventional fashion, employing an excavator or a road-header.

The method used in ground freezing is that via a cooling medium, circulating in the freezing pipes, heat is removed from the ground. After a period of time has elapsed, a closed supporting collar of frozen ground forms around the designated tunnel area, which provides a protected area for the subsequent tunnel driving operation.

The hydraulic and mechanical parameters of frozen ground depend from several influences, e.g:

- Type of soil, with its
  - Porosity
  - Degree of water saturation
  - Temperature
  - Thermal conductivity
- Cooling medium, with its
  - Temperature
- Velocity of groundwater flow
- Freezing time
- Diameter of freezing pipes

The uniaxial compressive strength versus the degree of water saturation of undisturbed frozen soil samples from silt, sand and gravel is shown in Fig. 1 at a temperature state of -10°C.

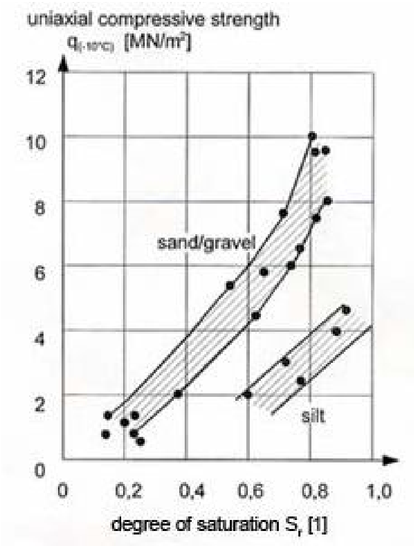

Fig. 1: Strength of frozen soil (after Borkenstein et al., 1991)

2 SUBWAY LOT U 6/3, VIENNA

The Vienna subway section U 6/3 connects the valley of the river Vienna with the centre of Meidlingen. In the nineties along with this section the two single track tunnels were driven mainly underneath existing buildings, the NATM having been selected as the basic construction method in combination with dewatering, compressed air and grouting. The most difficult component of the section was tunnelling underneath a telecommunication building with its sensitive equipment posed particular problems. There was only 1.6-2.0 m clearance between the building's foundation and the tunnels. To fulfil the owner's safety requirements for the building during tunnelling a 65·22 m continuous freeze plate, 1 m thick, above the tunnel crowns was built.

Due to limited experience with ground freezing technique in the ground of Vienna an extensive test program with two test fields was executed, evaluating the in-situ behaviour of the frozen soil and to determine the best means of intermittent freezing (Fig. 2).

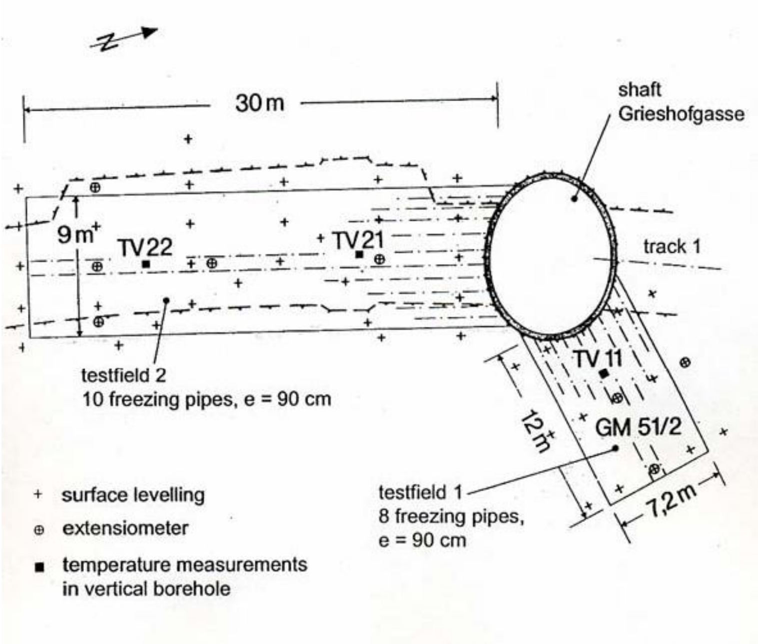

Fig. 2: Layout of test fields, construction lot U 6/3, subway Vienna (after Arz et al., 1988)

Measurement results from these test fields are shown in Fig. 3 to 5.

