Closing the gap of the U5 underground line in Berlin

Special tunnel and foundation engineering challenges due to geotechnical constraints

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The existing U5 underground line in Berlin ends in Berlin-Mitte at the underground station Alexanderplatz. Planning has been completed and work is currently in progress on an approximately 2.2 km long section that closes the gap in the underground line between the existing tunnel structures at Berlin's Rotes Rathaus (Berlin City Hall) and the station Brandenburger Tor. Construction work commenced in the spring of 2012.

Two parallel tunnel tubes are being built using the shield driving method, each tunnel tube measuring approximately 1.6 km in length. Passing underneath the banks of the river Spree, accommodating for the new construction of the Berliner Schloss (Berlin castle) and the connection to the existing Brandenburger Tor station all present special challenges to the planning and implementation of the shield drive.

The plan is to build the missing link of the U5 underground line between the stops Alexanderplatz and Brandenburger Tor. The present U5 line in Berlin ends at the station Alexanderplatz. The planned new line will connect the two tunnel structures at Berlin's Rotes Rathaus (Berlin city hall) and the Brandenburger Tor station. In the course of construction work on transport facilities in the city centre the tunnel section (U55 underground line) from the Hauptbahnhof (main station) to the Brandenburger Tor has already been completed. Through the connection of the U55 with the planned new U5, Berlin-Mitte will be connected to the Hauptbahnhof.

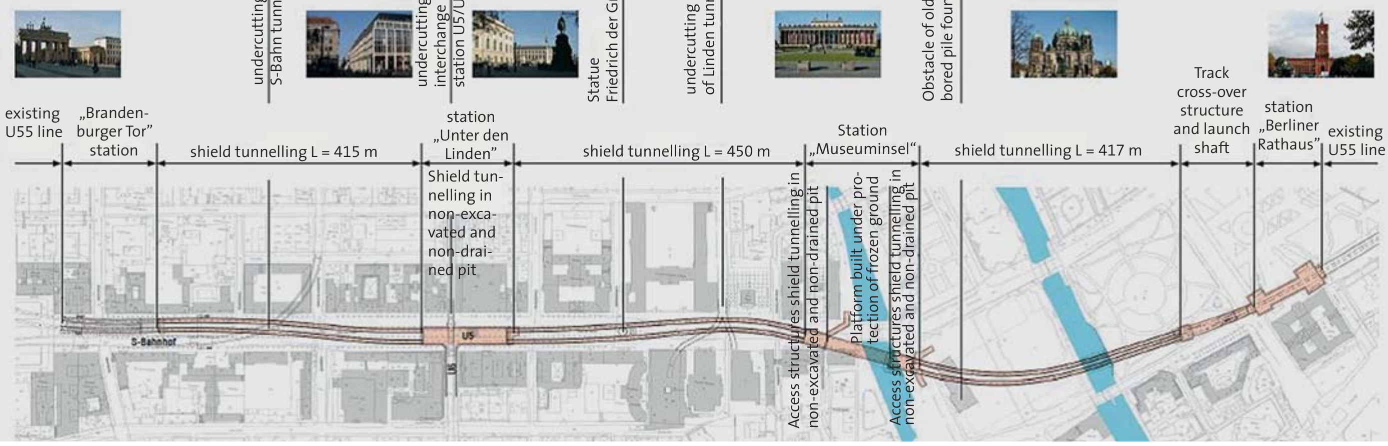
The U5 project in Berlin includes the new construction of three underground stations and an interconnecting two-track tunnel to be built using the shield driving method. The project comprises two Lots. Lot 1 covers the track switching structure (GWA), the station Museumsinsel (MUI), the station Unter den Linden (UDL), the connection to the station Brandenburger Tor (BRT) as well as the tunnel systems that connect these stations. Lot 2 covers the new construction of the station Berliner Rathaus as well as the connection to the existing tunnel in the direction Alexanderplatz.

