Freezing techniques made a new tunnel possible

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ABSTRACT
In the centre of Copenhagen, at Nørreport Station, a new tunnel with 2 escalators has been constructed. The area around Nørreport Station is one of the busiest places in Copenhagen and the construction site was in the middle of it. The construction site was extremely tight, 10x40 m. The execution phase was separated in two main construction stages, a pit and a tunnel. This paper focuses mainly on the tunnel part, which was made underneath an existing bus area and a train tunnel, close to neighbouring buildings and just above two existing metro tunnels. The tunnel part was constructed by using the New Austrian Tunneling Method and freezing techniques.
Züblin A/S was commissioned to plan, design and construct the new tunnel Ny Metrotrappe.

1 GENERAL DESCRIPTION

Frederiksborggade is a busy street with small shops, cafes, restaurants and bank branches. Pedestrians, people with prams and bicycles, etc. come daily in the street as shown in Figure 1.

Figure 1: The construction pit was between the buildings in Frederiksborggade

Frederiksborggade is located in a pedestrian area. Each day 200,000 people pass Nørreport Station and about 40,000 people walk through Frederiksborggade. The construction site was in the middle of one of the busiest parts of Copenhagen.

A new pedestrian tunnel was connected to the existing transfer tunnel at Nørreport Station. At Nørreport Station it is possible to take long distance trains, commuter trains and metro trains.

The proposed tunnel was constructed close to existing buildings, metro tunnels and the Boulevard tunnel (Track No. 1). The Boulevard tunnel is about 100 years old but in good condition. From the construction drawings, it seemed that the base slab as the side walls was slightly reinforced and a membrane had been placed approximately 30 cm above bottom level. The drawings indicated that there were construction joints between the side walls, footings for the columns and the base slab. Furthermore, a retaining wall (soldier pile wall with wooden cladding) had been left in the ground from a previous project. Underneath the new tunnel two metro tunnel tubes were installed. The pedestrian street was in level +9.0m DVR90.

1.1 Soil condition

Fill (FYL): Generally fill was described as sandy, gravelly clay containing organic matter and silty sand. Locally, the fill has been encountered as peat with traces of sand.

The thickness varies from 7m to 10m close to the Boulevard tunnel.

Sand (Gravel): Below the fill layer, fine to medium sand, locally gravelly sand was encountered. This layer was also described in some borehole logs as clayey, gravelly sand till. The thickness has been encountered up to 7m.

Clay Till: The sand layer was underlain by clay till layer with a thickness ranging approximately from 3 to 5m. This soil layer was described as sandy, gravelly clay till, locally with lime grains and flint.

Sand/Gravel: Below the clay till layer, a sand/gravel layer was encountered in general with a thickness of approximately 2m. Locally, this layer is described as gravel till.

Limestone: Below the sand/gravel layer and clay till layer, respectively, limestone was encountered about 18m below the ground surface.

2 Structural form

Figure 2: Construction pit in a late stage

The aim of the brine freezing task was to create a stable body of frozen soil with defined dimensions during excavation.

In general, construction of the tunnel was divided into two different construction methods - a traditional construction pit and a tunnel. The new tunnel connects to the existing metro station, drilled below Nørre Voldgade and up into the street of Frederiksborggade no. 14 (see Figure 2). The width of the tunnel was about 4-5m and the height is about 2.75m. The length of the tunnel is approximately 50m in total.

The execution phase was separated into two main construction stages as follows:

1. pits were constructed from street level with varying excavation depth
2. a tunnel was constructed using the New Austrian Tunnelling Method and freezing techniques to connect to the existing transfer tunnel

It was excavate soil within dry pits formed by secant pile walls. The connection itself was to be constructed by using the New Austrian Tunnelling Method (NATM) and freezing techniques. Freezing pipes were drilled generally from inside of two deep pits (see figure 3 & 4). Prior to excavation under the level of the groundwater the soil was frozen and sealed against the groundwater. The excavation of the tunnel was conducted in steps while the surrounding soil was frozen and a primary lining in the form of shotcrete was installed to create a temporary load-bearing ring. After the connection to the transfer tunnel had been made, concrete works were carried out to construct the permanent tunnel lining. Finally, this was followed by fit-out works.

