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# Ground freezing for tunnelling under historical structures

## Congélation de terre pour le construction des tunnels sous les structures historiques

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### ABSTRACT

The newly constructed City-Tunnel Leipzig, Germany consists of two tubes manufactured by a hydraulic shield with segmental lining. On its way below the historical city centre of Leipzig it crosses a housing complex composed by a building constructed in 1908 and a modern structure of 1995 both separated by a reinforced bored pile wall, which intersects with the tunnel clearing. The lower edge of the bored pile wall needs to be removed prior to tunnelling. For this purpose an auxiliary tunnel 3,5 m in diameter is constructed directly underneath the two buildings starting from a vertical shaft. The excavation of this 60 m long tunnel is performed by mining technique supported by a ground freezing body of approximately 5,000 m<sup>3</sup>. Due to geometrical necessities the tunnel consists of three parts including two caverns of approximately 7 m in diameter to allow for a sudden change of direction. Ground freezing is performed by liquid nitrogen flowing through a total of 120 pipes, installed in 35 m long horizontal boreholes below ground water table. The design of the ground freezing measures includes numerical analysis of the thermal and mechanical behaviour of the soil. A total of 180 temperature gauges are installed in the ground in order to allow proper control of the ice propagation. Control parameters were determined for all temperature gauges by prior numerical analysis and are constantly adapted to real soil-ice behaviour. The structural analysis takes account of the highly non-linear performance of frozen ground and enables the prediction of deformations both of the tunnel and the adjacent buildings. Due to previous damage the allowable deformations of the historical structures are as low as 10 mm accompanied by a relative distortion of 1/2000. Supervision of displacements is realized by highly sensitive barometric levelling.

### RÉSUMÉ

Le nouveau tunnel jumelé de chemin de fer de Leipzig en Allemagne a été creusé par la méthode dite de cheminement horizontal au bouclier. Le front de taille était stabilisé par un liquide et la maçonnerie de la voute par des anneaux de revêtement. Sous le centre historique de Leipzig, le tunnel passe entre deux bâtiments voisins. Le premier datant de 1908 est très fragile et l'autre de 1995 est constitué d'une structure moderne. Les deux bâtiments sont séparés par un écran étanche en pieux forés. Le tunnel traverse la base de cet écran. Il a fallu démolir la base de cet écran pour libérer l'accès pour la foreuse. A cette fin un puits d'une profondeur de 15 m a été creusé d'où a été construit une galerie horizontale d'un diamètre de 3,5 m et d'une longueur de 60m, pour permettre l'accès à la base de l'écran sous les deux bâtiments. La galerie a été forée après avoir gelé environ 5000 m<sup>3</sup> de sous-sol. En raison des restrictions géométriques la galerie est constituée de trois sections différentes et de deux cavernes d'un diamètre de 7 m, qui permettent de changer la direction de l'axe de la galerie. La stabilisation du sous-sol a été effectuée par congélation du sol au moyen d'azote liquide. L'azote liquide a circulé dans 120 tubes d'une longueur de 35 m installés à l'aide de forages horizontaux sous la nappe phréatique. Le design de l'installation réfrigérante a été calculé tenant compte du comportement mécanique et thermique du sol. Au total 180 points de mesure de température ont été installés pour contrôler le développement de la zone de gel dans le sous sol. Au cours des travaux les températures mesurées sont comparées avec les températures calculées pour chacun des points de mesure. Les analyses structurales tiennent compte du comportement non-linéaire des déformations du sol gelé. Les analyses permettent de prédire tout tassement des bâtiments et toute déformation du tunnel. En raison des dégradations du vieux bâtiment les tassements absolus du sol ont été limités à 10 mm et l'inclinaison à 1/2000. Le contrôle des tassements a été effectué au moyen de points de mesure altimétriques de haute résolution (méthode barométrique).

Keywords : ground freezing, nitrogen, tunnelling, horizontal drilling, historical structures

### 1 CITY-TUNNEL LEIPZIG - GERMANY

The "City-Tunnel Leipzig" currently under construction connects the two terminal stations „Leipziger Hauptbahnhof" and "Bayerischer Bahnhof" by means of two tubes via two additional stations "Wilhelm-Leuschner-Platz" and "Markt" which are constructed in open excavation pits. The interconnecting tunnel tubes are erected using a tunnel boring machine with a slurry shield.