The alignment takes the new Underground line through tunnels from the new station Rotes Rathaus, that is yet to be built, under the river Spree, under the planned New Berliner Schloss and the Spree Canal along the road Unter den Linden to the station Brandenburger Tor. The length of the section closing the gap is approx. 2.2 km from the connection to the existing facilities to the east of the future station Rotes Rathaus, up to the connection at the existing station Brandenburger Tor (Fig. 1).

There are two parallel tunnel tubes planned, each measuring approx. 1.6 km in length. The tunnels will be excavated by a tunnel boring machine with slurry supported face, using the shield tunnelling method. In this project the tunnel driving under the banks of the river Spree and the Spree Canal, the provision for the construction of the future new Berliner Schloss and the connection to the existing station Brandenburger Tor have a particular impact on the planning, design and implementation of the shield tunnelling process.

Three new stations are to be built using the cut-and-cover method and the top-down method. The station Rotes Rathaus is being built using the top-down method in direct proximity to Berlin's Rotes Rathaus (city hall). The station includes the connection to the tunnel sidings of the existing U5 line already in operation. In the continuation of the station a track cross-over is planned that will be built using the cut-and-cover method and also using the top-down method in some areas. This is where the shield drive begins.

Fig. 1: Overview of alignment from the station Rotes Rathaus (right) to the station Brandenburger Tor (left)



The station Museumsinsel will be in the area of the Spree Canal. The plan is for the platform area of the station to be built from the two station shafts under the protection of ground freezing and using the mining construction method.

In the station Unter den Linden the existing U6 underground line and the new U5 line will cross. To build the crossing structure the existing tunnels have to be demolished underground and rebuilt to provide the interchange facilities.

Geology

The Berlin-Mitte area is dominated by a glacial valley running from east to west. It formed as part of the Warsaw-Berlin glacial valley at the end of the last ice age and consists of thick sand and gravel sediments serving as aquifers. At some points these sands are covered by sands interspersed with organic matter or peat and muds that are very thick in some places. Particularly in the area between the river Spree and the Spree Canal, layers above the sands consisting of sludge as well as sands interspersed with organic matter and silts can extend into the excavation cross-section of the shield tunnelling.

When building the stations, in the area of the station Museuminsel the foundation will have to extend into the marlstone layers beneath the sands. Investigations carried out indicate that large boulders and rocks are likely to be encountered during the construction of diaphragm walls and during the shield driving. The sandy soils are classified as highly abrasive due to their quartz content.

The water table lies approx. 3 m beneath the surface level on average. The thick valley and melt-water sediments form a coherent and abundant aquifer in the investigated area.

Shield tunnelling with slurry supported face

The tunnels are driven using a shield with slurry support at the face. The tunnel headings start in the launch shaft of the track cross-over structure and end in front of the station Brandenburger Tor.

The inside diameter of the tunnel tubes is 5.70 m. The tunnel tubes are lined with RC segmental linings. A block segmental ring measuring 35 cm in thickness is planned. The width of the ring is of a conical design and measures 1,500 mm on average (Fig. 2). The sealing of the segmental lining joints is in the form of a closed elastomer frame embedded in a groove. The seal is to be designed for a max. water pressure of 3 bar. There is a borehole pattern provided in the segmental linings for successive grouting of the annular gap.

The tunnel tubes are driven one after the other. It is planned to first drive the tube for track 1 and then the tube for track 2.

The shield tunnelling machine starts in the launch shaft in the area of the track cross-over structure (Fig. 3). To excavate the pit for the launch shaft and the track cross-over structure the diaphragm wall method is used. The pit wall to be cut through by the shield tunnelling machine has glass-fibre reinforcement in the area where the shield cuts through. For the launch process a redundant sealing system is planned comprising launching block with lip seals, inflatable emergency seal as well as a jet-grouted block in front of the diaphragm wall on the soil side.

