Shield tunnelling in difficult ground - approach and experiences from the City-Tunnel project in Leipzig/Germany

Construction des tunnels dans terrains difficile – approche et experiences du projet City-Tunnel à Leipzig/Allemagne

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ABSTRACT

Since the end of 2006, a 1.8 km long twin tube railway tunnel is under construction in the City of Leipzig, Germany. It will connect two terminal stations which are already existing at opposite sides of the central city. Each of the 9 m wide tunnels is excavated by a slurry shield and lined by tubbings. The tunnel is constructed in difficult ground and below the ground water table. Besides a lot of natural obstacles such as monolithic hard sandstone layers embedded within soil there are numerous artificial obstacles, e. g. tendons, steel beams and sheet piles, piles, slurry walls and other underpinning elements. The tunnel line crosses the densely populated heart of the city. It runs close to the ground surface beneath about 60 residential and office buildings. The contract specifies that tunnel-induced settlements are to be limited to a maximum of overall 3 cm for both tubes. The project includes 4 stations which are under construction in large and deep construction pits. This publication deals with the experience so far collected.

RÉSUMÉ

Depuis la fin de l’année 2006, un tunnel avec deux tuyaux et d’une longueur de 1.8 km est en construction au-dessous de la ville de Leipzig en Allemagne. Il raccordera deux gares en impasse qui se trouvent aux extrémités opposées de la ville. Le tunnel d’un diamètre de 9m est excavé avec des tunneliers à pression de boue et armé avec anneaux. Il faut le construire dans du sol difficile et sous la nappe phréatique. De l’eau d’infiltration acide avait créée des bancs monolithique de grès dur encadrés dans du sol aux profondeurs supérieures. Selon toutes prévisions, des obstacles artificiels comme des câbles, poutres en acier, poteaux, parois et sous-oeuvres seront trouvés à coté des obstacles naturels. Le tunnel traverse le cœur peuplé de la ville. Il est proche à la surface et environ 60 immeubles d’habitation et bureaux seront minés. L’abaissement causé par le tunnel est limité à un maximum de 3 cm par contrat pour les deux tuyaux. Le long du tracé du tunnel, quatre gares sont en construction avec des excavations grandes et profondes. Cette publication présentera les expériences qui avaient été fait jusqu'à présent.

Keywords: shield tunneling, settlement control, site investigation, groundwater management

1 INTRODUCTION

1.1 *HISTORY OF THE CITY TUNNEL PROJECT*

The plans for the tunnel are as old as Leipzig's Main Station itself, which was built in the years 1902 to 1915. It is the biggest terminal railway station structure in Europe, where about 250 trains and about 150.000 passengers are dispatched each day. First construction plans for the city tunnel date back to 1913 - the eve of World War I. Planning resumed in 1934, but again it had to be postponed because of World War II. There were also plans in 1970, but the former GDR in eastern Germany had not the economic resources to realise the project. This changed after unification. The new preliminary planning was completed in 1997. The official approval of the project was given in 2000. Construction of the deep excavation pits of the two inner-city stations Wilhelm Leuschner Platz (WLP) and Markt is ongoing since 2005. On the 15th January, 2007 the tunneling shield commenced its run through the city's underground.

1.2 *CONSTRUCTION JOB*

As one of the most important infrastructure projects in Germany, the city tunnel Leipzig is attracting considerable interest within the region and amongst geotechnical engineers. The tunnel provides a direct connection between the two existing terminal stations located at opposite sides of the city centre, which are the Bayerischer Bahnhof in the south and the Main Station in the North. The alignment of the new connection is right through the city centre. In the south, the tunnel is running underneath the Windmühlenstrasse, a wide street with a double-tracked tramway. Further to the north it passes underneath high-density areas with multi-storey buildings (Fig.1).

Fig.1: Alignment of the City-Tunnel Leipzig including the stations 1 – Bayerischer Bahnhof, 2 – Wilhelm-Leuschner-Platz, 3 – Markt, 4 – Main Station

The total project length is 4.654m and includes the gateways at the two existing terminal stations for the regional trains. The city tunnel itself is located between the two above-named stations. The tubes have a sectional area of 63,7 m^2.

