Challenging Construction Projects Related to Urban Tunnels

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ABSTRACT: The growing size and population density of metropolitan areas and the along going traffic demands lead to the construction of large infrastructure projects. In many cases these infrastructure projects are close to sensitive properties. The construction of new underground structures and the deconstruction of existing structures often have a significant influence on existing (underground) structures. The experiences of two large projects from Spain and Germany will be presented in the paper. The first of the presented projects is the new tunnel of the Spanish high speed railway line under the city centre of Barcelona, Spain. The tunnel boring machine (TBM) with a diameter of 11.55 m passed next to two buildings that belong to the World Heritage Properties of the UNESCO. The second project is the deconstruction of an up to 14 storeys high building in Frankfurt am Main, Germany. Under the deconstructed building are an underground station and tunnels of the urban metro system. The uplift and deformation of the underground structures had to be limited to guarantee the serviceability of the sealing. The paper focuses on the extensive geotechnical and geodetic measurement programs that were installed regarding the observational method and the measurement results. The experiences made in the planning and construction phases of these complex projects are explained and for new inner urban projects recommendations are given. In order to reduce the subsidence risk, earth pressure balanced shield machines are a good solution in an urban environment in comparison to other tunnelling methods. Settlements are evoked by changes in the stress conditions or changes in pore water pressure. With an active support pressure of the face, of the gap between the shield and the surrounding soil and the gap behind the tail of the shield these changes can be reduced to a minimum. Nevertheless settlements or ground subsidence occur in every tunnel construction process. To characterise the settlement trough in width and depth over a tunnel section the volume loss factor V_l can be used. V_l describes the volume of the settlement trough to the theoretical tunnel volume.

1. INTRODUCTION

Due to continuously growing traffic volume in most metropolitan areas large infrastructure projects are accomplished, manly in order to improve the public transport (bus, metro, train, tram) and the individual traffic (cars, pedestrians).

That means, underground constructions in high density urban areas like metro, tunnel, road and railway tunnels are realised in almost every big city in Europe, for example the metro in Vienna [Moritz, B. and Koining, J. (2011)], the metro in Rom [Hofmann, A. and Cresto, A. and Kraft, O. (2010)], the metro in Budapest [Bäppler, K. (2009)], road tunnels of the M-30 in Madrid [Marqués, M. F. and Lorenzo Romero, J. (2010)], the metro and railway tunnels in Berlin and the high speed railway line in Barcelona.

Because of the location in urban sites, these underground constructions have to be realised in a context of very sensitive neighbourhood [Kastner, R. and Emeriault, F. and Dias, D. (2010)], as for example high-rise buildings and World Heritage Properties like the Sagrada Familia. Therefore the requirements on those infrastructure projects with regard to precision and the minimization of impacts on the heritage properties are extremely high. The interaction between existing building, intervention caused by the tunnelling process, groundwater and subsoil conditions is very complex. The quantity of the impacts cannot be easily predicted, even with the existing state of the art calculation methods [Knitsch, H. (2010)].

Based on high-level soil investigations extensive in combination with a qualified, comprehensive construction supervision and the consistent application of the observational Method can guarantee for the safety and serviceability of the world heritage properties.

The observational method generally covers the following aspects:

- Predictions with computational models
- Definition of acceptable limits
- Plan of contingency actions
- Careful and permanently monitored construction works
- Safety systems at the historical buildings itself, independent from the tunnel construction works.

On one hand, acceptable limits have to be defined for the parameters of the tunnel construction according to the chosen tunnelling method, on the other hand acceptable limits for the displacements of the world heritage properties have to be adhered to. One example admissible settlements are given in three steps; green, amber and red in Table 1.

Table 1 Admissible settlement according to MINTRA

Control threshold	Admissible settlement [mm]		
	Green	Yellow	Red
Zones without buildings.	<50	50 to 100	>100
Buildings with deep or slab foundations, in good state. Pipes but not gas.	<20	20 to 30	>30
Underground structure or existing tunnels.	<15	15 to 25	>25
Buildings with surface foundations, without apparent damage.	<10	10 to 15	>15
Buildings with surface foundations with damage. Monumental buildings. Buildings with more than 10 stories. Gas pipes.	<5	5 to 10	>10
Existing tunnels	10 mm / 10 m		

2. DISPLACEMENTS RELATED TO EPB TUNNELLING

In order to reduce the subsidence risk, earth pressure balanced shield machines are a good solution in an urban environment in comparison to other tunnelling methods [Saczynski, T. M. and Pearce, M. and Elioff, A. (2007)].