The total length amounts to 2,940 m. The outer diameter of the tubes is 9 m and the clearance between the tunnels measures between 5 m and 10 m. The distance between the tunnel and the ground surface ranges between 7.5 m to 15.6 m, whilst the minimum distance between the tunnel and the foundation of

adjacent buildings is as low as 2 m. Figure 1 depicts the tunnel boring machine used in Leipzig.

The tunnel is driven through glacial, non cohesive, quaternary soil as well as non cohesive and cohesive tertiary sediments. Medium and coarse gravels are encountered below loose fill and a boulder clay package of up to 10 m thickness. In deeper portions of the tunnel tertiary medium to fine sand as well as soft to stiff silt is met. The maximum ground water level reaches approx. 18 m over tunnel floor. In the course of the tunnel natural and artificial obstacles had to be expected. Blocks of sandstone with strengths of up to 250 MN/m<sup>2</sup> as well as coal layers and trunks of old trees may be encountered. Other manmade obstacles including old water wells must be expected since Leipzig is a settlement area since medieval times.



Figure 1 Tunnel Boring Machine.

## 2 DEMOLITION OF OBSTACLES PRIOR TO SHIELD TUNNEL DRIVING

Modern tunnel boring machines are able to drive through almost all kinds of obstacle on account of their high-quality tools and high torque. Nevertheless deliberate driving through such obstacles is avoided, because it is connected with incalculable risks. These reach from decreasing tunnelling advance as well as wear and tear leading to blockage of the tools up to a possible large amount of volume loss in the ground or a complete destabilization of the tunnel face. Beside economic losses results of these risks can be threats to buildings and human life.

For security reasons it was therefore decided to remove a known obstacle despite of most difficult conditions. The obstacle consists of the bottom part of a reinforced bored pile wall crossing the western tunnel in a flat angle underneath a building complex called "Hallisches Tor". It encloses the building „Hotel Marriott“, which was established in the middle of the 1990s, and the listed historical building „Goldene Kugel“. The distances between the tunnel roof and the foundation amounts to 2.5 m for the Marriott hotel and 7.2 m for the "Goldene Kugel". Shoring of the former excavation pit for the Marriott consists of an anchored overlapping bored pile wall which now reaches partially into the cross section of the western tunnel tube (Figure 2 and Figure 3). It must therefore be partially removed beforehand.

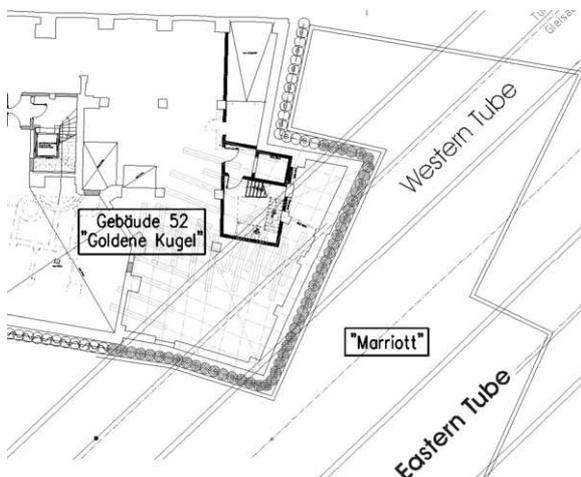


Figure 2 Plan view of the situation (red: bored pile wall to be demolished).

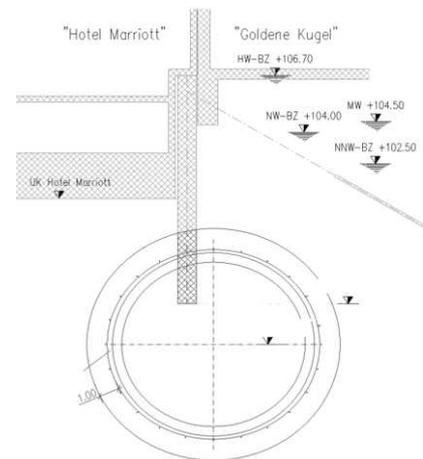


Figure 3 Cross section of the western tube with the bored pile wall to be demolished.

The remaining excavation pit consists of sheet pile walls which were removed in the area of the tunnel route completely. Removal of the lower segment of the bored pile wall below both buildings is accomplished from an auxiliary tunnel which is constructed using a shotcrete lining protected by a ring of frozen ground around it. This tunnel incorporates an abrupt change of direction of almost 90°. By this way the eastern tunnel tube can be built independently from the measures to remove the bored pile wall.

