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SHOTCRETE IN TUNNELLING IN FROZEN GROUND

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ABSTRACT

The use of shotcrete in tunnelling in frozen ground will be presented for an actual project. There are specific demands on the mixture of shotcrete and the construction because of the frozen ground. The basics for the design especially the safety concept and the experiences made during construction will be presented.

INTRODUCTION

In Berlin the Line U5 has been extended by a station to the east of the Pariser Platz in order to accommodate a shuttle service between the Central Station and the Pariser Platz/Unter den Linden. This building is located right alongside the North-South Urban Railway that was built back in the 1930s and is settlement-prone. For the first time in Berlin, tunnelling is being undertaken mainly underground protected by artificial subsurface freezing.

In order to minimise the risks of execution and to restrict the subsurface deformations resulting from the applied construction methods the dimensioning concept foresees the approx. 180 m² cross-section being driven in sections protected by a dense frozen zone providing temporary support. In this way, both the final form of the station cross-section as well as the choice of construction method is determined.

There are specific demands on the mixture of shotcrete and the construction because of the frozen ground. The basics for the design and the experiences made during construction will be presented and compared with experiences of other suburban projects.

PROJECT

Station building „Brandenburger Tor"

In the centre of Berlin the metro line station "Brandenburger Tor" is under construction. This station will serve as a temporary terminus for the metro shuttle connecting the Brandenburger Tor to the new central station Lehrter Bahnhof and the Reichstag. The shuttle service is scheduled to be put into operation in 2009. For details of that project see (1-5).

On behalf of the Berliner Verkehrsbetriebe BVG (Berlin public transit authority) the design and the tender documents for the station were prepared by the joint venture "Ingenieurgemeinschaft U5" (ZERNA INGENIEURE GmbH, PSP Beratende Ingenieure, CDM Consult GmbH und DMT Bauconsulting).

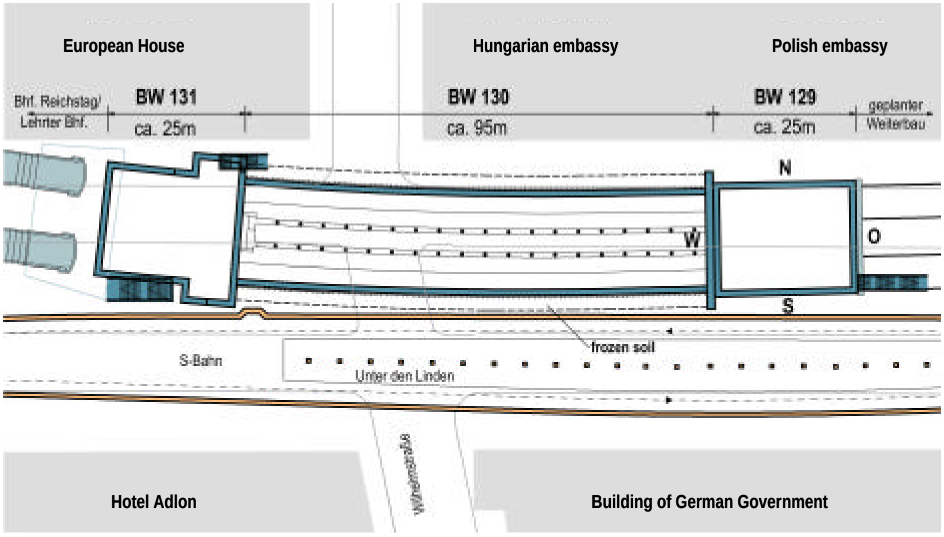

Fig. 1: Plan view of metro station "Brandenburger Tor"

The construction of the station is divided into three parts: Two entrance buildings at the eastern and western ends of the station and a platform building with a length of approx. 90 m and a cross section of approx. 180 m^2 between them. The plan view is shown in Fig. 1.

Construction methods

The construction site is in front of the Brandenburger Tor. Due to its exposed location at the tourist site "Brandenburger Tor" and directly in front of the hotel Adlon adverse effects at the surface had to be reduced to a minimum. Therefore the subterraneous platform building will be driven by conventional mined excavation into a load bearing body of frozen soil.