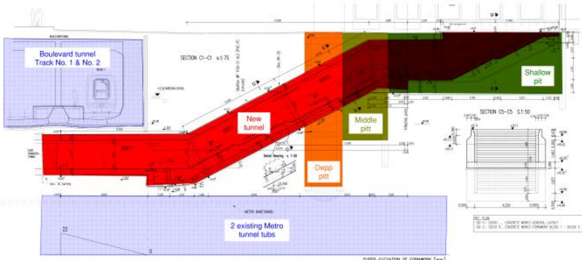

Figure 3: 3 Pits, new tunnel and existing tunnels

In previous freezing projects in Denmark a method with jacks-up had been used. If the freezing was extended too much, then the jacks-ups were prepared to compensate for the vertical deformation. In this project a different method was used. The expected deformation was calculated in the design stage and by monitoring work on site the actual deformation was measured. If the measured deformation values were critical the freezing system was shut down for a period, while still observing the limits for maximum temperature in the freezing profile.

Due to the narrow location of the new tunnel to the existing metro tunnel the space for placing of freeze pipes was very limited. For that reason the freeze pipes were drilled as steered drilling to achieve a high accuracy of the drilled holes. Furthermore, the location of the holes during drilling was controlled constantly to know the location of the drill head at any time due to the risk of drilling too close to the existing tunnels.

2.1 Construction pits

For the construction of the new pedestrian tunnel, an "entry shaft", in fact pits needed to be constructed. The location of the pits and its geometry was dictated by the new tunnel, the restricted site layout and surrounding buildings and tunnels. These pits vary in excavation depth and were divided into a shallow pit, middle pit and two deep pits (see figure 3 & 4). The pits were excavated in steps and dewatered. The shallow pit, middle pit and deep pits were excavated in different construction sequences. During the excavation, the archaeological excavations were commenced. The archaeological excavations were performed to 6m below ground level, which is above the groundwater level.

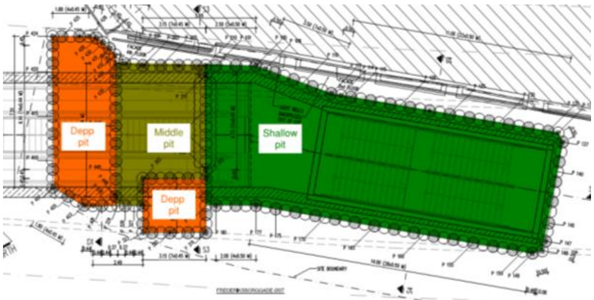

Figure 4: 2 deep, middle and shallow pits

Construction pits were formed by using secant piles. The method of using a secant pile wall minimised noise and vibrations induced in the surrounding buildings and tunnels. This type of construction is very stiff compared to other constructions and only small deflections are anticipated, which could impact the surrounding buildings. The diameter of the piles and reinforcement depends on the geometry, support conditions and static loads from soil, water, neighbouring buildings and surface loads. Furthermore, piles were embedded in clay till, resulting in a groundwater cut-off and it was expected that no groundwater would leak into the pits during construction. The shallow pit is shown in figure 5.

Figure 5: Shallow Pit with freezing system on top

However, jet grouting was planned to be performed to form a deep grouted sealing blanket but it did not work out and instead an ice block was made. After repeated adjustments of the jetgrouting setup it was not possible to get a watertight blanket and furthermore the strength of the blanket was not fulfilled according to the design. No groundwater lowering outside the pits was carried out because of considerations for the surroundings. The pit was secured against uplift of the ground and water ingress. It was intended to the use freezing method for the deep pits after the installation of the secant pile to form a watertight plug close to the level of the pile toe (see figure 6). Freezing pipes were installed from ground surface and only inside the deep pits and the middle pit. The excavation level of the shallow pit was higher than groundwater level in the middle pit.