Shield tunnelling takes place after construction of the pit enclosures for the station structures and before draining and excavation of the pits. Inside the pits the support pressure has to be reduced due to the smaller volume of soil present for the machine advance. For this reason, the available water pressure in the pits has to be adjusted to the required support pressure using the wells provided for the draining process.

Special shield tunnelling challenges

The shield tunnelling machine passes underneath the river Spree, the area of the former Palast der Republik, on the foundation of which the planned Berliner Schloss (Humboldtforum) is to be built, the Spree Canal, the Bertelsmann buildings, the Linden Tunnel, the equestrian statue of Friedrich the Great as well as the S-Bahn tunnel of the north-south line in the area "Unter den Linden".

Details of the tunnelling work under the river Spree and under the Humboldt Forum are given in the following. The stations Museumsinsel and Unter den Linden that are included in this Lot, as well as the connection to the existing station Brandenburger Tor are also looked at.

Tunnelling work for track 1 commenced in June 2013.

Undercutting the river Spree

Undercutting the river Spree poses particular challenges to shield tunnelling for reasons concerning the geology and the distance to the river bottom of approx. 6 m. Under the given constraints, without the implementation of additional measures shield driving approaches its feasibility limits. In order to increase safety and avoid a break up of the soil, it was originally planned to ballast the river bed with steel slabs or heavy-concrete cubes, while maintaining shipping operations throughout.

An alternative to the planned ballasting of the river/canal bed was then designed.

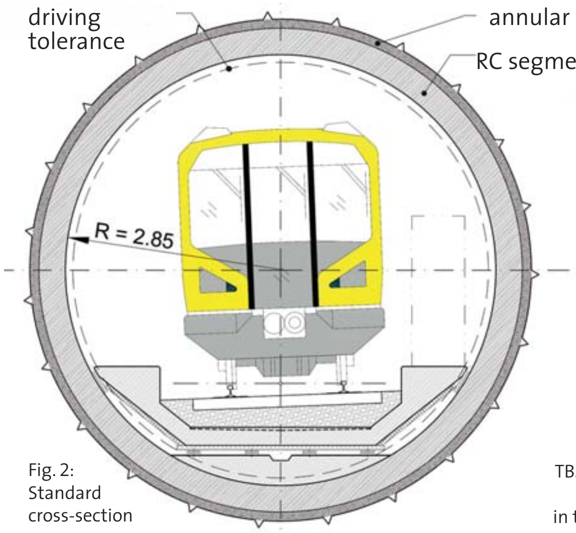


Fig. 2: Standard cross-section

Fig. 3: TBM during set-up and assembly in the launch shaft

This alternative proposal plans to reach the level of safety against blowout and soil collapse achieved with the ballasting method by using the High-Density-Suspension-Method (HDSM),

To prove that this method produces the same effect in the in-situ soil, an in-situ test field was planned for testing different suspension densities in interaction with the tunnel boring machine and the soils on site. For this purpose, a test field of approx. 50 m in length was set up between the launch shaft and the river Spree. In the area undercutting the Spree and the Spree Canal a supporting suspension was used with a density of 1.3–1.4 g/cm³. The tunnelling machine and the separation had to be modified substantially for the production, handling and preparation of the high-density suspension. The undercutting of the river Spree and the Spree Canal was carried out without complications and the settlements measured on the surface were on average less than 1 cm.

On the west bank of the Spree is a sheet pile wall that was left in the ground after being used as part of the pit shoring for the construction of the Palast der Republik. This wall projects into the shield tunnelling cross-section.

The sheet pile wall dates back to around 1970. It was planned that divers should downsize the sections lying in the tunnelling line in a temporary excavation in the river Spree, using the back-step method. The function of the sheet piling as a river wall for the federal waterway was, however, to be maintained. During the implementation of the project it was later decided to omit the construction of an excavation pit and to pull up the sheet piles instead.

The 40 year old, welded sheet piles have now been individually pulled up to the required degree, out of the tunnel section, and have been shortened respectively. It wasa then possible to continue unhindered shield driving.