Settlements are evoked by changes in the stress conditions or changes in pore water pressure [Maidl, B. and Herrenknecht, M. and Maidl, U. and Wehrmeyer, G. (2011)]. With an active support pressure of the face, of the gap between shield and surrounding soil and of the gap behind the tail of the shield, these changes can be reduced to a minimum [Maidl, B. and Herrenknecht, M. and Maidl, U. and Wehrmeyer, G. (2011)]. Nevertheless, settlement or ground subsidence occurs in every tunnel construction process.

In order to characterize the settlement trough evolution in width and depth over a tunnel section, the volume loss factor V_l can be used. V_l describes the volume of the settlement trough related to the theoretical tunnel volume as shown in Figure 1; [Burghignoli, A. and Di Paola, F. and Jamiolkowski, M. and Simonacci, G. (2010)]. As seen in Figure 8, V_l is an instantaneous value, changing with the position of the TBM and the analyzed tunnel section. The final V_l usually ranges from 1 to 2% for tunnels excavated with the conventional method. In the case the tunnel is constructed using an earth pressure balanced shield lower values can be observed, sometimes below 0.5% [Kastner, R. and Emeriault, F. and Dias, D. (2010)].

The factors influencing the shape, the depth and the length of the settlement trough related to EPB tunneling are numerous. Basically, they can be divided into geotechnical, geometrical and operational parameters of the TBM [Boubou, R. and Emeriault, F. and Kastner, R. (2008)].

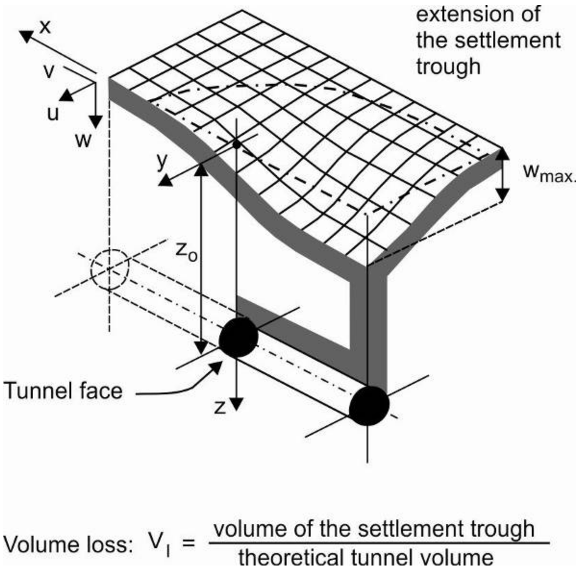

Figure 1 Settlement trough and volume loss factor V_l [Burghignoli, A. and Di Paola, F. and Jamiolkowski, M. and Simonacci, G. (2010)]

2.1 Geotechnical parameters

The boundary conditions for the tunnelling process are given with the geotechnical parameters, i.e. the soil characteristics as for example rigidity, friction angle, cohesion, deformability, permeability and abrasiveness. Based on a good soil investigation, the choice of the tunnelling method and the specification of operational parameters can be done efficiently. Good knowledge of ground parameters and groundwater conditions enables realistic calculations and then the possibility to define requirements and adequate thresholds for the operational parameters of the TBM.

2.2 Geometrical parameters

The geometrical tunnel parameters are essentially the depth of the tunnel, the diameter of the tunnel and the lining geometry, meaning the thickness and shape of the lining and the width of the gaps.

Besides the geometry of the tunnel, the distance and geometry of adjacent buildings and structures have a significant influence on the magnitude of settlement [Mair, R. J., 2005]. This might be for example pile foundations, another tunnel or – like in Barcelona – a protection wall influencing the settlement behaviour.

Also the geometry of the TBM itself influences the development of settlement; especially the conical shape of the shield has to be mentioned in this context [Kastner, R. and Emeriault, F. and Dias, D. (2010)].