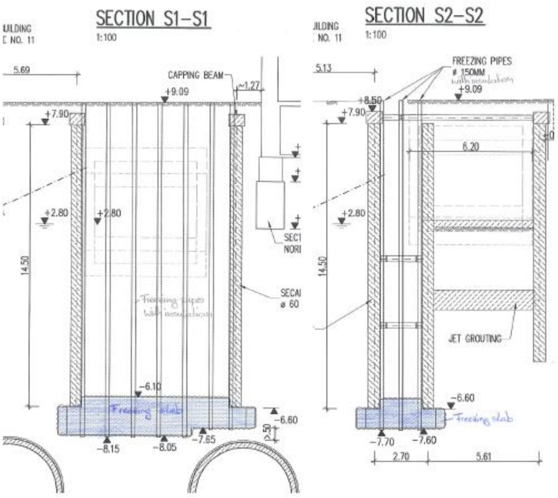

Figure 6: Freezing slab

A capping beam was installed on top of the piles. Depending on the depth of the excavation and loading, the pits were supported by struts and wailings, which were either concrete or steel. Anchors were used too. Ground anchors should maintain a sufficient distance to existing structures to avoid damage.


Figure 7: Temporary bridge on track no. 1

Track no. 1 (see figure 3) in the Boulevard tunnel was temporarily supported before excavation below the track could be commenced. It was intended to install a “rail bridge” inside the Boulevard tunnel and the span of the bridge was the same as the width of the temporary freezing profile. The bridge prevented any trainloads from track no. 1 on the Boulevard bottom slab just above the working area (see figure 7 & 8). The concentrated load was precisely above the centre line of the freezing profile. The design of the track support was done by others.

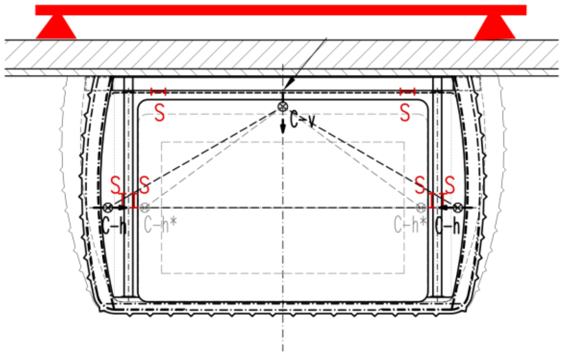

Figure 8: Temporary bridge above working area.

The self-weight of the Boulevard tunnel is mostly carried by the outer wall and the middle pillar between track no. 1 and no. 2.

Main site layout includes grouting plant, agitators, cement silos, disposal collection tanks or basin, workshops, generators, site offices, locker facilities and changing rooms. Mobile equipment consists of a crawler tunnel drilling rig with excavator for handling of the drill rods and the specialized shaft drill rig. For the set-up and dismantling of the site installations a mobile crane or equivalent was needed.

2.2 Freezing system

The following steps had to be executed successfully before switching on the freezing machinery:

1. Drilling of the freezing pipes and the pipes for the temperature monitoring
2. Pressure tests of the freezing pipes
3. Installation of the inner pipe inside the freezing pipes and the pipe heads as well as connection of the pipes with the machinery. The freezing pipes were connected together in groups of approx. 5 pipes.
4. Filling of the brine circuit
5. Start of the temperature monitoring system
6. Start of the freezing process.

Preparations:
First the formation level for the drilling rig was prepared. The starting points of the bore holes and the direction were set out by a surveyor. Secondly the boreholes were

marked out according to the layout specified on the drawings.

Pressure test:
Before starting, the freezing pipes were tested with a pressure test to ensure that no loss of brine would occur. Therefore the pipes were filled completely with water. The pressure for the test was around 10 bar. The system was considered to be pressure-tight, if there were no loss of pressure after 15 min.

Installation:
For the installation of the freeze tubes horizontal boreholes with the length of up to approx. 35m were drilled. The freezing pipes were connected together in groups of approx. 5 pipes. In general, the boreholes were drilled as rotary drilling with casing as drill rod and lost drill bit. The diameter of the casing was outer/inner 114 mm/94 mm. The drill bit was fixed on the casing and was disconnected with the installation of the freeze pipe. Disconnection was initiated by pushing the freeze pipe against a special device, connected with the drill bit. After disconnection of the bit it remained in the bore hole and the casing was pulled back. During the freezing activity the ingoing temperature and the outgoing temperature of every group was metered in the brine itself. In addition the main stream temperatures (ingoing and outgoing), the volume flow rate and the brine pressure were measured and recorded continuously.