Drilling of the horizontal bore holes for the freeze pipe installation starts from a shaft in the north of the wall and is carried out in stages. Each stage ends in an enlarged section from where drilling for the next stage is performed. Following a design optimization process a 3-stage ground freezing procedure is implemented with the segments 1a, 1b and 2 (Figure 4).

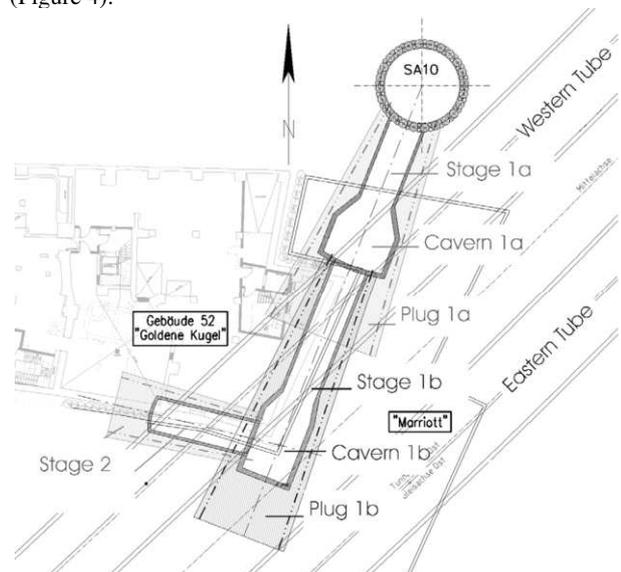


Figure 4 Plan view of the three stage ground freezing measure.

## 3 GEOMETRICAL CONSIDERATIONS

The sealing end of each segment is generated by an ice plug built by centrally arranged freezing pipes. Since these central pipes cannot be operated during tunneling the freezing body needs to be designed in such a way as to maintain its sealing function against almost 10 m water pressure during the preservation phase only by operating the outer freezing pipes. The necessary plug length was determined by thermal calculations with 75% of the diameter of the outer ring of the freezing pipes.

As cooling media liquid nitrogen was chosen due to its ability to freeze the ground very fast. An additional advantage over the alternative of cooling the ground with circulating brine was seen in the fact that a possible leakage occurring during the excavation of the tunnel itself in the direct vicinity of the freezing pipe does not lead to an outflow of brine resulting in a potential meltdown of the freezing body.

The position of the freezing pipes is optimized based on extensive numerical analysis of the heat transfer in order to speed up freezing time and to minimise the nitrogen consumption. The thickness of the freezing body is designed to satisfy structural demands and amounts to 1.50 m. The auxiliary tunnel has a diameter of 3.50 m, which widens to 7.60 m in the cavern. The bore holes for the installation of the freezing pipes form a cone to account for this geometrical conditions (Figure 5). About 120 horizontal bore holes below ground water table with length of up to 35 m were drilled and measured during execution in order to correct the position of the subsequent bore holes if necessary.

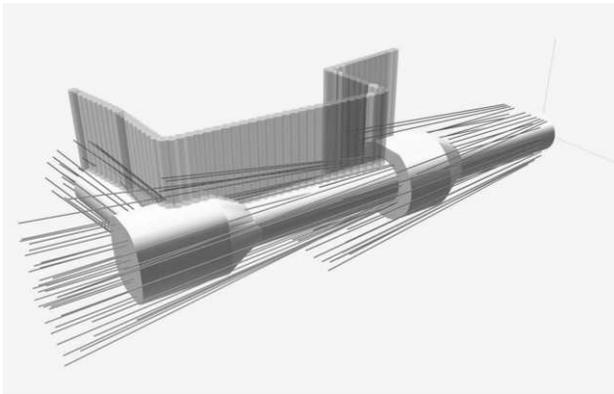


Figure 5 Conical shaped freezing pipes (from Elsner et al. 2008).