2.3 Operational parameters

Numerous operational parameters of tunnel boring machines with earth pressure balanced shields exist, all influencing the reaction of the soil around the TBM. The following 10 TBM parameters were identified as having the greatest influence on the magnitude of surface settlement [Boubou, R. and Emeriault, F. and Kastner, R. (2008)]:

- Face pressure
- Pressure and volume of filling the gaps
- Torque on the cutting wheel
- Total thrust force
- Power excavating 1 m³
- Back filling pressure
- Grouted volume of mortar
- Rate of advancement
- Time for boring and installing 1 ring
- Change in vertical angle of the TBM
- Change in horizontal angle of the TBM

With a numerical study Vanoudenheusden [Vanoudheusden, E. and Petit, G. and Robert, J. and Emeriault, F. and Kastner, R. and Lamballerie, J.-Y. and Reynaud, B. (2006)] identified that essentially the rate of advancement, the torque on the cutting wheel, the face pressure and the change in vertical angle of the TBM could be correlated to surface settlement.

3. CONTSTRUCTION WORKS NEXT TO SENSITIVE HISTORICAL BUILDINGS

Performing construction adjacent to historical building very often presents special difficulties already in the design phase of the new project. The structural elements, especially foundation elements, of ancient buildings are not or not exactly know [Kastner, R. and Emeriault, F. and Dias, D. (2010)]. Drawings very often do not exist or do not give enough details. Former structural calculations cannot be reconstructed any more.

Usually, careful and extensive site investigations are needed to analyse the structure and the foundation of historical buildings.

The possible repercussions on sensitive historical buildings induced by the construction of new objects are not only displacement of the soil that might induce dangerous settlement to the historical building, but also vibrations during the construction process or changes in groundwater conditions during the construction or the serviceability time of the new object.

4. TUNNEL CONSTRUCTION CLOSE TO SENITIVE STRUCTURES

4.1 Tunnel

Currently a tunnel with a length of 5.6 km is being built under the city centre of Barcelona as a part of the new Spanish high speed railway line (AVE) connecting Madrid, Barcelona and the French border.

The tunnel of the high speed railway line passed directly next to the famous church of Sagrada Familia and a building called “Casa Milà”, both belonging to the World Heritage Properties of the UNESCO.

The tunnel has an outer diameter of 11.55 m. The bottom of the tunnel is located in a depth of at most 40 m below the ground surface. The average groundwater table is approx. 19 m above the bottom of the tunnel.

4.2 Soil and groundwater conditions

The location of the project is the comparatively plain area in the City Centre of Barcelona.

Most of the soil layers passed by the tunnel boring machine are tertiary layers (Figure 2). In the first kilometre of the tunnel the TBM passed through the tertiary clay. Then, a section of tertiary silty sands follows. In this section the world heritage properties Sagrada Familia and Casa Milà have been passed.

In the vicinity of Sagrada Familia the layering is given as follows: Artificial filling are reaching thicknesses of up to 2 m. Below the filling quaternary sandy silts in alternating layering with silty sands with a thickness of the entire layer of 4 – 10 m were encountered. Tertiary sand was observed down till the explored depth of 60 m. Tertiary clay layers of various thickness of 0.4 – 2.0 m are intercepted in the tertiary sands.

Because of these dense clayey interceptions various aquifers are underlying the city of Barcelona. The highest aquifer is a free aquifer, the lower ones partly have confined groundwater conditions. In the vicinity of Sagrada Familia, the free groundwater level lies about 16.5 m below the surface.

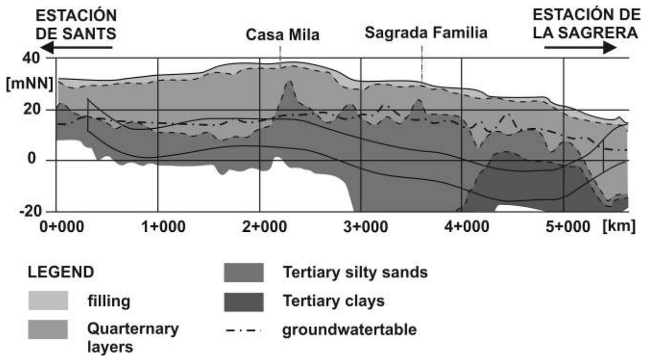

Figure 2 Geotechnical longitudinal section

4.3 Tunnelling method

The tunnel is built with a tunnel boring machine (TBM), using an earth pressure balanced shield (EPB) as shown in Figure 3. The TBM is working and monitored continuously 24 hours a day. With the chosen EPB shield, the soil is conditioned with water and foam injections at the cutter head. The homogenized, excavated earth slurry is used as support medium [Göbl, A. (2010)]. The gap between the TBM shield and the excavated soil is injected with bentonite [Maidl, B. and Herrenknecht, M. and Maidl, U. and Wehrmeyer, G. (2011)]. The gap behind the tail of the shield is permanently grouted with mortar to provide a compensation grouting procedure [Kastner, R. and Emeriault, F. and Dias, D. (2010)].