Undercutting the planned Berliner Schloss

When the Palast der Republik was demolished the massive foundation slab had to be left in the ground. It could only have been downsized by lowering the water table substantially, and this is no longer allowed today. The foundation slab is therefore to be integrated in the new construction of the Berliner Schloss.

Construction work on the new Berliner Schloss started in March 2012, with the award of contract for the Lot „Excavation for the new Berliner Schloss“. The works are being carried out at the same time as the shield tunnelling. This means that both the foundation slab and the excavation pit are being undercut by the shield tunnelling machine, resulting in interdependencies of both projects. These have first and foremost an impact on the shield advance with regard to support pressure conditions that change at short intervals, and the work schedules of both projects that have to be coordinated.

In the area of the new Berliner Schloss an historic pile foundation was discovered during the tunnelling works. These are the remains of the foundation of a former, almost 100 m high coining tower. Some of the piles are 400 years old. They are approx. 11 m long and have a diameter of approx. 30 cm. The distance between the piles is approx. 40 cm (Fig. 5). The piles have been removed completely from the area passed through by the shield tunnelling machine.

The station Museumsinsel

The Museumsinsel station starts on the east bank of the Spree Canal and ends in the area of the Kommandantur (garrison's headquarters) (Fig. 6). The structure has two shafts at the ends of the station with corresponding access ways and distribution levels as well as the intermediate platform tubes. The shafts are constructed using the top-down method with a maximum depth of up to 43 m. The securing of the pit bottom is carried out using low-lying jet grouted slabs with stiffing grids arranged above.

Before the mechanical tunnel driving reaches the station area the enclosures of the pits to be excavated later on are built using the diaphragm wall method. The pit walls to be broken through by the shield tunnelling machine are designed with GFR reinforcement in the break-through cross section. On the earth side of the pit walls jet-grouted blocks are built to accomplish a defined sealing of the annular gap between segmental linings and diaphragm wall with special segmental lining mortar.

The platform hall is located in the area of the Spree Canal and is built under the protection of ground freezing using the mining construction method. The minimum cover between frozen body and bot-