Tunnelling of the two tubes (diameter D=9.0m) is carried out in a staggered, synchronised formation from south to north by means of closed shields which is propped up by a liquid. The spacing between the two tubes is approximately one diameter D of the tube. The overburden depth is between 7,5 m and 16 m. The smallest distance between the roof of the tunnel lining and the foundation of a building is 2.2 m (Petersbogen). To a large extent, tunnelling is carried out beneath the ground water table with a water head to the tunnel invert of up to 16m.

Since 1997 several site investigations have been carried out in the form of project-dedicated geotechnical and hydrogeological studies. In the following, some of the most important findings and conclusions will be presented.

2 SITE INVESTIGATION RESULTS

2.1 *GEOLOGY*

The ground of the City of Leipzig essentially consists of a rather complex series of Quaternary and Tertiary sediments. Lithologically, a total of 13 Quaternary and 10 Tertiary layers were discriminated.

Especially in the southern part of the tunnel track and beneath the artificial fill at the top, there is an up to 10m thick Pleistocene boulder clay (S 6) of glacial origin. Embedded within that clay are layers of laminated clay (S 9) as well as erratic blocks with diameters of up to 1 m. In the stratigraphic sequence, some fluvial layers (S 12) are following with thickness of approximately 17m. In the northern part of the tunnel track the ground, beneath the artificial fill, consists of about 10 m thick Holocene deposits of the local Mulde River consisting of cohesive components in the upper and non-cohesive components (gravel) in the lower parts (S7).

In the middle part of the tunnel line there is, beneath the river gravel, an about 9 m thick series of Tertiary sediments locally known as "Bitterfelder Flözkomplex" (S 14). That series consists of medium sand intercalated with layers of lignite containing silt and clay. Locally there are also some thin deposits of almost pure lignite. The series contains some xylithe and silicified residuals of tree trunks. Of particular importance for the tunnelling project, however, are two horizons of very strong quartzites which are embedded within a series of otherwise soft Tertiary layers. The horizons are lens-shaped and can be up to 4 m thick.

In the central and northern parts of the tunnel there is, beneath the above-mentioned quartzites, a 7 to 16 m thick series of Tertiary fine to medium sand locally known as "Bitterfelder Sandkomplex" (S 15). Further down is a 15 m thick layer of greenish-greyish-coloured silt ("Grüngrauer Schluff"; S 17). That layer prevails particularly in the southern and central parts of the tunnel. Along the entire tunnel, the above-mentioned layers are underlain by a 4 to 8 m thick silt ("Muschelschluff"; S 19) which is known to be an important regional aquifuge and groundwater barrier.

The structure of the ground is particularly complex in the central part of the tunnel line. Here, deep re-sedimented erosion channels of the Pleistocene area cut sharply into the series of predominately undulated and lens-shaped Tertiary layers. Locally, the cover of Quaternary sediments is completely absent, as is the case at the Wilhelm-Leuschner Place where Tertiary sediments are prevailing right at the surface (Fig. 2).