Temperature monitoring:
For the temperature monitoring beside the freezing pipes additional pipes were drilled. Inside the pipes temperature sensors in the form of chains were installed. The exact position of the pipes was surveyed to determine the right distance to the freeze body. The sensor chains were connected to the central server. The measurement was continuously and online from the beginning of the freezing activity until the shutdown of the freezing plant. A few days before start-up initial measurements were carried out to verify the initial groundwater temperature.

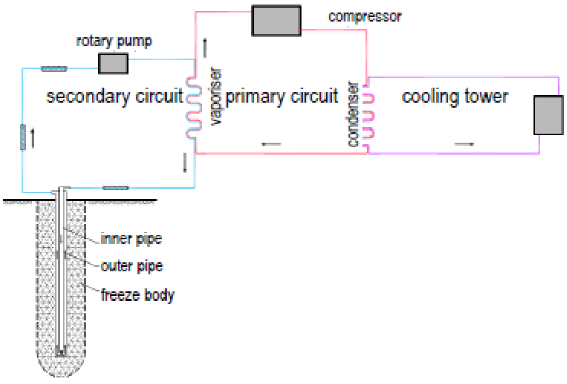

Figure 9: Freezing system

Cool Brine ($CaCl_2$ dissolved in water) was the freezing agent, which extracts the heat of the soil by the freezing pipes which distribute the cooling energy inside it. As a result of this permanent extraction of heat, the groundwater freezes and later on the freeze body is conserved during the works. The brine circulates in a closed system (secondary circuit). In the primary cooling circuit Ammonia (NH_3) is the used inside the mobile freezing plant, see figure 9.

The freezing pipes consist of two pipes laying one inside the other. They are both connected with the freezing plant by isolated flexible pipes. The brine passes through the inner pipe and returns to the plant through the outer pipe.

The drilling was executed in steps together with the excavation of the deep pits. In general drillings were carried out in the shafts with a small specialized drill rig. The upper holes above the groundwater level (from level +5.0m and from level +2.8m) were drilled with the crawler rig Huette 505, wherever possible. Therefore the rig was lifted into the pits and the walls between deep pits and the middle pit were removed.

Most of the grout holes were drilled from excavation level +5.0m. A crawler drill rig carried out the TAM-grouting. The rest of the grout holes could not be reached from level +5.0 m and were drilled after freezing. The work was carried out by a smaller shaft rig.

3 TAM-GROUTING

Grouting was needed because of the insufficient ground water content in the soil and used for pore filling to increase the saturation level of the soil (groundwater accumulation). TAM-Grouting was only needed beyond the upper part of the freezing profile. Tube á manchettes, TAM-grouting, was carried out horizontally from the deep pits and was typically drilled and grouted before drilling of the freeze holes.

For the installation of the TAM-pipes, horizontal or horizontally inclined boreholes with a length between 5.5 m and 22.5m were drilled. In general, the boreholes are drilled with drill tubes of 114.3 mm diameter and lost drill bit.

General procedure for drilling and installation of the TAM-pipes:

1. Setting out the starting points for the bore holes
2. Core drilling through the secant pile wall
3. Establishing the drill rig on the starting point of the bore hole
4. Cased drilling with lost drill bit, casing diameter 114.3 mm
5. Installation of the TAM-pipe
6. Extracting the casing, drill bit remains in the bore hole
7. Closing annulus between bore pile and TAM-pipe with cement
8. Filling the annulus between the bore hole and the TAM-pipe with sleeve grout.

Requirements of the first grouting sleeve were set with W/C value 3.0 pump rate 5-8 l /min. Grouting pressure 3-10 bar. Max 200 l or 10 bar. Requirements of the second grouting were set with W/C value 3.0 pump rate 3-5 l /min. Grouting pressure 3-10 bar. Max 100 l or 10 bar.