Fig. 4: Pulling up sheet piles

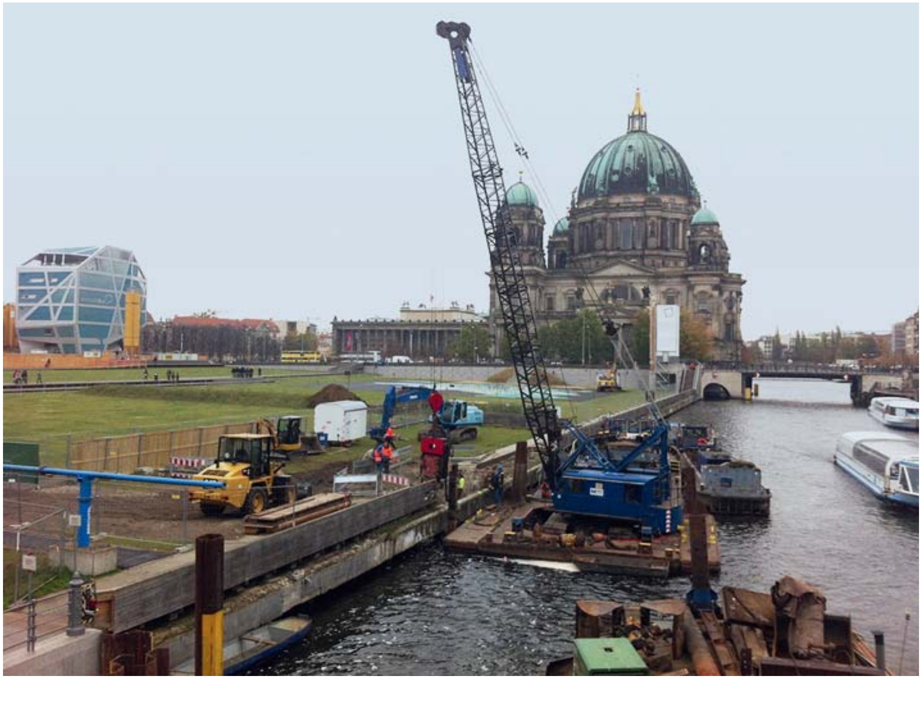


Fig. 5: Berliner Schloss, 400 year-old foundation

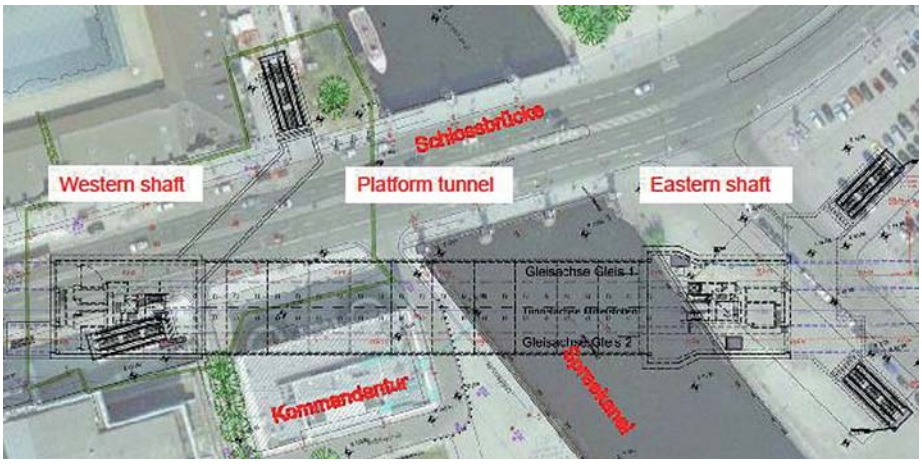


Fig. 6: Layout Museumsinsel station

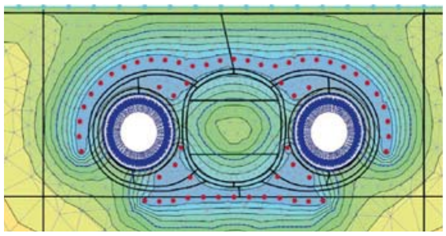


Fig. 8: Thermal calculation result – an example

tom of the Spree Canal is approx. 4.5 m. The frozen body is created using max. 105 m long horizontal, controlled boreholes. Due to the station's geometry it is necessary to drill the boreholes from just one side. The frozen body is designed with a structural thickness of 2 m (Fig. 7 and 8).

The platform hall is excavated with a three-cell cross section, with a middle tunnel and two side tunnels. First the middle tunnel is excavated and then, at staggered intervals, the side tunnels using the top heading advance method with immediate invert closure. Excavation is carried out using a milling cutter. The tunnels are lined with shotcrete. The excavation of the side tunnels is implemented by widening the cross-section in the area of the segmental rings. For this purpose the segmental lining is broken out in individual portions and the exposed face secured. Installation of the reinforced lining in the middle tunnel is carried out before the cross-section expansion in the side tunnels begins. Following the advance of the side tunnels the reinforced linings are installed in the side tunnels and connected by friction fit with the lining of the middle tunnel. The thickness of the linings varies and is min. 45 cm thick (Fig. 9).