As a first step, two excavation pits are constructed using the cut-and-cover method. They consist of reinforced concrete diaphragm walls with multiple bracing and a jet grouted base. In the second step the platform building were constructed with conventional mining in frozen ground.

The construction phases were based on a high safety concept to secure the adjacent buildings and minimise the influences on the inner city surface.

- In the first phase (stepwise excavation with calotte, bench and floor) the frozen body was designed to the loads of earth- and waterpressure.
- In the second phase the shotcrete layer was designed to protect against earth- and waterpressure while the frozen body is only designed watertight. The load-bearing capacity of the frozen ground was neglected.
- In third phase the tunnel construction of the platform building is designed as watertight and with a load bearing capacity against earth- and water pressure.

The different construction phases are shown in Fig. 2.

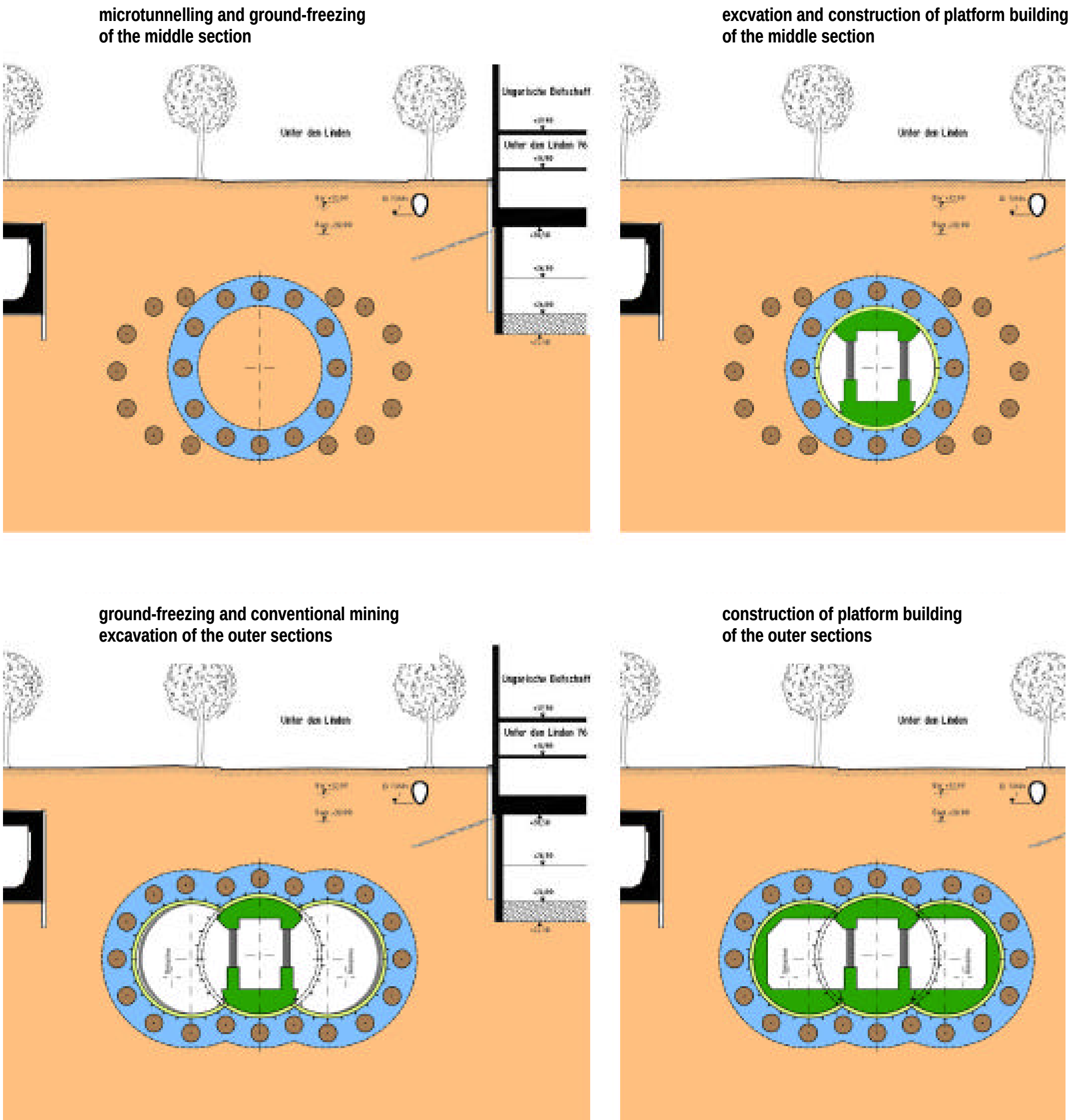

Fig. 2: Conventional mining in frozen ground

The high demands on the frozen ground led to some geometrical conditions and various construction phases for the platform building. The cross section was divided into three sections, the middle section and two sidesections. The frozen ground around the middle section looks like an horizontal tube between the diaphragm walls of the two pits.

Ground conditions and hydrology

The boulevard "Unter den Linden" and the “Pariser Platz” in the inner city of Berlin are located in the so-called Urstromtal, a stream bed formed by glacial runoffs during the ice age. Here, below a layer of fill and debris approximately 3.3 m thick, the ground relevant for construction consists of glacially deposited soils. The upper soil strata mostly consist of fine to medium sands with some gravel (alluvial sands and so-called “Talsand”) in a medium dense state. Below this in a depth of approximately 15 m below the surface there lies the ground moraine of the Saale glaciation in form of either a heavily over consolidated glacial till (“boulder marl”) or - as a result of erosion - a layer of boulders in the former base of the moraine. Even where the marl is completely eroded this characteristic layer of boulders remains. Its base is located at depths between 16 m and 26 m below street level. Underlying the marl there are dense glaciofluviatile sands, gravels and till. In a depth of about 42 m, marls or silts and clays containing xylite were encountered. Closer to the surface lenses of peat and soft organic clays or trenches filled with sapropel can be found.