Figure 3 Face of the TBM

4.4 Tunnel construction close to Sagrada Familia

The basilica of Sagrada Familia is a church still under construction. The construction of this outstanding building began in the year 1882. In 1883 it was re-designed by the architect Antoni Gaudí. He planned a totally new supporting structure and combined the architectural styles of many different eras.

Antoni Gaudí planned a church with a 50 m high main nave with a length of 90 m and at large 18 steeples, from which the highest is planned with a height of 170 m.

The church of Sagrada Familia has a pile foundation. The piles under the main nave are estimated to have a depth of approx. 20 m, but the exact pile length is unknown since most of the original plans have been lost.

Until his death in the year 1926, Gaudí could finish the apse and the so called Nativity façade. The parts of the church built in Gaudí's lifetime belong to the world heritage property of the UNESCO since 1984.

The works on the church of Sagrada Familia have been continued after the death of Gaudí. The end of the construction works is currently planned for 2026.

Until today, the main nave, the Nativity and the Passion façade with altogether 8 steeples are finished. The construction works on the 6 central steeples and on the so called Glory façade have been started.

The AVE tunnel lies in a horizontal distance of only 4 m parallel to the Glory façade, the bottom of the tunnel in a depth of approx. 37 m as shown in Figure 4.

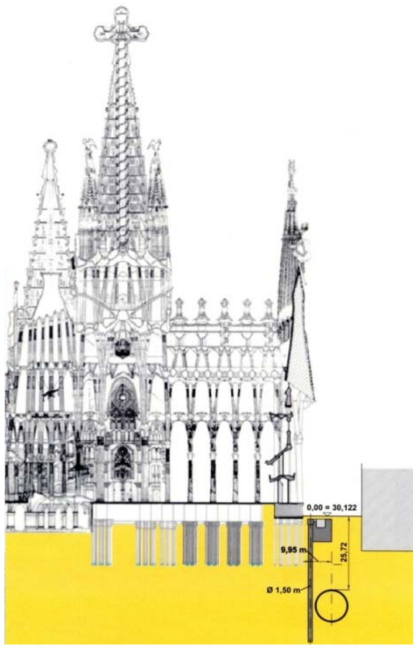

Figure 4 Cross section at Sagrada Familia and AVE tunnel

In order to guarantee the safety of Sagrada Familia and to avoid settlements soil improvements (grouting, soil exchange) were executed and a bored pile wall was constructed between Glory façade of Sagrada Familia and the AVE tunnel. The diameter of the piles is 1.5 m. They have an axial distance of 2 m and a length of approx. 40 m.

4.5 Tunnel construction close to Casa Milà

The AVE tunnel also runs next to another building designed by Antoni Gaudí and belonging to the world heritage property of UNESCO, the "Casa Milà", built from 1905 to 1910 (Figure 5).

The AVE tunnel has a minimal horizontal distance of approx. 4 m to Casa Milà and a depth of approx. 30 m (Figure 6).

In order to fulfill the special requirements in control and construction of the AVE tunnel, between Casa Milà and the AVE tunnel a bored pile wall has been installed. The diameter of the piles is 1.2 m. They are approx. 37 m deep. The drilling works for this redundant safety margin have been complicated due to the form of the balconies (Figure 5).

The settlement due to the construction process of the bored pile wall was about 0.1 cm. The TBM passed in February 2011 and induced additional settlement of less than 0.1 cm.

4.6 Monitoring results

During the construction every task had to be executed under special control and supervision requirements following the observational method according to Eurocode EC 7 [14] in order to ensure a safe construction of the AVE tunnel and to give the maximum possible security for the sensitive building in vicinity.