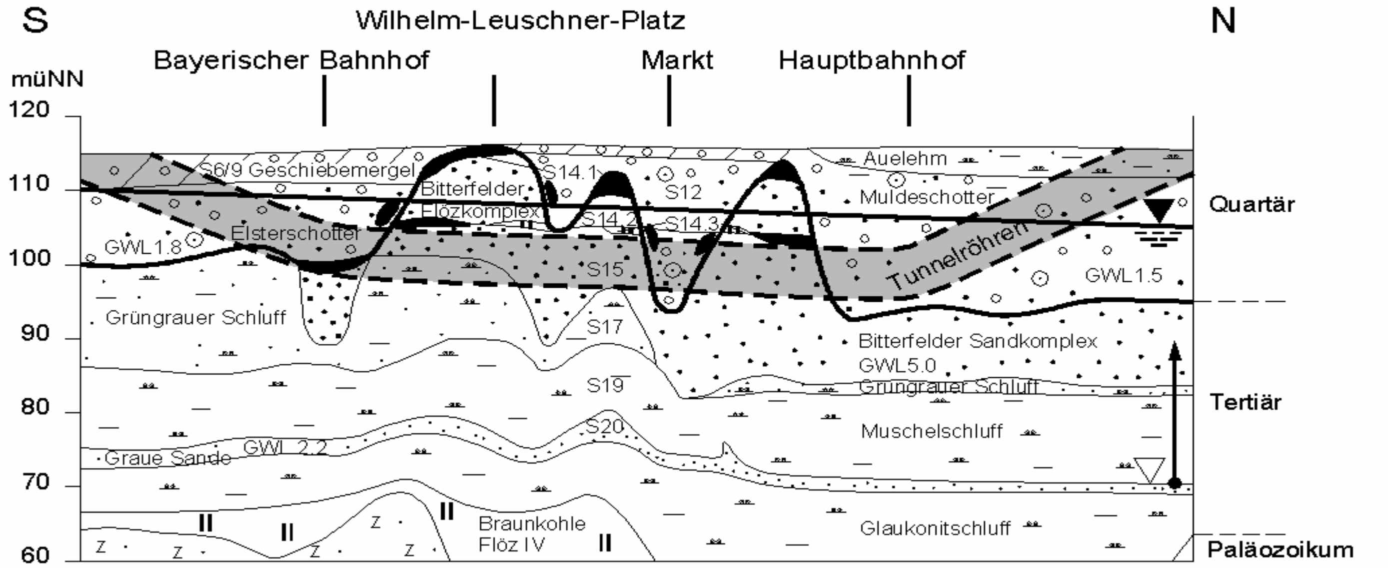

Fig. 2: Schematic geological model of the tunnel line. Tertiary quartzites indicated in black

Prior to the tunnel project, the existence of the quartzites of the "Bitterfelder Flözkomplex" (S 14) in the form of autochthonous banks or dislocated blocks was geologically reasonably well established (Fig. 4). However, not such much geotechnically as, historically, the geotechnical construction activity, carried out in Leipzig's city centre, was focussed on rather shallow foundations where the existence and properties of the Tertiary quartzites were of limited importance. Tunnelling in the deeper parts of the city's ground is an entirely new topic. What with respect to the quartzites is generally known is that they are vastly irregular in both vertical and lateral extent. Locally, they can be concentrated in bodies of considerable dimensions. Against this background it is understandable that within the geotechnical site investigation programme of the city tunnel project, it was hardly possible to delineate the Tertiary quartzites along the entire tunnel line in such a detail as it would have been desirable for the tunnel engineer.

Since 1998, however, new detailed information became available with the construction of very deep foundation excavations (16 m deep for the Petersbogen, Marktgalerie) and the excavation of new stations for the city tunnel project (the up to 24.5 m deep stations Wilhelm-Leuschner Platz and Markt). In these excavations the Tertiary quartzites were intersected in both their undisturbed as well as dislocated states. The latter state e. g. was disclosed immediately next to the future Station Markt of the city tunnel. The blocks measured between 0.5 and 7.5 m in length, 0.4 and 4.0 m in width and 0.3 and 3.0 m in height. They were irregularly deposited within river gravels of the earliest cold period (S 12) and the Tertiary sands of the Bitterfeld complex (S 15).

2.2 *HYDROGEOLOGY*

In the area of the City of Leipzig, the main groundwater storeys are located within the Pleistocene river terraces (gravel) and the Tertiary sands. Due to the existence of deep local erosion channels and strong accumulation processes, most of the groundwater storeys are directly interconnected. The hydraulic permeability k_f depends on the content and structure of the sediments in the respective aquifers. Fig. 3 gives some k_f-values for the upper ground water storey in the vicinity of the Station Markt in the central portion of the tunnel line.

Layer	Ground water level	Number of samples	Hydraulic conductivity k_f [m/s]	
			min.	max.
S 12	1.8	80	$2{,}5 \times 10^{-5}$	$2{,}0 \times 10^{-2}$
S 15	5.0	108	$2{,}5 \times 10^{-8}$	$8{,}4 \times 10^{-4}$

Fig. 3: Hydraulic conductivity of the layers in the upper groundwater storey at the Station Markt.

The depth of the groundwater level varies considerably and amounts from about 3.0 m beneath the surface (Main Station) to some 18 m maximally. The depth of the tunnels is almost entirely below the groundwater level. They thus constitute an obstacle within the natural groundwater flow (Fig. 2). Furthermore, it was quite evident that the deep excavations of the stations created some local barriers of the main aquifers, e. g. at the Station Markt a barrier of the aquifer units S 12 and S 15.