The sand and gravel strata form one coherent aquifer with a shallow gradient and slow flow velocity. The groundwater table is situated approximately 3.2 m below the surface with a range between high and low water of about 1 m.

The new metro line mainly runs through poorly graded non-cohesive soils. To simulate the ground in the deformation analysis the following soil parameters (Tab. 1) are used as given in the site report (BBI, 1996):

Stratum	**?/?'** [kN/m³]	**f '** [°]	**E_S** [kN/m²]	**K_0** [-]	**?** [-]	**E** [kN/m²]
Fill type II	17.0 / 10.0	33	50000	0.5	0.33	33750
Alluvial sands	17.7 / 10.45	34	75000	0.45	0.31	54100
Sands	17.7 / 10.45	34	120000	0.425	0.30	89150
Sands, overconsolidated	17.8 / 10.7	34	250000	0.65	0.39	125300
Sands and till	17.8 / 10.7	36	350000	0.65	0.39	150000

Cohesion: c' = 0 kN/m²

Table 1: Soil parameters, from Baugrundgutachten (1996)

We assume the strata below the Saale marl and the deeper parts of the "Talsand" to be over consolidated due to the weight of the glacier. With regard to the soil parameters assigned to the strata this is taken into account by appropriately higher K_0- and μ-values compared to the upper layers and by high stiffness moduli.

FROZEN GROUND

Design and static concept

For safety of the construction site high demands on design, construction and controlling of frozen grounds were necessary.

The frozen ground was designed as a watertight body with a temporarily load bearing capacity for every part of the cross section. This load bearing capacity is necessary when conventional mining had started up to the moment the stepwise excavation had finished and the shotcrete layer had reached his bearing capacity.

The material parameters of these frozen body are not determined like the parameters of for example concrete or steel.

For this some finite element calculations were made in the design phase to describe the interaction between frozen and unfrozen ground in the whole construction steps of the conventional mining. Due to this calculations a thickness of the frozen body of approx 2.5 m meters were necessary to guarantee the temporarily load bearing capacity.