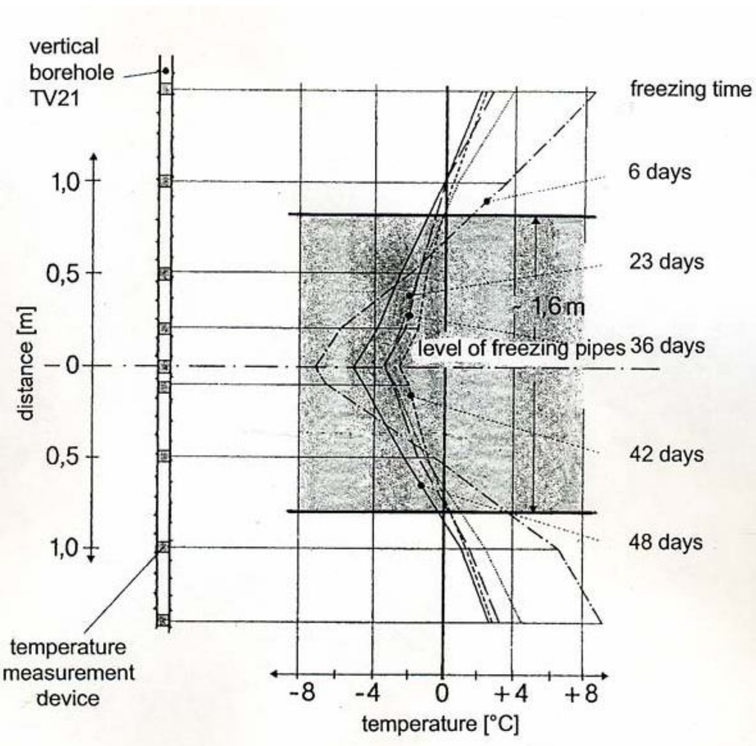

Fig. 3: Temperature distribution inside of frozen body (after Arz et al., 1988)

Fig. 3 shows the temperature distribution inside of the frozen body depending from the freezing time. The minimum results to -8°C. Obvious the temperature along with the upper and lower surface is about 0°C.

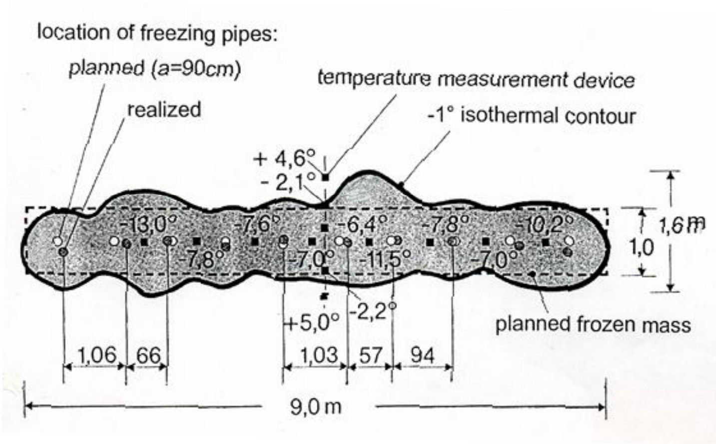

Fig. 4: Cross section of frozen body; 30 m far from shaft (after Arz et al., 1988)

A cross section of the test field 2 in a distance of 30 m from the shaft is shown in Fig. 4. With respect to inhomogenities in the ground and deflections of the freezing pipe alignments the shape of the frozen body is formed irregular. On the other hand the thickness of the freeze plate is 1 m in average as planned.

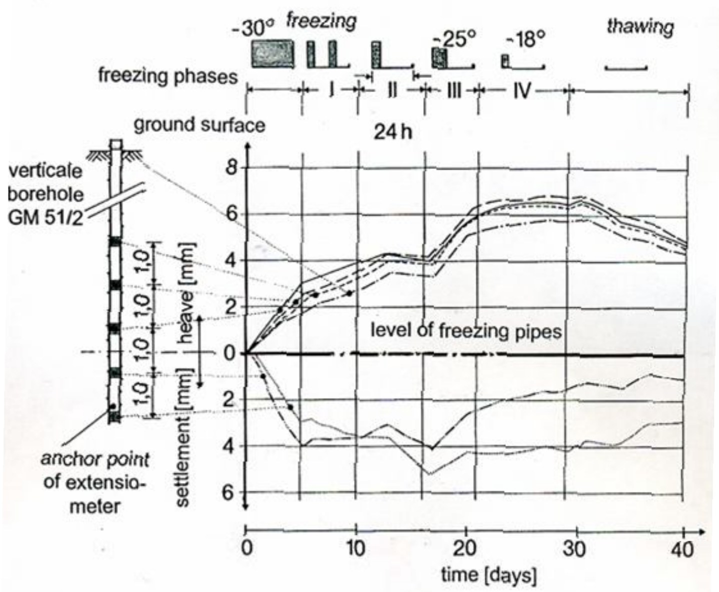

Fig. 5: Displacements of frozen soil along borehole GM 51/2 (after Arz et al., 1988)

Frozen soil results to an increase of volume, which leads to displacements in the ground. Fig. 5 shows the increase of the thickness of the freeze plate versus freezing time. The 1 m thick plate expands of about 10 mm in total. The consequence of this volume change is a reduction of the settlements induced by the excavation process during tunnelling.