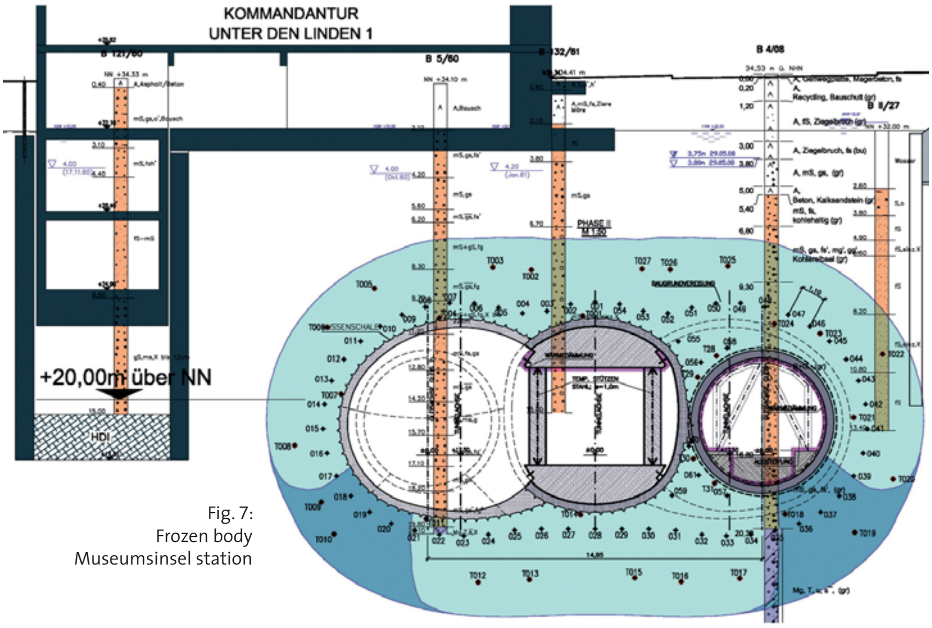
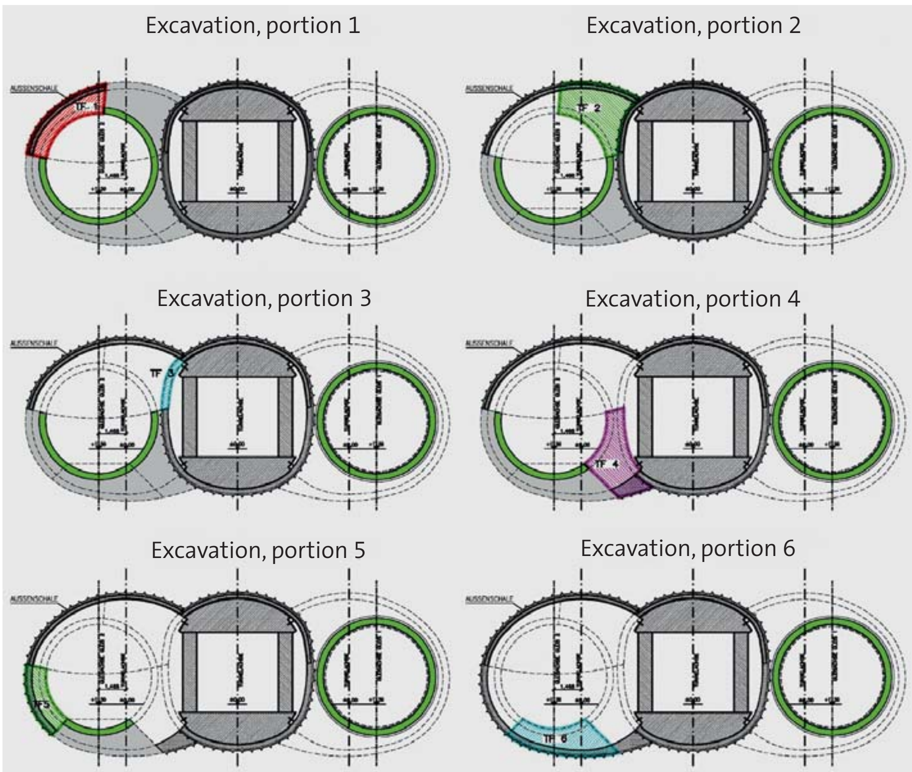


Fig. 7: Frozen body Museumsinsel station

Fig. 9: Sequence of excavation in portions Museumsinsel station



The station Unter den Linden

The interchange station with its T-shape layout lies beneath the boulevard Unter den Linden in the east-west direction and beneath the Friedrichstrasse in the north-south direction.