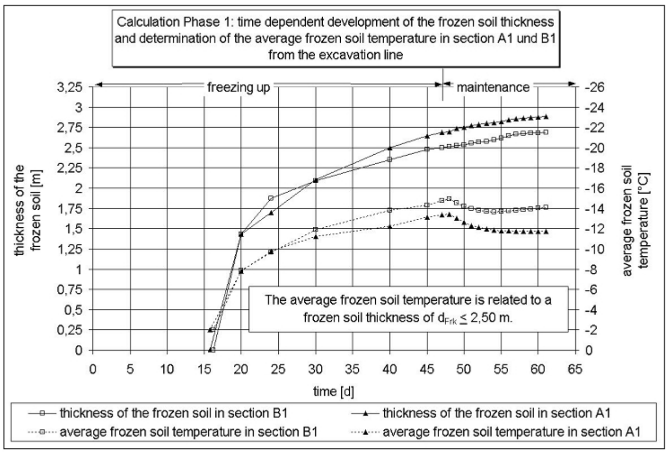

Fig. 3: Numerical calculation of ground freezing

With thermal calculations the time dependent growth of the frozen body was described (Fig. 3). One of the results of these thermal calculations is the determination of an average temperature of the frozen body. This average temperature is necessary to describe the material parameters of the frozen body for the FE-calculations to determine the load bearing capacity of the frozen body. These parameters are roughly temperature and time dependent.

With the results of the thermal calculations the economic and safety design of freezing lines is possible.

As shown in Fig. 2 30 microtunnels are bored to take the freezing lines at the exact place. The results of measuring during micro tunnelling took place in the design of frozen lines. Therefore the construction phase impacts on the design phase and vice versa.

According to the static calculations the deformations of the adjacent buildings and on the surface were predicted. There were only a few influences an the adjacent buildings.

Measuring system

Local effects in the frozen ground could have a great impact on the safety of conventional mining (for example the beginning of thermal erosion). Therefore a complex measuring system was installed which gave results to:

- temperatures in the frozen body and around these areas,
- water pressure inside the frozen body during growth of it to verify the density completeness

and

- volume of water during lowing water level inside the frozen body.

A cross-section with the installed measuring system for temperatures is shown in Fig. 4.

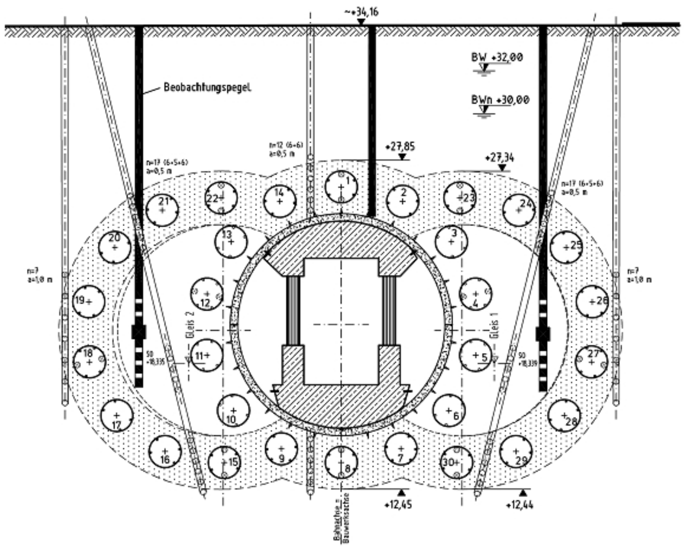

Fig. 4: Cross-section for measurements of temperatures v

Additional to the measuring systems in the cross-sections another measuring system were installed along the 30 microtunnels to check the ground temperatures and to detect local errors in the frozen body.

SHOTCRETE LAYER

Design

The demands on the shotcrete layer in a tunnelling project in frozen soft ground are different to those of shotcrete layers for rocktunnelling.

While the frozen ground is designed with a temporarily load bearing capacity to avoid deformations of the ground due to the excavation it is not necessary to guarantee a high initial strength of the shotcrete. The frozen ground had such a high strength.

Consider that the shotcrete lining is sprayed against the frozen ground which could have an influence on the initial setting of the shotcrete; in the design concept 5 cm of the shotcrete lining were neglected. With regard to this and the static requirements of a load bearing capacity the shotcrete lining had a total thickness of 35 cm.

The temperatures during the shotcretesetting could raise the temperature of the frozen ground to the dewpoint in a small layer. This could led to a decrease of the bond strength of frozen ground and shotcrete. Consider this effect it’s necessary for the initial strength that the shotcrete layer could take the dead load rapidly.