The monitoring in Barcelona was realised with a dense grid of geodetic and geotechnical measurement devices in the surrounding of the tunnel on one hand and with a permanent monitoring of the most important operational parameters of the TBM on the other hand.

The diagrams in the subsequent sections illustrate the clear correlation in the monitoring results of the aforementioned.

Figure 5 Casa Milà and drilling works

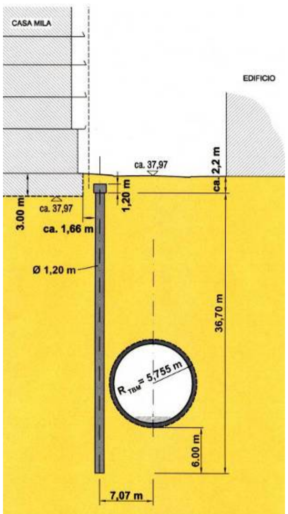

Figure 6 Cross section at Casa Milà

4.6.1 Influence of geotechnical parameters

The final surface settlements above the tunnel axis after the TBM passage for a part of the tunnel are shown in Figure 7.

The depth of the tunnel below groundwater level and the zones of significantly different soil conditions, i.e. tertiary clay in the first part and then a change to tertiary silty sands, are marked in Figure 7 as well.

The measured surface settlement do not exceed 0.5 cm over the whole tunnel length. The volume loss factor V_l is in the range of only 0.1%. The biggest settlement occurred at the start of the TBM between PK 5+800 and PK 4+700 in the tertiary clay. It is possible to explain the decrease of the settlement over the tunnel length by the adaptation of the gained experience of the soil and tunneling conditions during the first part of the tunneling process concerning the definition of adequate thresholds and limits for the TBM operation.

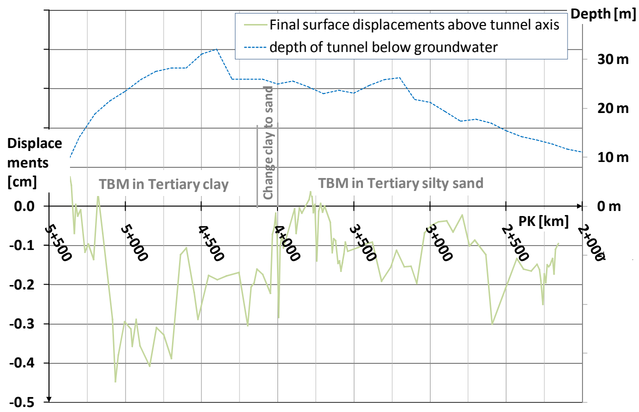

Figure 7 Surface settlements and geotechnical parameters

Small heaving of less than 0.1 cm occurred between PK 4+200 and 4+300, directly after the change from tertiary clay to tertiary silty sands. The settlements in the tertiary clay are up to 0.4 cm. in the tertiary silty sand the settlements are up to 0.3 cm.

An influence of the groundwater height over the bottom of the tunnel on the displacements cannot be noted.

In all reflections about the magnitude of the displacements the measurement accuracy for the surface leveling of approx. 0.1 cm has to be taken into consideration.

4.6.2 Influence of geometrical parameters

In Figure 8, the change of the depth of the tunnel is shown in comparison to the measured surface settlement above the tunnel axis.

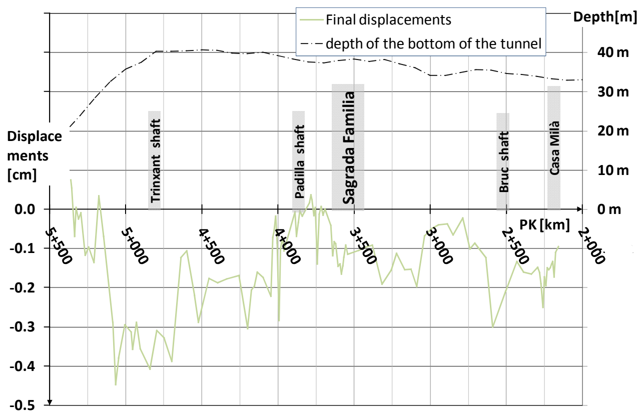

Figure 8 Surface settlements and geometrical parameters

Because the distance of the adjacent buildings is almost the same over the whole tunnel length, just the positions of Sagrada Familia and Casa Milà are marked.

