Construction of the North-South-Metro Line in Cologne and the accident on March 3rd, 2009

Prof. Dr.-Ing. Alfred Haack
STUVA, Cologne, Germany
Former President of ITA

Since 2004, the 3.8 km long North-South-Metro Line in Cologne with 7 underground stations is under construction. The running tunnels were excavated by Tunnel Boring Machines (TBM) and finished already in summer 2008. The stations, two emergency shafts, and an underground turn-off are to be constructed by special methodologies, applying partly cut-and-cover methods, partly mining methods in combination with ground freezing.

On March 3rd, 2009 in the open pit of the 28 m deep turn-off, an inrush of groundwater and ground material occurred and resulted in a total collapse of the Historical Archive of the City of Cologne consisting of five storeys above ground and two storeys underground. The archive contained about 33 km total length of shelves with historical documents partly going back to the 9th century, covering not only the history of the City of Cologne but also of the entire surrounding region and all Germany. Collaterally, one neighbouring building on each side of the archive also collapsed. Two fatalities were missing for a couple of days, covered by masses of meter-high debris.

So far neither the technical nor the first juridical investigations are finalized and the earliest results are not expected before the end of spring 2010. Therefore, all explanations regarding the reason of the accident are based on assumptions only. A possible explanation seems to be a failure in the diaphragm-walls of the shaft, not visible from the bottom of the shaft, for example a larger hole or a severe honeycomb or a weak joint between two neighboured wall sections.

A hydraulic ground seepage could also be the reason for the accident. This will be clarified by special investigations like seismic impulses or by digging out the deeper parts of the diaphragm-wall.

The paper describes the construction methods applied, the first political reactions after the accident occurred and the consequences taken after the accident

1. DESCRIPTION OF THE PROJECT

One of Europe's largest building projects is under construction taking the approx. 4 km long North-South-Metro Line in the about 2000 years old City of Cologne – an inner urban tunnelling measure, which is influenced by extremely tricky constructional and local marginal conditions (Thon & Spohr, 2003). It finally shall link the southern part of central Cologne to the urban railway network in form of a direct connection. Instead there are only bus routes nowadays, which represent a completely inadequate public transportation service as in some cases they have to pass through narrow winding streets in the historic city centre. The urban railway only reaches the densely populated areas of the southern part of the city via time-consuming and unattractive detours. In other words, the parts of the southern downtown and new town area that lack direct transporting links as a consequence suffer deficits that hamper urban development.
As a result, Cologne thus decided to construct a north-south urban metro line that will help remedy this state of affairs.
The first 4 km long construction stage of the new North-South-Metro Line mainly runs underground – with seven subterranean stations and one on the surface (figures 1-2). Towards this end, the projected tunnel route passes through major sections of the old Roman town – touching the former Roman port. It was reckoned that important archaeological finds will be discovered in the soil that had to be recovered and evaluated. Such digs have to be integrated in the construction cycle from the very beginning. The route then follows the former Roman north-south axis and runs along the Roman road connecting Cologne and Bonn through the medieval part of the city.

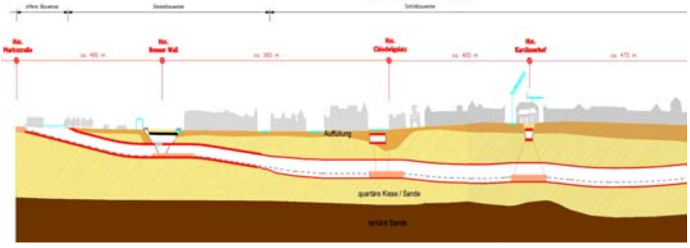

Figure 1. Southern section of alignment with 3 underground stations.

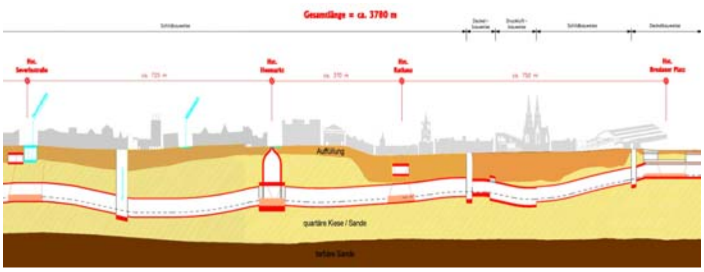

Figure 2. Northern section of alignment with 4 underground stations.