The station area Unter den Linden is where the existing line U6 and the new line U5 will in future cross (Fig. 10). The station Unter den Linden is being built in sections in separate construction areas.

For the construction of the new interchange station with changeover between the existing U6 and the new U5 a new section of the U6 is being built. For this purpose, it is necessary to shut down operations of the U6 for approx. one year. The new section of the U6 will also be built under the protection of a diaphragm wall pit. Because the U6 will later be passed under by the U5, the new U6 tunnel has to be designed as a bridge.

The connection to the existing structure is implemented under the protection of jet-grouted blocks for sealing purposes. To this end, the outer sealing of the existing tunnel has to be exposed and repaired for the connection to the sealing of the new U6 tunnel.

The station is built using the top-down method. In the east section an open pit is required for construction of access ways to the station levels. Analogous to the construction of the station Museumsinsel, the pit shoring is made of diaphragm walls with a depth of up to 35 m, as well as a low-lying sealing slab. The station is designed with joint-free concreted floors over a length of up to 40 m. This poses particular challenges for the production and working of the concrete.

The shield tunnelling machine passes through the station after completion of the pit enclosure and construction of the new section of the U6 line. At this time, the pits have not yet been excavated and drained. For a reliable waterproofing of the joints jet-grouted columns are provided on the outside of the diaphragm walls and the joint between diaphragm wall and segmental ring is subsequently jet-grouted. On track 2, the shield tunnelling machine has to cut through an area with anchors and grouted obstacles from excavation pits of the adjacent buildings. It is necessary to remove these before advance of the tunnelling machine. The anchors and grouted obstacles are drilled over and the anchor elements are removed ahead of the shield.

Approach to the station Brandenburger Tor

The tunnel tubes connect up to the east pit wall of the eastern shaft (structure 129) of Brandenburger Tor station. The station was built as reinforced RC concrete structure protected by a reinforced diaphragm wall lining (pit lining d = 1.20 m). Joint strips have already been stowed in the east end wall of structure 129. The joint strips and a transitional block enable the watertight connection of the tunnel lining to the existing end wall. To this end, the diaphragm wall provided for the entry of the shield tunnelling machine, measuring 1.50 m in thickness and without reinforcement, is supplemented with a jet-grouted block measuring approx. 10 m (Fig. 11).

The shield tunnelling machine drives into the jet-grouted block and the non-reinforced diaphragm wall until reliable sealing of the tunnelling machine is made possible. Around the shield skin, the gap in the cutting chamber and the shield skin are now successively sealed using compressed air, and the gap between the shield tail and the last segmental lining is sealed under atmospheric pressure. Before lowering of the air pressure, a frozen body has to be formed from the surface making it possible to seal the water-bearing space between the end wall and reinforced diaphragm wall, the construction-related longitudinal joints between the diaphragm wall lamellae as well as the joint between the reinforced and non-reinforced diaphragm wall.

To this end, freeze and temperature-measuring boreholes are sunk into the reinforced diaphragm wall in two rows one behind the other, as core drill holes. Freezing is implemented using brine. Dismantling of the shield tunnelling machine cannot commence until all joints are tight.

Dismantling and removal of the shield tunnelling machine is not possible from the station due to operational and safety reasons. The break-out of the tunnel tubes into the station can therefore not take place until the shield tunnelling machine has been dismantled.

The shield tunnelling machine is dismantled after reaching the Brandenburger Tor station and it is then transported back to the launch shaft. The shield skin is left in the ground. After reassembly of the machine, driving of the tube for track 2 can commence. The shield tunnelling machine is then dismantled again and transported back to the launch shaft. As with the first tube, the shield skin is again left in the ground of the tube for track 2.

The remaining advance for cutting through the diaphragm wall and the wall construction is carried out manually under the protection of the frozen body. During this process the frozen body is maintained by repositioning the freeze pipes at the edge of the excavation. The joint strips retained in the end wall are exposed, activated and concreted in the transitional block of the tunnel lining.