3 FAHRLACH TUNNEL, MANNHEIM

In 1988 a joint venture under the technical leadership of Bilfinger + Berger Bauaktiengesellschaft was commissioned by the City of Mannheim, Germany, to construct the 489 m long Fahrlach Tunnel, a road tunnel with two tubes, two lanes each, and a cross section up to 100 m^2 each to be excavated in water bearing cohesionless soils with only small surface settlements permitted. The tunnel crosses 11 tracks of the Deutsche Bundesbahn including the high speed railway line Mannheim-Stuttgart. The cross-section of the tunnel is in the form of two open jaws placed side-by-side and touching in the middle. The combined width of the two tubes amounts to approximately 23 m, with a vertical clearance of about 7 m. Excavation of the tunnel floor will be to a maximum depth of 17 m below ground surface. The overburden will amount to 9 m maximum.

A 184 m long section of the Fahrlach Tunnel places the greatest demands on the skills of the engineers involved in the project, since it involves driving a tunnel with large dimensions through water-bearing soil, with only very small amounts of settlement permissible. The tunnel was to be excavated by NATM combined with ground freezing technique to form a ring-shaped collar around the boundary of the excavation. With a total of 27,000 m^3 of frozen ground the Fahrlach Tunnel is still today one of the world's largest horizontal ground freezing projects (Semprich et al.,1990, Arz et al., 1993).

The city of Mannheim is situated in the middle of the Rhine Basin which stretches from Frankfurt in the north to Basle in the south. Close to the surface here are quaternary sediments which are widely used for construction purposes. The ground conditions of the area proposed for the tunnel alignment were investigated in a first phase by drilling 23 boreholes to a depth of 24 m and completing 28 soundings by dynamic probing. The results indicated alternating layers of gravel, sand and silt, with thicknesses varying from a few centimetres to several meters. The groundwater level varies between 3.5 to 7.5 m below the surface, depending of the time of the year and the level of the nearby River Rhine (Fig. 6).

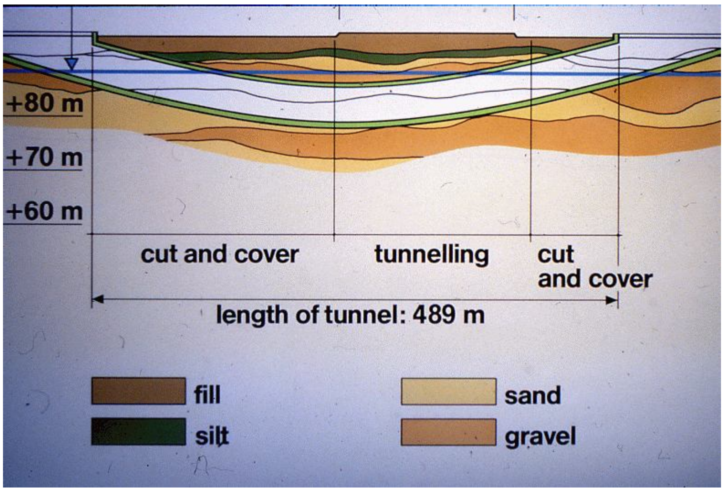

Fig. 6: Longitudinal section, Fahrlach Tunnel, Mannheim

Field measurements and laboratory tests produced the following results:

To ascertain the flow rate and the direction of flow of the groundwater, the data obtained from piezometers and from tests using tracer media were applied. Taking mean permeability levels of $k = 1\text{-}2\cdot10^{-3}$ m/s as the basis for calculation the data indicates rates of less than 1 m/day. Above of the groundwater level, water content of both the gravel and the sand was only 2 to 4% and the degree of water saturation was determined as 10 to 50%. Corresponding values for the silt were notably higher: 15 - 30 % and 70 - 95% respectively. Uniaxial compression tests gave a compressive strength of $q_u = 2 – 7$ MN/m^2 for the frozen silt depending on temperature and water content. Due to the low water content of the gravel and the sand the corresponding values for samples above the groundwater level have been only 0.4 – 6 MN/m^2.
Samples from below the groundwater level, on the other hand, due to the high level of degree of water saturation, exhibit much higher compressive strengths of up to 12 MN/m^2. Depending on type of soil, temperature and degree of water saturation values of the modulus of deformation E = 200 – 700 MN/m^2 were obtained for the frozen ground.