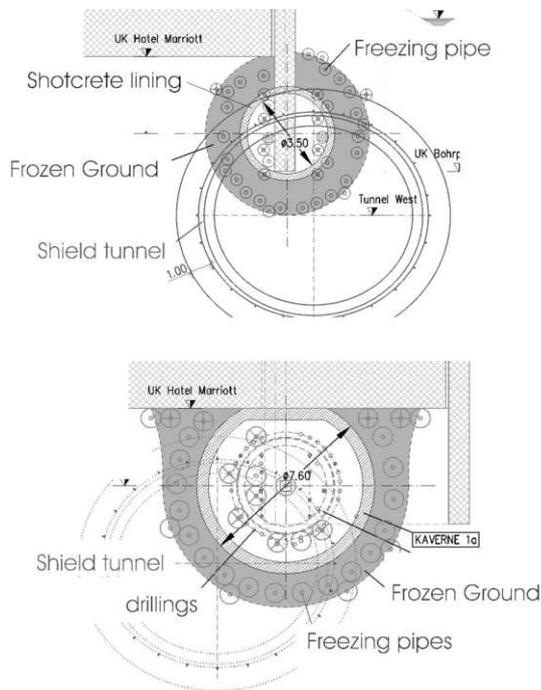


Figure 6 Cross section through tunnel stage 1a and cavern 1a respectively.

From Figure 6 it is evident that the caverns, which are necessary for the drilling of the bore holes of the subsequent stages 1b and 2, are directly situated below the concrete slab forming the foundation of the Marriott hotel. A close connection of the frozen ground with structural concrete from the bored pile wall and foundation slabs becomes therefore necessary whereby

the joint between them needs to be able to transfer normal and shear forces with a sufficient factor of safety, which has to be verified in the analysis.

4 STRUCTURAL ANALYSIS

The behaviour of water-saturated, frozen soil is characterized by the mechanical behaviour of both the granular structure and the ice filled voids. Frozen ground shows high initial elasticity and high short-term strength. But ice undergoes considerable creep deformation. The mechanical behaviour of frozen grounds is therefore marked by the same effects. Creep deformation can be described by a potential law (see e.g. Jagow-Klaff & Jessberger 2001) such as:

$$\epsilon_{\text{creep}} = A \cdot \sigma^B \cdot t^C \tag{1}$$

with:

- creep strain  $\epsilon_{\text{creep}}$
- stress level  $\sigma$
- time  $t$
- creep parameters A,B,C

Generally modelling of the actual creep behaviour is renounced in the calculations and instead a time and temperature dependent elasticity modulus  $E_g(t)$  as well as time and temperature dependent strength parameters  $\phi_g$  and  $c_g(t)$  are defined (Table 1).

$$E_g(t) = \left( \epsilon^{(1-B)} / A \cdot t^C \right)^{1/B} \tag{2}$$

$$c_g(t) = \left( \frac{1 - \sin \phi_g}{\cos \phi_g} \right) \cdot \frac{1}{4} \cdot \left( \frac{\epsilon_f}{A \cdot t^C} \right)^{1/B} \tag{3}$$

The structural analysis is performed with a continuum model at plane strain on the basis of the finite element method using PLAXIS V8.2. Figure 7 shows the deformations resulting from the excavation of cavern 1b and the degree of utilization of the shear stresses within the frozen ground. Accordingly the design of the of the frozen ground body leads to a necessary thickness of 1.5 m between the  $-2^\circ\text{C}$  isotherms with an average frost body temperature of  $-20^\circ\text{C}$ .

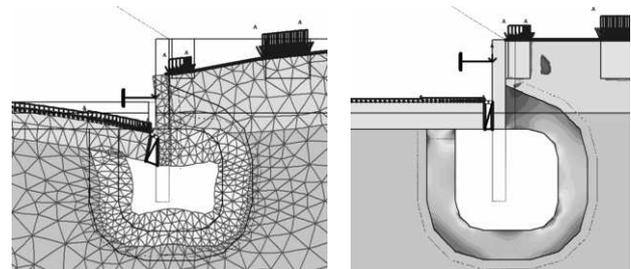


Figure 7 Deformations and utilization level of shear stresses.

Table 1 Decisive structural parameters of frozen ground.