Considering these described requirements the following mixture for a C25/30 shotcrete was used: CEM I (400 kg/m^3) with 7% accelerator.

Static concept

The static concept was based on the Safety Concept described ahead. For the estimation of the needed load bearing capacity of shotcrete layer the load bearing capacity of the frozen ground was neglected.

This assumption based on the not well known material time behaviour of frozen ground and led to an shotcrete layer with an high degree of reinforcement.

Probabilistic methods

The high degree of reinforcement was discussed in the design phase intensively.

Nowadays, national or international standards are generally used to design constructions in the field of civil engineering. Besides the statistic distribution of material data or insufficiency during the building, these standards consider many other effects, which can influence the safety level of a structure. Therefore, the planning engineer has got a tool firstly to work with and secondly to control the risks associated with his design.

In the tunnel project in Berlin problems occurred that will prevent us from using standards. Therefore, concerning the results of soil exploration and other investigations, special proofs, analyses and models must be developed for every single problem. They are based on parameters and assumptions that have to be chosen carefully by expert judgement. In this context, statistics help to quantify risks and to avoid their underestimation. On the other hand, the less knowledge there is, the higher the safety level an engineer takes into account before giving a statement regarding input data or modelling will naturally be. As a consequence the employer may carry higher costs because of overdimensioning when dealing with sophisticated problems.

In both cases, as described in Heimer et al (6) a probabilistic uncertainty analysis based on a large number of realizations with varying input data helps us to avoid static or economic disadvantages in the design. It allows a realistic estimation of the actual risks and a rating of the influence of single input parameters, boundary conditions, modelling aspects and other assumptions on the results of dimensioning. Data relevant to safety can be identified as well as details of the design that don’t increase the safety level significantly. However, these comments are not only valid for risks concerning to the statics. For example, they may also be important for questions associated with construction time or foundation soil, which may be relevant in a fair contract.

The effects of the probabilistic methods described in Heimer et al (6) were illustrated for the dimensioning of shotcrete layer of the middle section. As shown in detail in Heimer et al (6) and Klönne (7) the use of the methods leads to the possibility to reduce the degree of reinforcement of the shotcrete shell. This helps to speed up the construction of shotcrete lining

EXPERIENCES ON CONSTRUCTION SITE

Frozen ground

The growth of the middle section of the frozen body needs time of about 3.5 months.

Fig. 5 shows the time dependent development of temperature in accordance to the distance of the freezing line. This graphic shows a nearly linearly decrease of temperature.

After the frozen body had been closed the conventional mining of middle section started in may 2007.

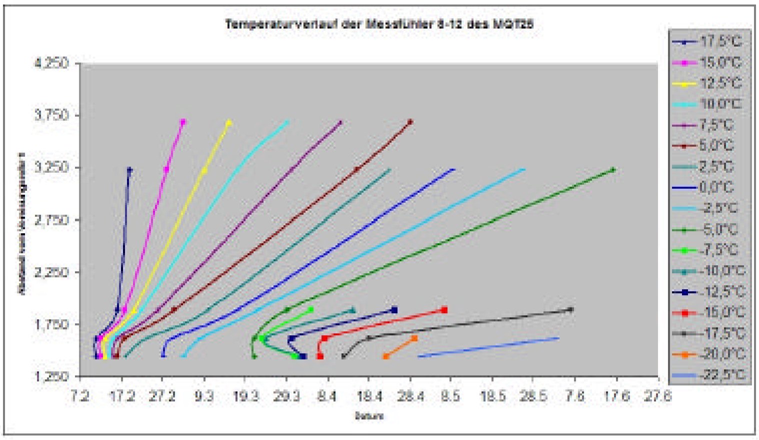

Fig. 5: Growth of frozen ground

Due to the tunnelworks the temperature of the frozen body increased rapidly. They rose over the allowed temperature of - 3°C in the layer between frozen zone and shotcrete layer. This problem could be handled with a layer of PE on the shotcrete layer.

The complete tunnelling with conventional mining and construction of tunnel structure was finished in summer 2008 and the frozen aggregate were stopped.