Other significant buildings are the vertical maintenance shafts for planned maintenance stops of the TBM that will be emergency shafts in later operation of the tunnel.

There is no noticeable effect of the depth of the tunnel below the surface, but it is notable that the settlement in vicinity of Sagrada Familia and Casa Milà are quite small in comparison to the other sections. This effect may be caused by an effect of the bored pile wall or an especially careful operation of the TBM.

In vicinity of the maintenance shafts at the crossing of Padilla Street (PK 3+930) and Bruc Street (PK 2+500) bigger settlements than in the neighbored sections occurred. Although the maximum values are only about 0.3 cm an influence of the complex procedure of the TBM for entering and leaving the shafts – including measures for groundwater drawdown inside – can be remarked.

4.6.3 Influence of operational parameters

The operational parameters of the TBM that are expected to be the most important ones, i.e. the performance over construction time, the average advance velocity, the torque on the cutting wheel and the face pressure at the top of the working chamber, in comparison to the surface settlement above the tunnel axis are shown in Figure 9.

A correlation between the comparatively low face pressure and the comparatively high settlements (max. 0.4 cm) in the starting section of the tunnel can be remarked. The used face pressure was smaller according to the lower weight of the vertical cover above the tunnel crown and the soil parameters of the tertiary clay in the first section of the tunnel. The other operational parameters show no significant influence on the measured settlements.

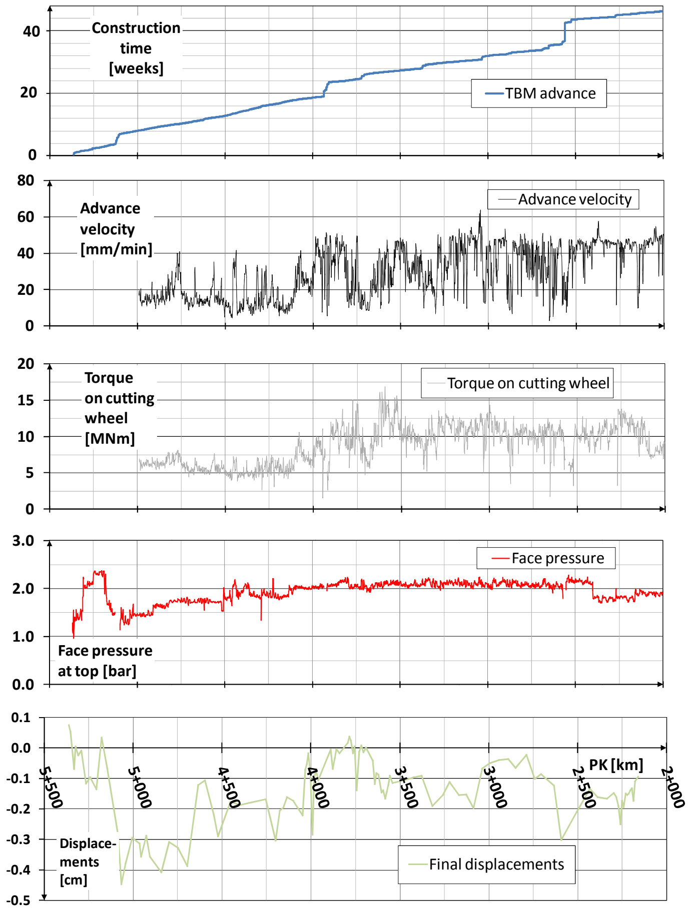

Figure 9 Surface settlements and operational parameters

The three larger steps in the graph at the top of Figure 9 (construction time vs. tunnel length) show the three planned maintenance stops in the shafts. The smaller steps in the section beginning at approx. PK 4+200 show additional maintenance stops of the TBM to change the cutting tools caused by the higher abrasion in the sandy soil. These works were made under hyperbaric conditions.