Frozen sand, T=-20°C	t = 3 days	t = 42 days	t = 365 days
E-Modulus $E_g(t)$ [kPa]	394,000	351,000	318,000
Poissons ratio $\nu$ [-]	0.3	0.3	0.3
Cohesion $c_g(t)$ [kPa]	1,220	1,060	940
Friction angle $\phi_g$ [°]	30.6	30.6	30.6
allowable $\sigma_{\text{tension}}(t)$ [kPa]	860	740	660

## 5 THERMAL ANALYSIS

Liquid nitrogen is stored in pressure-vessels on site and flows through the freezing pipes in a central leader pipe to the end, where pressure reduction to atmospheric pressure takes place. At atmospheric pressure the nitrogen evaporates creating a temperature of  $-196^{\circ}\text{C}$ . Gaseous nitrogen flows back within the annulus formed by the freezing pipe and the leader pipe to the mouth of the bore. There it passes a temperature-steered valve at temperatures between  $-70^{\circ}\text{C}$  and  $-120^{\circ}\text{C}$ . After additional warming it is then released into the atmosphere. The necessary energy for warming up the nitrogen is taken from the ground which leads to its cooling. The theoretical heat quantity  $Q$  which is extracted from the ground by 1 kg of liquid nitrogen and its warming by e.g.  $\Delta T=100^{\circ}\text{C}$  taking into account the specific heat of nitrogen ( $c_p=1.04 \text{ J}/(\text{g K})$ ) and the evaporation enthalpy ( $H_{v,N_2}=199 \text{ J/g}$ ) results from the formula:

$$Q = c_p \cdot \Delta T + H_v = 303 \text{ kJ} \quad (4)$$

Thermal analysis is made using the finite element program TEMP/W. For the calculations the drilling accuracy of 1.5% is considered by shifting the decisive freezing pipes in each case unfavorably within the cross section considered. Then the necessary freezing period is determined in such a way that the geometrical conditions set in the structural analysis are matched by the frost body thickness at average frost body temperature.

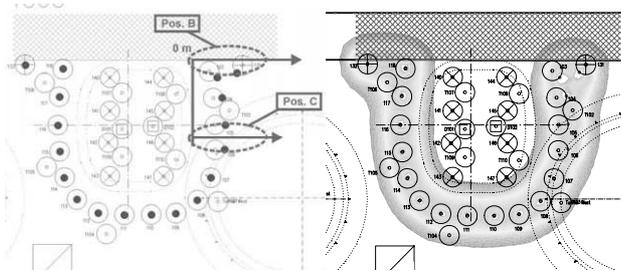


Figure 8 Position of the freezing pipes and temperature distribution in the ground.

After surveying of all bore holes the temperature field calculations are adapted accordingly for the later control of the freezing regime.

## 6 CONTROL AND MONITORING

Besides the freezing pipes additional measuring pipes for the installation of approx. 180 temperature gauges are drilled. They sum up to 24 measuring sections for the supervision of the actual frost body development. The results of the measurement in comparison to the design values from the thermal analysis are used to control the frost propagation by means of setting the threshold values of the valves at each freezing pipe.

The control of the frost propagation is achieved by continuous observation and evaluation of the on-line measured temperatures and the water pressure in the central drainage pipes. Within the scope of the control, in particular the definition of the exhaust gas temperature to be set individually for each freezing pipe, it was found that they follow more or less exactly the designed cooling paths (Figure 9).

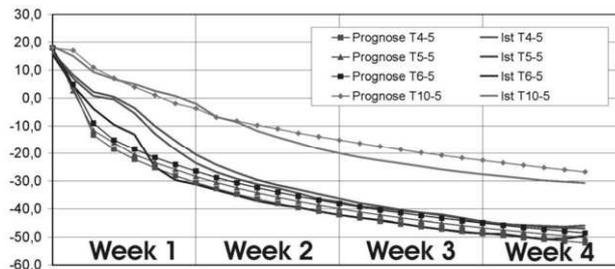


Figure 9 Predicted and measured ground temperatures during freezing.

## 7 CONCLUSIONS

The removal of a reinforced bored pile wall prior to construction of the western tube of the City-Tunnel Leipzig could be achieved by means of a multistage ground freezing with liquid nitrogen while building the eastern tube at the same time (Figure 10). The lengths of the horizontal drillings were limited to a maximum of 32 m. The installation of a fully load-bearing tunnel lining allows the deactivation of the previous freezing stage which reduced the nitrogen consumption considerably. The use of glass fibre reinforced concrete and the subsequent filling of the auxiliary tunnel with binder material allows unhampered tunnel driving underneath the historical building complex without harmful deformations of the structures.



Figure 10 Tunnel drift protected by ground freezing.

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