3.1 Tunnel work and freezing

Figure 10: 2 deep pits

NATM tunnelling started from the big deep pit (Figure 10 & 11) when the soil freezing had gained enough strength. The frozen soil mass was designed to carry the load from the groundwater pressure and excavation was conducted in steps. A primary lining in form of shotcrete was installed to create a temporary load-bearing ring. After approximately 12m of excavation in a slope of about 28°, the tunnel runs horizontal and after further approximately 15m of tunnelling, the new pedestrian tunnel connects to the existing pedestrian tunnel under the Boulevard tunnel.

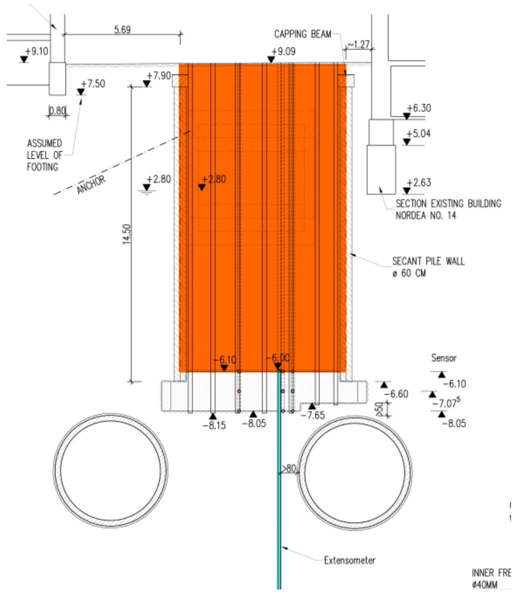

Figure 11: The largest deep pit

The excavation was carried out using a special tunnel excavator (see Figure 12).

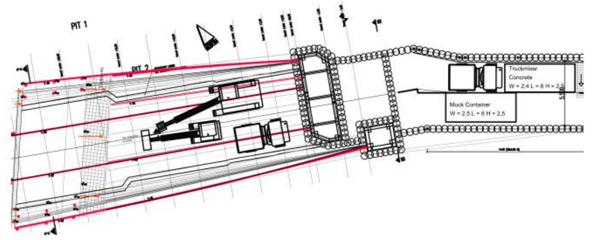

Figure 12: Works in the slope of the tunnel with tunnel excavators

Figure 13: The slope of the new tunnel

The following figure 14 shows possible locations for the sensor chains and the single measurement points. The exact position of the sensor chains and the single measurement points was fixed on site in collaboration with the site management. They were fixed based on the actual position of the freezing pipes and the geometrical situation of the existing structures.

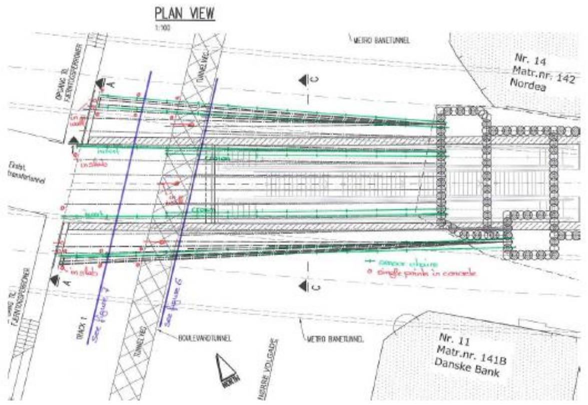

Figure 14: Plan view of the tunnelling/freezing segment with monitoring installations

Beside the freezing pipes additional pipes were drilled for the temperature monitoring. Inside these pipes sensor chains were installed. The sensor pipes were located at the top, the middle and the bottom of the planned freezing slab. The measurements itself were done continuously and online from the beginning of the freezing activity until the shutdown of the freezing plant. The online monitoring system gives several data about the freezing plant (brine temperature, brine pressure, power), the brine in the freezing pipes and the temperatures from the temperature sensors of the chains.

The temperature monitoring gives the real temperatures in the freezing slab, which are decisive for starting the pumping of the water inside the pit and the excavation activity.