5. SOIL-STRUCTURE-INTERACTION AT EXISTING UNDERGROUND STRUCTURES

5.1 Project

The city of Frankfurt am Main (Germany) plans to redesign the historic centre. Historic façades and buildings will be reconstructed. To create the necessary space on the surface an high-rise building complex was deconstructed. The complex had on tower with 14 storeys (measuring point 2 in Figure 12), one tower with 11 storeys (measuring point 1 in Figure 12), one tower with 10 storeys (measuring point 3 in Figure 12) and one tower with 6 storey (measuring point 4 in Figure 12). According to the present state of planning the deconstruction was carried out down to the sublevels. The high-rise building and its underground parking overlay 2 tunnels and an underground station of the urban metro system. The loads of the superstructures are directly transferred onto the tunnels and underground station. Figures 10 and 11 give an overview on the primary situation before the deconstruction. The sealing of the structures was made of outside layers of bitumen-based materials. It must be guaranteed that during the deconstruction of the existing high-rise building and the construction of the new buildings the sealing of the underground structures and the sublevels remained intact. For this purpose especially the uplifts due to the deconstruction and the deformations of the underground structures and the sublevels had to be monitored during the execution of the project according to the observational method.

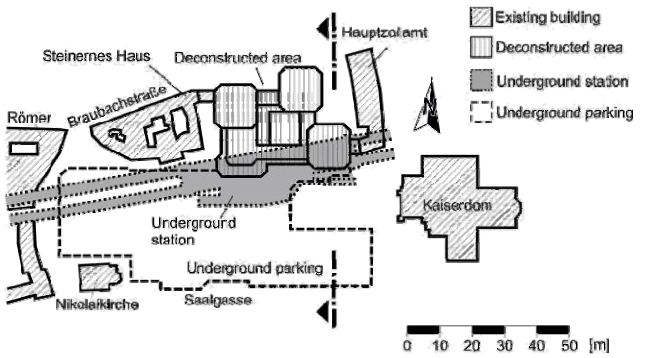

Figure 10 Overview of the project area

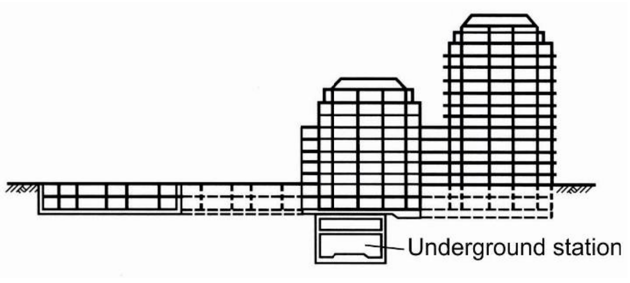

Figure 11 Cross section from Figure 10

5.2 Soil and groundwater conditions

The soil and groundwater conditions are as follows:

- 0 m to 7 m: quarternary sands and gravel
- 7 m to 30 m: Frankfurt Clay
- below 30 m: Frankfurt Limestone
- groundwater level in a depth of 6 m

The tertiary Frankfurt Clay is over consolidated.

The groundwater level is influenced by the river Main which is 180 m far away. In the course of the geotechnical survey two aquifers have been encountered. The top aquifer is located in the no cohesive soil. The lower confined groundwater layer is located in the Frankfurt Clay and in the Frankfurt Limestone.

5.3 Measurement data

According to the classification of the project into the Geotechnical Category 3, that is the Category for very difficult projects in Eurocode EC 7, an extensive geodetic monitoring program with 580 measuring points was installed. 220 measuring points are located around the deconstructed building, 110 are located in the underground parking and in the sublevels of the deconstructed building, 30 are in the underground station and the remaining 220 are located in the tunnels. The existing buildings were deconstructed down to the 2 sublevels. The uplift that occurred due to the unloaded of the soil is shown on selected points (Figures 12 and 13). The selected measuring points 1 to 4 are in the sublevel of the former high-rise building. Measuring point 5 is at the transition of the underground station to the tunnel. At the measuring points 1 to 4 an uplift between 1 cm and 5 cm was detected in the deconstruction time (March to December 2010). The measured uplift of measuring point 5 is less than 0.5 cm. After the deconstruction down to the sublevels in December 2010 the modification of the sublevels began. In that phase the loads only were changed insignificantly.