Fig. 4: Allochthonous block of Tertiary quartzite. approx Length 4.5 m, width 2.5 m, height 1.8

As a consequence, in 1998 a comprehensive site investigation was initiated for the determination of the relevant geohydraulic parameters. This required a dense net of observation wells, particularly in the area of the stations. Parallel to that observation a numerical 3-D flow model was implemented and calibrated. Besides the study of the effects of the underground construction onto the groundwater regime, the more general purpose of the model was to provide a rational base for the necessary approval of the construction work through the authorities.

The model was continuously adjusted to the actual state of planning and to the observational data available. Both the shape and size of the modeled area were optimized in line with the adjustment of the numerous input parameters of the model. The actual size of the model amounted to about 30 km². Additionally, detailed models were implemented for the areas of the two inner-city stations and for the area of the northern tunnel ramp. The grid in these models was densified in respect to the general model by a factor of eight, resulting in respective basic grid areas of 56 × 56 m².

3 TUNNEL CONSTRUCTION

3.1 *SHIELD TUNNELLING*

The tunnelling shield is driving trough the predominantly noncohesive fluvial soil layers (S 12), the sands of the Bitterfeld complex (S 15) and the cohesive layers of the green-gray silt (S 17). In course of tunnelling different natural obstacles are to be expected, particularly the above-mentioned Tertiary quartzites with blocks measuring up to 15m³ in volume and also petrified trees. Additionally, the tunnel is heading through layers of lignite and xylit. At two sites, the city tunnel is crossing the historical moat of Leipzig at a depth of about 4 m.

The cohesive layers and, to some degree, also the non-cohesive ones are abrasive. An additional risk in the shield tunnelling operations is the potential sticking of the clayey gray-green silt onto the cutter tools and the soil inlet chute. Provisions have been made to overcoming that potential problem by specific measures. The non-cohesive layers are erosive which leads to the possibility of a hydraulic recovery. From the grain size distribution characteristics of the sands of the Bitterfeld complex (S 15) it can be deduced that the risk of liquefaction of the sand remains rather low.

The tunnel support system consists of a ring of 7+1 pre-cast concrete tubbings. For the specification of the concrete of the tubbings the chemistry of the groundwater had to be taken into account. Because of its degree of salinization the groundwater is aggressive to concrete and could potentially cause flocculation / coagulation of the fluid sustaining the tunnel face.

Different types of artificial obstacles might be anticipated in the tunnelling ground and also in the ground adjacent to the groundwater barriers of the excavation pits of the stations. Such obstacles could be remnants of previous ground construction works, in particular anchor cables from the support system of deep excavations, parts of sheet and diaphragm walls and grout injection piles. Some artificially-induced voids might also be expected, e. g. insufficiently backfilled drill holes, old water wells and open anchor holes. The existence of any such voids can critically interfere with the earth balancing pressure of the shield. Because of this, all known artificial obstacles had been recovered before start of tunnel heading.

At the planning stage, particular emphasis was placed on the interaction between the tunnelling ground and the above-surface structures. Even with the utmost care a certain degree of soil extraction, additional to that of the tunnel excavation, is unavoidable. That soil extraction leads in some ways to a settlement trough of the ground surface. Initial stages of that trough can regularly be observed some distance ahead of the tunnel face, a feature which indicates to significant excess soil extraction at the tunnel face.

The degree of soil extraction can often quite effectively be reduced by appropriate tunnel operation and support measures, however not totally avoided. The geometry and magnitude of the settlement trough depends not only on the degree of soil extraction but on a number of geological, geotechnical and geometric factors, such as the type, structure and shear strength of the overburden layers and the overburden height itself. Considering the particular conditions in Leipzig, an about 60 m wide settlement trough over the two tunnel tubes is expected.

Near-surface and inner-city tunnelling beneath all types of modern and medieval buildings as well as overcoming natural and/or artificial ground obstacles require highly flexible shield operations. Particularly severe conditions are met at the entries/exits of the tunnel tubes into the water-pressure subjected shafts of the stations. Whenever possible, the entry/exit blocks were hereby supported by grab buckets. In case of a confinement due to existing buildings, however, special soil improvement measures such as the placement of an umbrella of jet-grouted columns had to be taken instead of the bucket support. Again special measures have to be employed to avoid any jetting shadows and also geometric and material strength deficiencies within the columns. Despite all these provisions the jet grouting operations experienced some problems in the lignite and xylithe-bearing tertiary layers.