The following sketches show the locations for the sensor chains. An example of temperature measuring in the freezing profile is shown on figure 15 and only the measuring point close to the warm transfer tunnel is minimally exceeded compared to the limit.

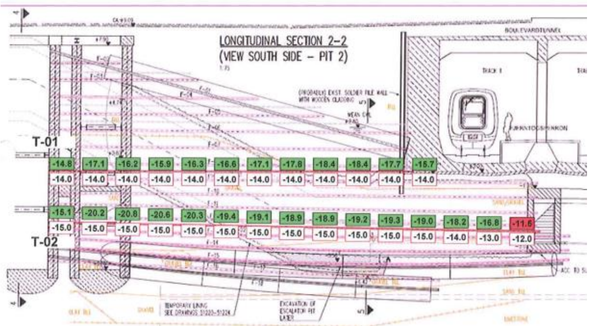

Figure 15: Example of temperature measuring

Figure 16 shows the layout of the freezing pipes and the freezing slab of the deep pit in its vertical expansion.

Figure 16: Layout of vertical freezing pipes in deep pits

In the deep pits vertical freezing was carried out with in situ freezing in the bottom. The freezing slab lies mostly between -6.1m DVR and -7.6m DVR (see Figures 6 & 16). The top of the metro tunnel is at around -8.2m DVR. The normal soil temperature was assumed to be +12°C. Inside the metro tunnel the temperature is surely higher because of the operating trains. The average temperature inside the freezing slab was -10°C. Based on the short distance between freezing slab and metro tunnel there was interference between them. To ensure the low temperatures inside the freezing slab, the freezing pipe distances above the metro tunnels were decreased.

The design calculations are carried out for single freezing columns. The figures of the slab layout (Figure 17) show various radiuses of the freezing columns. The minimum radius leaves little space in between the columns. The maximum radius results from the maximum pipe distances, but produces overlapping of the single columns. It can be assumed that there is an influence of the neighbouring freezing pipes. The freezing time was calculated to about 3-4 weeks depending on the freezing columns being small or large. But because of the water flow close to the new tunnel, the freezing time was extended.

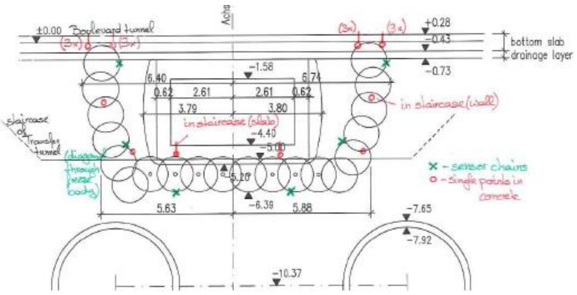

Figure 17: Monitoring installations in section below Boulevard tunnel

4 MONITORING

In addition to the sensor chains, single measuring points were planned to be installed from inside of the Boulevard tunnel to ensure the connection of the freeze body with the existing structure, the measuring points were located inside small boreholes in the base slab and the walls of the Boulevard tunnel and in the staircase conducting to the existing transfer tunnel. Furthermore, measuring points were on buildings, metro tunnel, on the surface of the street etc. The total system included automatic TCA measurements in the metro tunnel, hydrostatic levelling system in the station, vertical inclinometer in the secant piles, piezometer different places, data loggers, noise and vibration measurement system, etc.