The construction work began in 2003 and was planned to be finished in 2011 after a period of altogether 8 years including furnishing the stations and equipping the running tunnels with all the technical installations before the new line opens. The estimated overall costs amounted to around 650 million Euro for this section

A large number of different marginal conditions have to be taken into account during the development and design of inner urban tunnel facilities, which include many other special tasks in addition to the technical requirements for realizing the project. Intensive exploitation of inner urban areas and clashes among road-users and residents with respect to their various interests also signify that major construction measures of this nature can often only be undertaken under considerable difficulties. These factors influencing construction have to be set alongside the basic static-constructional, technical, hydrological and soil mechanical marginal conditions at the preplanning stage and often require innovative solutions to accomplish the project – resulting from a technical-economic comparison of the various possible approaches.

The roughly 4 km long route for the projected north-south urban railway mainly runs underground on account of the various inner urban factors of influence. The tunnel sections are for the most part located in water-bearing quaternary Rhine deposits consisting of sands, gravel sands and gravels. However, over a relatively short section they also pass through the deep-lying fills of the Roman port basin.

The two parallel single track running tunnels of the southern section with an internal diameter of 7.3 m were driven by mechanical means continuously from the starting shaft in the south to the target shaft in the north over a length of about 2.7 km using TBMs with an external diameter of 8.4 m (fig. 3). These were finished in summer 2008.

The underground stations and special structures partly are constructed by cut-and-cover and partly by trenchless methods. The basic concept for producing the underground station buildings involves the integration of the platforms in the side areas of the pre-driven tunnel tubes and connecting the side platforms at running level by means of cross-passages created by mining means. The generous cross-sectional design of these connecting structures with clear dimensions of approx. 9.0 x 3.5 m thus calls for high demands both on the formation of the subsurface freezing that will fulfill a sealing function and stabilize driving as well as on the stability of the single shell constructions in the segmental linings. The access structures for the stations will be produced in diaphragm excavation pits, which will continuously be set up between the running tunnel tubes.

This combined construction method was applied for 4 of the 7 underground stations. The 3 others were built by cut-and-cover method.

Conventional cut-and-cover method is also used for setting up the Waidmarkt turn-off, whose diaphragm walls are extended down into practically impermeable tertiary soil formations in a depth of more than 40 m below surface.

Figure 3. TBMs for southern section.

2. THE ACCIDENT

On 3rd of March 2009 during the final excavation work for the 28 m deep open pit of the Waidmarkt turn-off a catastrophic accident happened in the early afternoon. The seven storeys high Historical Archive of the City of Cologne collapsed including one neighbouring building on each side (fig. 4). This Historical Archive hosted 33 km of shelfs containing numerous original documents, some older than 1200 years. These documents are covering the history of the City of Cologne but also of the surrounding Rhine area and partly also of entire Germany. Two fatalities were missing for a couple of days covered by masses of debris.

On the day of the accident the circumferential diaphragm-walls of the Waidmarkt pit were completely finalized and dived for at minimum 5 m into the less permeable tertiary ground formations underlaying the sandy-gravelly quartery coverlayers. The final depth reached about 45 m below surface. The excavation works inside the shaft had nearly reached the finally planned level of 28 m below surface. The sections of the pre-driven running tunnels inside the shaft were already rebuilt and the final as well as the intermediate ceilings were installed (fig. 5). Even the blinding concrete of the bottom slap was in some section already brought in.

During this construction phase, groundwater was continuously pumped up to a quantity of about 200 l/s to lower and control the water table inside the shaft and so to enable the works. The four interconnections between the running tunnels and the shaft itself proved sufficiently water tight und well functioning during this construction phase.

Figure 4. Aerial view of collapsed Historical Archive.

According to eye-witnesses about ten to fifteen minutes before the collapse of the Historical Archive an increasing inrush of water and later up to 5500 m³ ground materials started. This occurred in the south-east corner of the shaft either at the bottom of the excavation or penetrating the diaphragm-walls in their visible areas.
As soon as the workers realized not any longer being able to control this situation, they climbed up to the surface and warned people on the roads and in the adjacent buildings: About 30 users and employees of the Archive and about 15 inhabitants of the neighbouring houses were rescued this way. Unfortunately two persons were sleeping in one of the neighbour houses that time and missed the warning. They lost their lives.
First spontaneous political reactions argued, that the construction of the North-South-Metro Line in the densely built up down town area of Cologne should never have been accepted and started. And furthermore this was focused on Cologne alone but generally seen regarding all densely built up city centers. This argument is completely wrong, because tunnelling in general is not dangerous and metro lines are not needed and not constructed in rural, but mainly in inner-urban densely populated areas.
The accident did not at all occur in connection with the pre-running TBM drives conducted in advance to the excavation of the shaft for the Waidmarkt turn-off and finished about one year before. This shaft was built consecutively by means of 1.0 to 1.5 m thick and 45 m deep diaphragm-walls. From this point of view it was a normal construction site for underground parts of a building and not a typical tunnelling construction site.
So far neither the immediately started technical nor the first juridical investigations are finalized and the earliest results are not expected before the end of spring 2010. Therefore, all explanations regarding the reason of the accident are based on assumptions only. A possible explanation seems to be a failure in the diaphragm-wall below the excavated level of the shaft, not visible from the bottom of the shaft, e. g. a larger hole or severe honeycomb or a weak joint between two neighboured wall sections. A hydraulic ground seepage could also be the reason for the accident. This will be clarified by special investigations like seismic impulses or by digging out deeper parts of the diaphragm-wall.