As already mentioned (e. g. Fig. 1), the city tunnel Leipzig connects the existing Station Bayerischer Bahnhof at its southern end with the existing Main Station in the north via the new stations Wilhelm – Leuschner - Platz (WLP) and Markt (Fig. 5). All stations are open-cast constructions. Immediately north of the Station Bayerischer Bahnhof there is the ramp into the southern end of the tunnel. A particular mention is to be made to the en-bloc relocation of the historic Portikus Building. At the WLP Station the former moat of the city will be crossed within the Tertiary sands of the Bitterfeld complex (S 15). The Markt station is located in the high-density area of the inner city, probably affected by a resedimented erosion channel with dislocated blocks of quartzite. The waterlogging of the Station caused by the hydraulic conductivity of the channel fill and the settlements of the buildings have to be tackled in this area.

3.2 *PROTECTION OF UNDERMINED BUILDINGS*

The driving of the two tubes will lead to settlements which affect the existing development. Compensation Grouting (CGV) is planned to avoid structural damage. The method involves the installation of TAMs (tubes à manchettes) to inject grout (a mixture of cement, sand and water) under pressure into the ground at chosen locations during the tunnel construction. The system allows repeated grouting through the same TAM if required.

Prior to any excavation, enquiries about the foundations of the buildings above the alignment had to be made by analyzing historical and contemporary building plans. The enquiries were verified by site visitations, surveying and mapping as well as by subsoil investigations. Aided by this input data Computer modeling of the tunneling was carried out to achieve predictions about the settlement of each building.

The drilling of the horizontal arrays of grouting tubes will be done from a set of vertical shafts (diameter about 3.5 to 6.5 m), an underground car park and an existing supply tunnel.

Fig. 5. Construction site of station Markt

The TAMs are up to 75 m long, the holes machined into them will be at an interval of 0.5 m. The drilling of the TAMs is planned at a distance of at least 2 m to the tunnel roof and more than 2.5 m to the foundations of the buildings above. The maximum spacing of the tubes will be 2 m. The procedure involves a permeation grouting to stabilize the soil, followed by a pre-excavation grouting to lift the ground in order to anticipate the calculated settlements. Compensation grouting during tunnelling of the tubes and final strengthening of the ground completes the process.

3.3 *GROUNDWATER MANAGEMENT*

According to the approval of the plans, the rise of the groundwater table due to the tunnel construction is restricted to 0.1m. The following criteria are taken into account:

1. Additional waterlogging of existing subsurface structures in the vicinity of the alignment.
2. Restrictions to subsurface engineering in the future.

For the excavations of the stations Bayerischer Bahnhof, WLP and Markt diaphragm walls are constructed down to the “Muschelschluff” (S 19). The walls have lengths of 150 to 250 m which are located perpendicular to acute-angled to the groundwater flow. The rise of the groundwater table due to the excavation lining is calculated with 0.15 to 0.60 m and exceeds the above mentioned demands of the authorities. Thus additional actions for construction and operation of the stations as well as the northern tunnel ramp are inevitable.

To avoid the increase of the water table, a groundwater management system was designed. Parts of the system are vertical shafts, horizontal filter wells and ducts. The groundwater will be transported by sag pipes from the direction of inflow to the groundwater runoff. The hydraulic gradient is sufficient for the water flow. Pumping is unnecessary.

The horizontal wells were dimensioned according to CHAPMAN (1956) for floating gravel drains. Parameters to be considered for the calculations of the wells were the quantity of water and the hydraulic gradient. An analysis of the volumetric capacity to determine the required filter surface was dispensable with respect to the low rate of percolation and the length of the perforated casing.

Operational experiences and execution methods of all groundwater management systems linked to underground constructions were considered for a feasibility study. In addition, the chemistry and bacteriology of the groundwater were analysed with respect to clogging and the risk of precipitation.

As a result of the studies an array of horizontal wells with lengths up to 100 m and a diameter of 100 mm drilled radial outwards from vertical shafts were proposed. The shafts were integrated in the stations as protruding parts of the diaphragm walls. The rectangular parts have a length of at least 4 m.

4 EXPERIENCE

4.1 *SHIELD TUNNELLING*

The tunnelling machine (TBM) started tunnel heading on January 15th 2007. Until now the advance is less than 10 m. For this reason, reports on the experience have to be postponed.