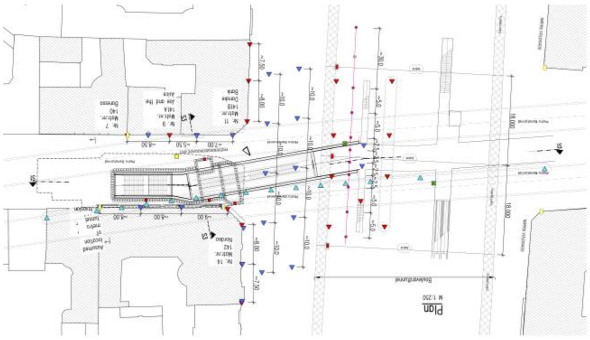

Figure 18: Monitoring plan

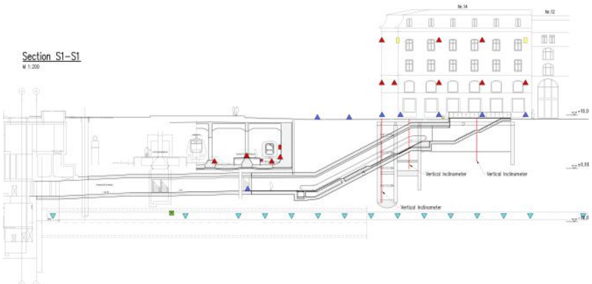

Figure 19: Monitoring

Before any kind of work was carried out reference measurements were made. Furthermore, some limit values for the deformations of the tunnels had been described. Each month a report was made and it described in detail the deformations hour for hour through the whole working period. Figure 18 & 19 show the monitoring set-up.

On the basis of the calculations and the deformations an alarm and emergency procedures were set up.

5 EXPERIENCE FROM SITE

The freezing profile led to vertical deformation in the temporary stages.

- In the paved area on top of the Boulevard tunnel the maximum vertical deformation was almost in line with expectations, but the main part disappeared when the freezing system was shut down (se figure 20)
- The 100 years old Boulevard tunnel had a vertical deformation, which was more than the limit value – this was difficult to

comply with. The freezing system was shut down from time to time to prevent an increasing deformation. Unfortunately, the new tunnel was just underneath an expansion joint in the Boulevard tunnel wall; if this had not been the case the vertical deformation would have been smaller.

- The metro tunnel had a deformation limit at 4 mm and the maximum measured deformation was 3 mm.

In the final design the deformation from the temporary stages was incorporated in the level of the permanent structure. Deformation from the temporary stages should not be a problem in the future for the Boulevard tunnel, metro tunnel, the street level and neighboring buildings.

Figure 20: Pedestrian street just above the tunnel

Figure 21: Freezing pipes at the starting point

The tolerance of freezing work/drilling of the freezing pipes on site was 0.5 m radius. The spacing of two freezing pipes is 0.50 m, at the starting point and it was not possible to reduce the spacing at the starting point in the secant piles (see figure 21). If the spacing between two pipes in the soil was more than 1m the duration of freezing have to be exceeds. To ensure the tolerance every drilling was measured and the result was integrated into an as-built 3D-drawing as shown in figure 22. Every drilling was drilled with high precision.

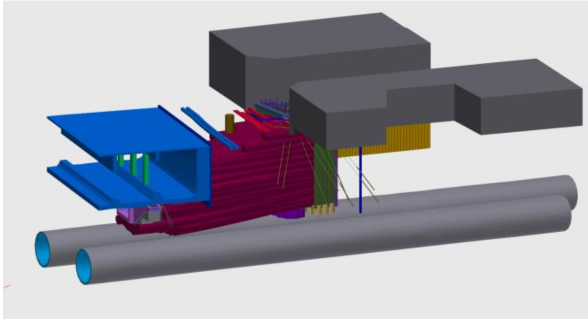

Figure 22: 3D model, as-built of freezing pipes (shown in red)

The vertical freezing pipes had to be very close to the secant pile wall (see figure 23). Therefore, the pit layout including the capping beam had to be designed such that all stages of the construction pit were possible. Furthermore, there had to be enough room for the drilling machine to work, even though the pit was narrow in the deep part. The drilling rig distance to propping systems had to be about 30-40 cm; otherwise it was very difficult to carry out the drilling work.

Figure 23: Vertical freezing pipes close to secant piles

Two dewatering pipes were installed inside the frozen profile. Valves and parker had to be installed at the starting points to avoid inflowing material. In the early stages, the dewatering pipes were a help for indicating watertightness of the frozen profile.

The freezing volume was difficult to control. Some parts of the future tunnel section were frozen and therefore the excavation was difficult to carry out.

Even though the TAM-grouting and the freezing profile combined should be watertight some leakage was observed. The local water flow was beyond the limit (approx. 40 l/hour). The water flow was stopped by local grout drilling as the excavation was carried out.

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