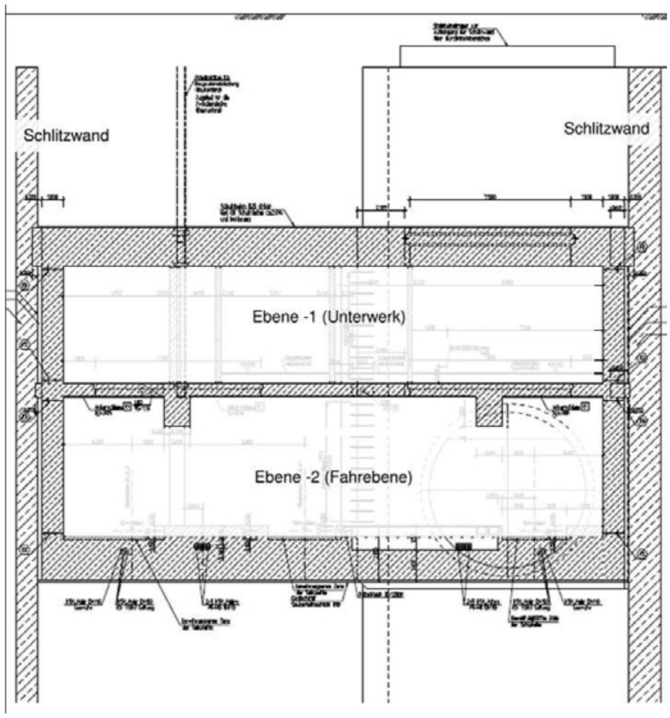

Figure 5. Cross section of underground turn-off.

The accelerating infiltration of water and soil into the Waidmarkt shaft caused obviously a significant loss of ground underneath the Archive (fig. 6). This finally resulted in a cone of collapse outside the Waidmarkt shaft in which the Archive building collapsed. An idea of this situation is given by fig. 7.
Soon after the accident it was started to rescue the precious archive documents. They are partly in good conditions, but partly severely damaged and were to dug out of debris and ground water. Up to the end of October 2009 about 85 % of the material was recovered. It will take years, perhaps decades to restore the severely damaged precious material. For recovering the remaining rest of the documents, a special pit outside the Waidmarkt shaft has to be constructed which should also serve for more detailed investigations of the reasons for the accident. This external pit is planned to be erected

immediately outside and adjacent to the south-east corner of the diaphragm box. These works are planned for summer 2010, so that the recovery of the rest of the documents as well as the final investigation concerning the reason of the accident can be done in autumn 2010.

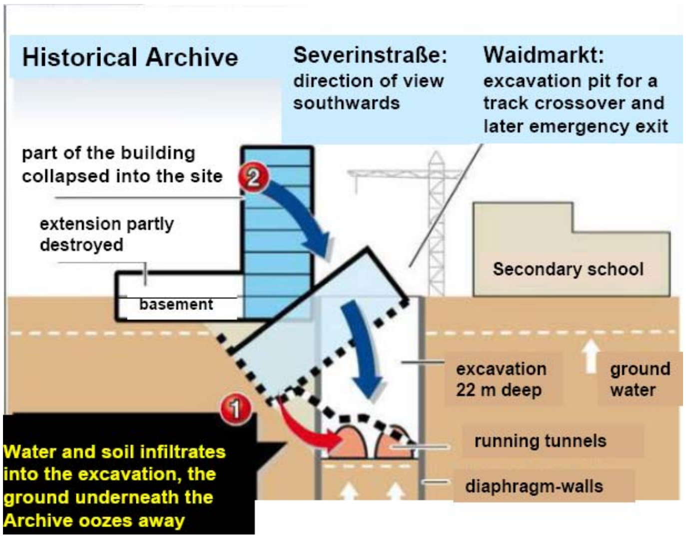

Figure 6. Assumed cause of accident.