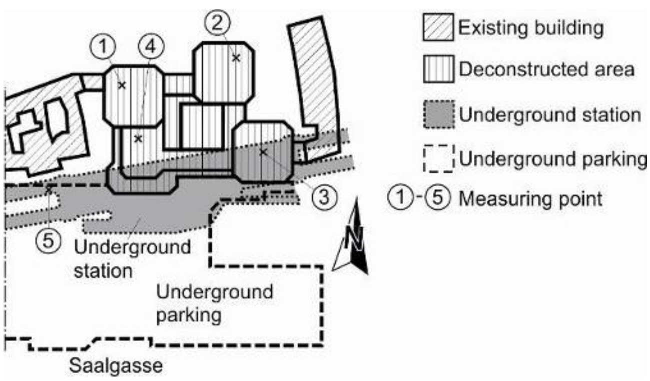

Figure 12 Selected measuring points

The uplift of the whole project area and the neighbourhood in October 2012 is drawn in Figure 14. The uplift due to the reduced stress level of the stress and time related deformation behaviour of the Frankfurt Clay is continuously raising due to the consolidation processes. A maximum uplift of 8.5 cm was measured in the area where the most storeys were deconstructed. The uplifts fade down related to the distance very quickly. So no dangerous deformations of the neighbourhood were measured.

The deconstruction of the different elements of the high-rise building complex was a challenging task. The well planned deconstruction did not lead to any damage of the underground structure of the urban metro system.

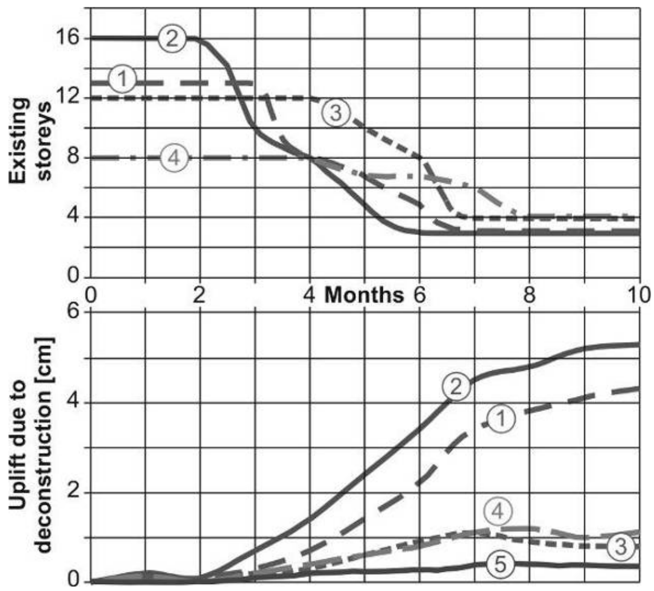

Figure 13 Measurement results of selected measuring points

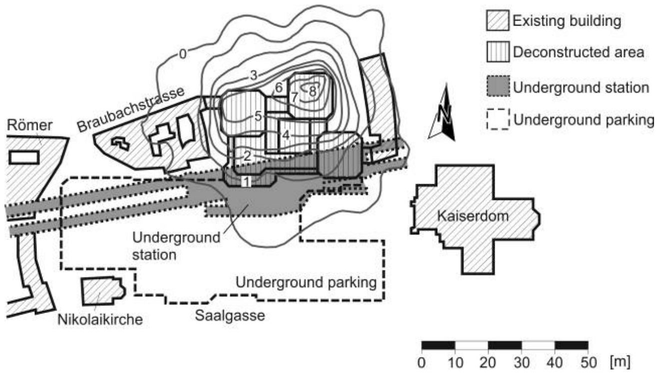

Figure 14 Measured uplift of the whole project area [cm]

6. CONCLUSION

The two examples from Barcelona and Frankfurt show that a careful and well planned and monitored construction process enables inner urban tunnelling projects even in the direct vicinity to sensitive historical buildings. The application of the observational method according to EC 7 with its special requirements in design, construction and monitoring is a tool of quality assurance.

The analysis of the data from the EPB drive in Barcelona show that the observed, very small surface settlements, that do not exceed 0.5 cm, cannot clearly be correlated with some special parameters. Among the geometrical parameters the position of the maintenance shafts seems to have an influence. The observed data shows that the surface settlements can be reduced to a minimum with a careful and highly supervised TBM performance.

The case of the project in Frankfurt demonstrates that during the deconstruction of existing building the soil is unloaded and relaxes due to the reduced stress level. Cohesive soil materials like clay react strongly time dependent. For example the tertiary Frankfurt Clay relaxes time-delayed due to the unloading in the dimension of centimetres.

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