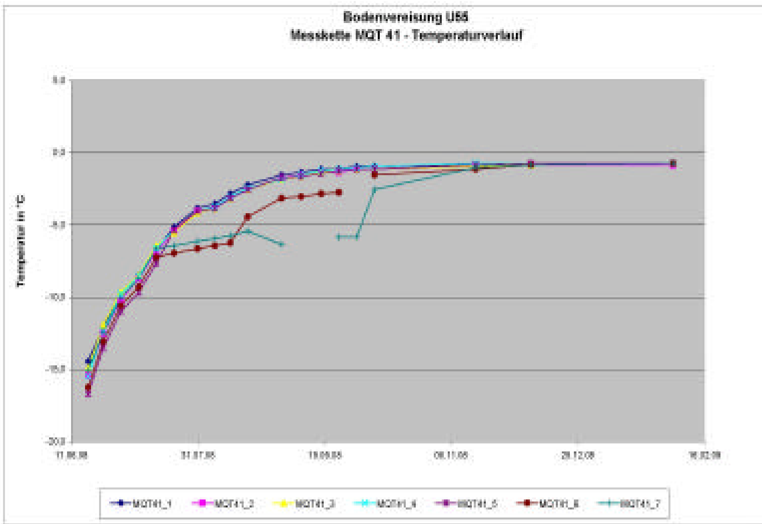

Fig. 6: Ground temperatures after finishing ground freezing

The measurement of the ground temperatures continues until the temperature increases to the normal level. As Fig. 6 shows eight month later the temperatures of the ground are nearly 0°C.

Excavation and shotcrete lining

The excavation was made partly with length of round of about 1.5 m. The calotte and bench excavation ran forward. Every round an arch was set. These arches didn't have a static function because of the high stiffness of the frozen ground.

As predicted with the thermal calculations the frozen area growth into the excavation part as seen in Fig. 7. Due to the frozen areas the excavation was made using mills.

Fig. 7: Frozen ground during tunnelling

The shotcrete with a total thickness of 35 cm was sprayed into two layers. The equipment like the silo for dry shotcrete was placed on construction site. Shotcrete, water and accelerator were mixed in a stationary equipment and the wet shotcrete was pumped to the heading.

The characteristics of the shotcrete were tested on construction site. For this a testing field was prepared with freezing lines. The initial strength according to 6, 9, 12 hours and the development of temperature during shotcretesetting were checked.

Cores out of the shotcrete shell were taken to check the strength of the shotcrete. The results of these tests verify the assumption that 5 cm close to the frozen ground hadn't considered for the load bearing capacity of the shell.

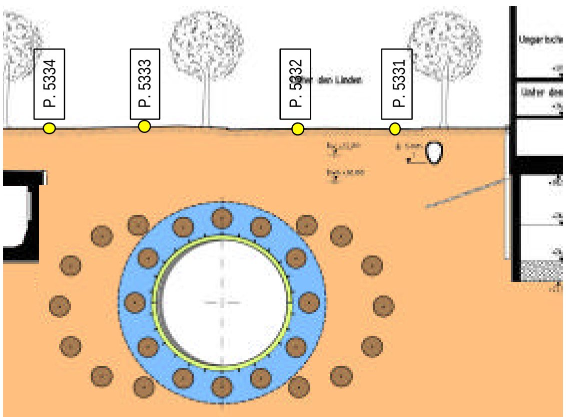

Fig. 8: Cross-section with measuring points on surface

The deformations on the surface measured during all phases of tunnelling were measured. A typical cross-section is shown in Fig. 8.

The measurements of these points on the surface will continued until the temperatures of the ground raise to the stationary ones. But the results of the last 8 months showed that there are no significant changes on the surface.

The deformations are shown in Fig 9.