Summary

Closing the gap in the U5 underground line is a complex and technically challenging project. The line of the selected gra-

Fig. 10: Station “Unter den Linden”, longitudinal section U6, cross-section U5

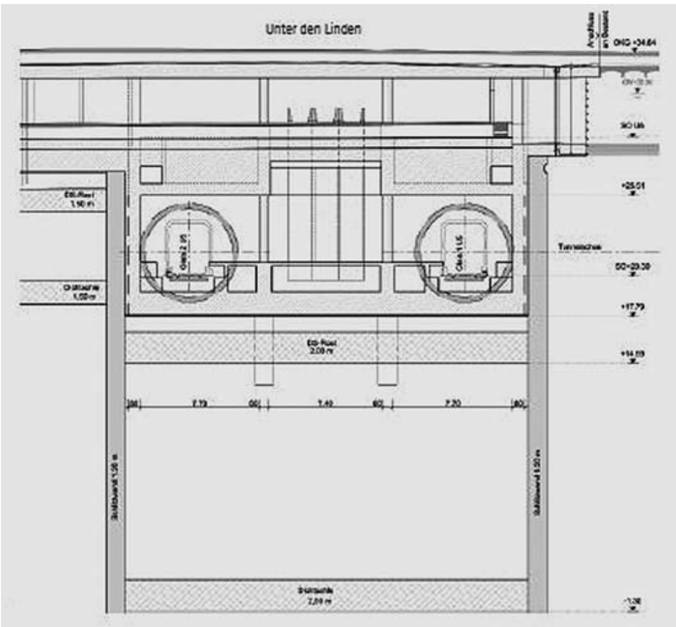
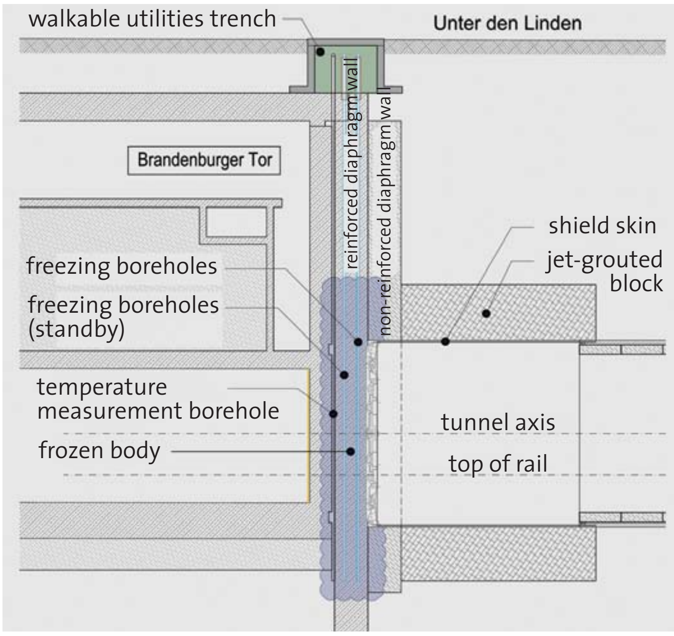


Fig. 11: Approach to the Brandenburger Tor station, longitudinal section, cross section of interchange area



dients is the result of planning constraints such as the undercutting of the river Spree and the Spree Canal as well as the adjacent buildings. The groundwater levels and the subsequent dimensions required for the individual components takes the chosen construction methods to their application limits. This applies to the drilling of the required boreholes for the low-lying jet-grouted slabs and to the length of the controlled freezing boreholes for the frozen body in the area of the station Museumsinsel.

Innovative solutions have been able to produce alternatives that facilitate the control of the shield advance in borderline cases. It was thus possible to maintain the safety margin of the design with regard to possible geotechnical failure mechanisms.

The construction of the stations has progressed and the stations Museumsinsel and Unter den Linden are now prepared for the shield tunnelling machine to pass through. Track 1 is currently being driven.

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