3. CONTROL MEASUREMENTS FOR THE HISTORICAL ARCHIVE BEFORE THE ACCIDENT

Since the beginning of the construction work different accompanying measurements were conducted. Especially those regarding the Historical Archive have been:

- weekly optical and tachymetric surveillance of movements of the structure regarding settlements and inclinations
- monthly observation of development of cracks in walls and ceilings of the Archive building, which normally occur in connection with shield drivings
- permanent observation of inclinometers in the diaphragm-walls of the Waidmarkt shaft
- quantitative and qualitative control of the pumping of the ground water out of the Waidmarkt shaft

The site supervision and management laid in the hands of KVB (Kölner Verkehrs-Betriebe AG), the client. They asked regularly for site records regarding all the most important measurements. They also ordered all different construction phases, steps and modifications regarding the original design proved and accepted by the authority.

4. CONSEQUENCES TAKEN AFTER THE ACCIDENT

Following the first measures for stabilizing the situation after the accident are listed and briefly described (see also Reinarz 2009):

1. Immediately after the accident and the interruption of the ground water lowering a total of about 2900 m³ concrete was poured into the Waidmarkt shaft to balance the buoyancy and stabilize the situation.
2. In addition concrete barrier walls were erected in the connected 4 running tunnels to stop any propagation of a mixture of soil and ground water into the already completed northern and southern tunnel sections and underground stations.
3. Specific soil-mechanical tests were conducted to check the remaining stability of the shaft and the neighbouring buildings.
4. Automatic measuring systems were installed to detect any further movements, settlements and deformations of the shaft walls. During the next couple of months, some of them were read and evaluated 4 times a day. Meanwhile the frequency of data reading was reduced to once a day.
5. Additional experts were involved to check and supervise the basic statical and procedural concepts of the originally planned methods of construction, controlling and management of all sites regarding the North-South-Metro Line in Cologne following the principle of „Second Opinion“.
6. A new site supervision has been installed (the client will not any longer be the supervisor at the same time).
7. The information policy of the public and the municipal bodies was revised, improved and intensified. This includes in first line also the site directly affected by the accident. The local and regional media like daily newspapers, but also audio and video channels get provided with news and findings as far as possible.

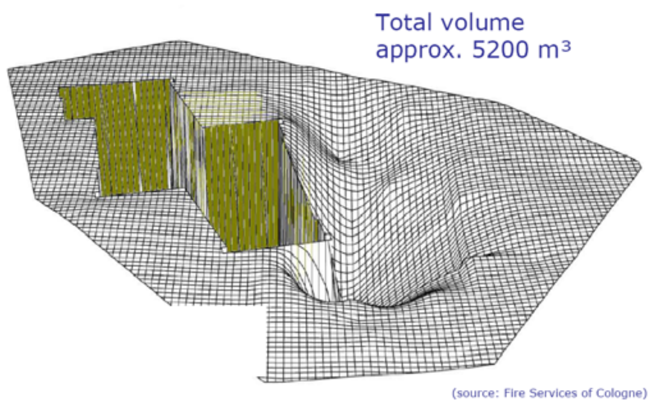

Figure 7. Assumed cone of collapse.

8. On the owner‘s side, the number of personnel was extended. This counts especially for the

sections of controlling and management of the works along all other parts of the North-South-Metro Line of Cologne, which are still under construction.
9. Furthermore, the activities in the departments of the owner dealing with matters of insurance, financing and juridical aspects have significantly grown.
10. STUVA was asked to assist and consult the owner KVB, to check and evaluate the proposals of all external experts and consultants. This has proved important.

5. CLOSING REMARKS

From the technical point of view, tunnelling can be regarded as being very safe as long as skilled planning and execution is applied. This is proven by statistics of many successfully finalised projects of hundreds of kilometres metro lines and underground stations in comparison to the worldwide very few severe accidents during the last decades.

In Germany e.g. about 600 km of metro lines were built since 1965, with only two accidents causing fatalities: Munich 1994 and Cologne 2009.

But generally the following also has to be kept in mind:

Underground construction asks for permanent and intensive observation of the interaction between ground and the structure under construction. Any unforeseen development or deviation from the prognoses has to be followed carefully and the concept of construction adapted to all changed conditions.

A fair sharing of risks between client and contractor concerning change of conditions is most important.

All numerical prognoses are to check concerning their plausibility and controlled by independent, well experienced and most skilled experts. The principle of „Second Opinion“ is recommendable.

The site manager and supervisor should not only check the list of delivery of materials and the completeness of the recordings of the measurements. Generally spoken they should also in addition – as far as needed – evaluate critically the results of each single measuring campaign, but also of the entire chain of various measurement activities considering the mutual dependencies. In general they contribute to solving possibly occurring problems.

As a résumé it can be stated:

All staff involved (workers, supervisors, engineers, managers, etc.) have to be aware of their responsibility. They have to form a team and keep in mind an optimum technical solution all the time and not primarily minimum costs. The first priority has always to be the safety of personnel, of the structure as well as of the life and property of thirds.

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