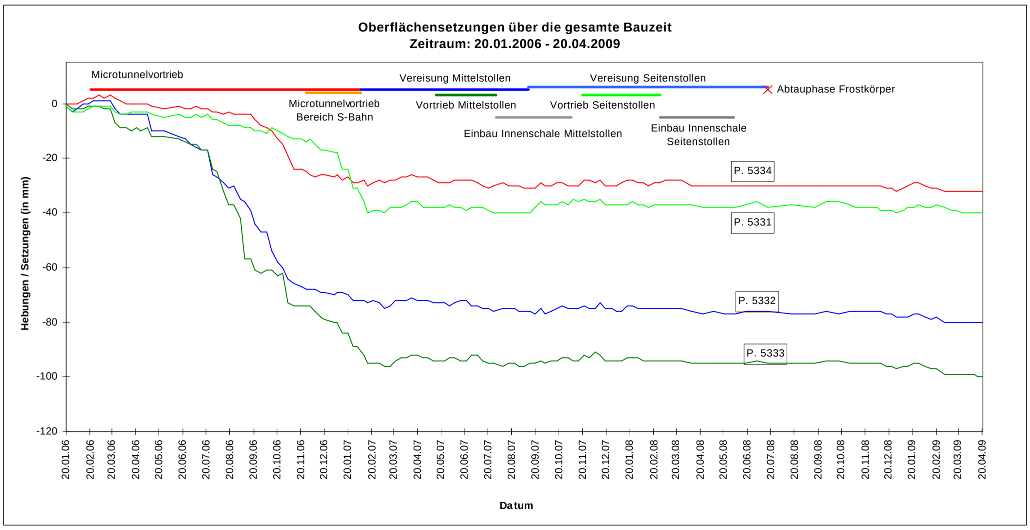

Fig. 9: Total deformation on the surface

Ignoring the deformations during micro tunnelling, there are only 2 to 3 mm settlements on the surface and no significant settlements depending on the increase and decrease of frozen body and conventional mining. This verified the assumptions of the safety concept that the frozen body is dimensioned against earth- und water pressure and that in the geology found in Berlin no settlements due to the frozen process occurs.

CONCLUSION

In Berlin the metro line station "Brandenburger Tor" is under construction. Starting in 2009 it will serve as a temporary terminus for the metro shuttle connecting the “Brandenburger Tor” to the new central station Lehrter Bahnhof and the Reichstag. For the first time a platform building with a cross section of nearly 180 m^2 was built by conventional mining in frozen ground.

Due to a safety concept on a high level the excavation in the “stable” soft ground led to no significant deformations on the surface and no influences on the adjacent buildings. The requirements to the shotcrete differs to those in hard rock. The used shotcrete mixtures, the static concept and technologies had proofed oneself.

According to the experiences made by construction it will be interested in the future to adapt the safety concept in an economical manner by using probabilistic methods. This is illustrated for the dimensioning of the shotcrete layer. It could be possible to reduce the level of reinforcement.

REFERENCES

(1) Internet references: www.bvg.de, en.wikipedia.org/wiki/U55_(Berlin)

(2) Haß, H., Seegers, J.: Planung der künstlichen Bodenvereisung für die Erstellung unterirdischer Bauwerke beim U-Bahnbau der Linie U5 „Unter den Linden“ in Berlin. In: Vorträge der Baugrundtagung (2000), Hannover, S. 91

(3) Dr. Speier, L., Dr. Görtz, S., Rath, Th.: Einsatz von GFK-Bewehrung bei der Ausführung des U-Bahnhofs Brandenburger Tor. In: Bautechnik 82 (2005) Heft 9, S. 614

(4) Liebich, C., Dr. Speier, L., Seegers, J.: U-Bahnhof Brandenburger Tor-Bergmännische Bauweise im Schutz einer Vereisung. In: Vorträge der Baugrundtagung (2006), Bremen, S. 91

(5) Liebich, C., Dr. Speier, L., Seegers, J.: U-Bahnhof Brandenburger Tor: Erfahrungen und Probleme der bergmännischen Bauweise im Schutz einer Vereisung. In Forschung + Praxis 42 (2007), S. 185-188

(6) Dr. Heimer, S., Dr. Spohr, I., Klönne, H.: On the application of probabilistics in economic dimensioning of urban tunnelling projects. In Tagungsbeitrag zu Probabilistics in Geotechnics (2002), Graz

(7) Klönne, H., Dr. Spohr, I., Dr. Heimer, S.: Numerische Erfassung des zeitabhängigen Tragverhaltens großflächiger Baugrundvereisungen bei der berg-männischen Herstellung von Tunnelbauwerken in wasserführenden Lockerböden. In Tagungsbeiträge zur 3. Österreichischen Geotechniktagung (2001), ÖIAV, Wien

KEY WORDS

Shotcrete, safety concept, probabilistic methods, ground freezing