4.2 *PROTECTION OF UNDERMINED BUILDINGS*

The installation of the TAMs was realised by means of flush boring equipments. The horizontal drilling was executed from vertical shafts, partly supported by hammer drilling but without a casing to stabilize the borehole wall (Fig. 7.).

Difficulties arose from the cutting across layers of coarse gravel and the even grained sands of the “Bitterfelder Sandkomplex” (S 15) which lead to a temporary breakdown of the advance. The breakdown was supposed to origin in the subsurface conditions at first. Exploration drillings from the ground level close to the neighbouring surface buildings were executed to verify suspicion.

A direct access to the subsurface conditions beneath the buildings could not be achieved. Thus a method to analyse the soil strata from the horizontal drilling mud was initiated. This method provides area-wide information to specify the soil strata, even under the building development. The reliability of the method was verified by drilling through the well known location of a slurry wall. The documentation of the drilling showed, that the difficulties to position the TAMs occurred mainly in the even grained sands. The sediments tend to liquefaction, if the pressure of the sustaining fluid decreases or the fine fraction of the soil is missing. Due to the drilling process, a pressure drop is inevitable to assemble additional rods. This problem occurred especially during the installation of the horizontal wells at the WLP Station and has to be taken into account for the driving of the TBM. Contingency plans have to consider this speciality.

4.3 *GROUNDWATER COMMUNICATION*

By now the construction of the main station is finished. About 30 m³/h of groundwater is lifted by means of 3 vertical wells on the direction of inflow and led to the main drain. A limitation of the rise of the groundwater table to 0.1 m is guaranteed and additional waterlogging of the existing station building is avoided. According to the computer modelling a quantity of 35 m³/h were expected.

Fig. 6: Preparing of tunneling machine

The central part of the main station is waterlogged since 1992. With respect to a planned permanent draw down of the water table, an additional groundwater management system is dispensable. The wells will be used to lower the groundwater table upon the completion of the permanent draw down. The capacity is even big enough to compensate an additional rise of the water table caused by construction works at the west wing of the station building.

An altered sheeting design of the northern ramp of the tunnel led apart from lower costs to less blocking of the upper aquifer. As a consequence, the extent of the groundwater management could be lowered. The interpretation of the monitoring results offers the opportunity to adjust the design of the groundwater management system. An improvement of the design is in progress.

The estimated rise of the groundwater table at the station Markt has been confirmed so far. The construction pit is finished since July 2006. A rise of about 0.1 m at the south end of the pit confirms the modelling. Further improvements of the groundwater management system and the risk assessment for the development are expected due to the additional knowledge of the soil strata during the driving of the tunnel. At the WLP Station the installation of a groundwater management system for the construction time was dispensed.

The necessity of the management system was verified. All in all a rise and fall of the groundwater table of about 0.6 m was noticed till December 2006. The computer simulation ended with 0.3 m rise. Under the assumption, that the rise equals the fall of the water table, the computations were quiet good.

In summary, the computations were confirmed to a large extent by the 3 operational groundwater management systems at the stations till December 2006. The systems at the WLP station and Markt will be adapted to the conditions of the construction.

Fig. 7: Shaft and horizontal drillings for the CGV

The management system at the main Station has to be modified due to the permanent draw down of the groundwater. A modified construction at the northern ramp of the tunnel will lead to additional adjustments of the groundwater management system. At present a rise of the water table is avoided by vertical wells.

5 CONCLUSIONS

The construction of the City-Tunnel in Leipzig is with respect to the geotechnical and hydrological situation, the alignment through the densely populated heart of the city and the calculated construction time a difficult project according to DIN 4020 (geotechnical category III).

The large extend of subsoil investigations in combination with the knowledge of the regional geology, the historical and future development of the city and its surroundings as well as the investigation and critical evaluation of the subsurface conditions provide the geotechnical basis for a successful and economical design of the construction.

The quality assurance according to the construction design as well as the build-accompanying quality control will have top priority now. Contingency plans for the construction parts will have to contrived and implemented. In addition, a fulltime geotechnical building-inspection and monitoring by specialized consultants is necessary.

Close, however at any time critical cooperation of the owner, engineering designer, geotechnical engineers, the constructor and the other participants is necessary to finish the City-Tunnel in the required high quality in time. At least a professional management is mandatory to reconcile with the different interests of all involved parties and finish the project in the focus of the public.

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