Because of stability reasons ground freezing above of the tunnel crown was necessary to form the ring-shaped collar. With respect to the low degree of water saturation in this area, it was necessary to supply additional water through irrigation pipes, which were executed from an additional auxiliary gallery located between the crown of the tunnel and the surface with an alignment parallel to the tunnel (Fig. 7).

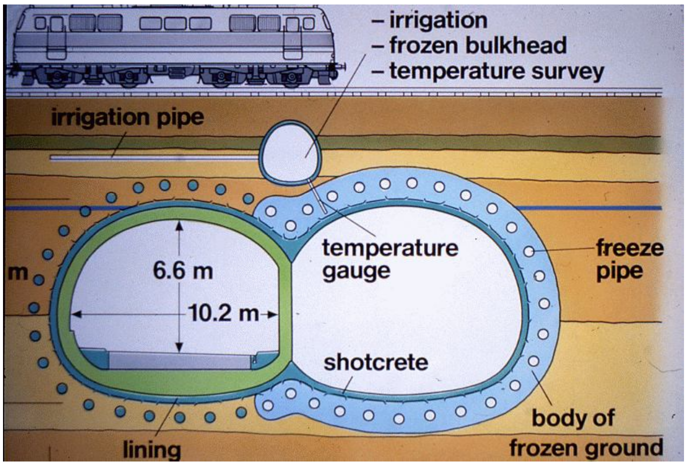

Fig. 7: Cross section of the tunnelling section

To create the ring of frozen ground 90 m long boreholes running parallel to the tunnel's axis were to be drilled from both ends of the tunnel section. The boreholes end in a frozen bulkhead 3 m thick in the middle of the tunnel section. This bulkhead was executed by freezing pipes installed from the auxiliary gallery. All drillholes require an extremely high level of alignment accuracy to avoid leaks in the frozen body. Therefore micro-tunnelling machines with a diameter of 470 mm were used in combination with the backwash removal technique and a steel casing tube inserted behind the machine. Inside of the steel pipes freezing pipes were installed and the remaining space was filled with mortar. The distances between the micro-tunnels vary from 1.8 to 2.7 m. 6 weeks were necessary to create a complete frozen ring with a 2 m thickness using the brine with a temperature of -10°C in average. Fig. 8 shows the freezing pipes at the tunnel portal (left) and inside of the auxiliary gallery producing the frozen bulkhead (right).

Fig. 8: Installation of freezing hoses

The excavation work was carried out in conventional fashion with an excavator and a roadheader (Fig. 9).

Fig. 9: Excavation work of the frozen bulkhead

A reinforced 35 - 45 cm thick shotcrete lining works as a temporary lining followed by a 50 cm thick inner concrete lining.
With respect to the observational method numerous measurements e.g. temperatures, displacements respectively settlements were carried out and the results have been compared with the results from analyses carried out during the design phase.

4 OUTLOOK

In these days in Austria and Germany 3 larger ground freezing projects are under construction. All are related to subway tunnelling using NATM.

In Vienna the ground freezing work for the subway construction lot U2/1 has been finished few months ago. Meanwhile the thawing period of the frozen ground takes place. Here the station tunnels cross the Donaukanal, where ground freezing was used for a 75 m long section. During the excavation work both single track tubes were protected by a mouth shaped frozen collar with a thickness of 2 – 3 m. For freezing work in the silt layer (Wiener Tegel) brine was used at the bench and the invert and liquid nitrogen above of the tunnel crown (Martak et al., 2005).

In Munich construction lot 6/3-15.1 of the Munich subway is under construction. This project contents a platform extension of the subway station Marienplatz direct under the city hall of Munich. To avoid larger settlements of the city hall the ground beside the benches and above of the crown of the excavation profile is frozen using brine. Measurements prove the success of the chosen ground freezing technique (Fillibeck et al., 2005).

The third example is going on in Cologne, where an approximately 4 km long North-South subway section is built. Limited sections are excavated in combination with frozen ground. Meanwhile test fields were already executed. The results of these test fields will be used as a base for the final design of the ground freezing works (Leondaris et al., 2005).

The above mentioned examples prove the applicability of the ground freezing technology in different soil conditions. Although this technology belongs to the more expensive ones, it could be conclude in special cases ground freezing technique is the most economical one.

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