Subway construction in the city of Munich - different ground conditions and different methods

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Abstract: The subway system of Munich is growing year by year. Although the geological and hydrological setting is well known, every tunnel drive in Munich offers an opportunity to learn more about tunnelling in soft rock. In the period 2001/2005 there was a large construction lot (U3 Nord 1) in the northern city area where five different ways of tunnelling in a city were used in different geological, hydrological and topographical settings. The different methods were: cut and cover-methods, NATM in single track tube drives, ground conditioning with horizontal soilcrete umbrella and soilcrete core columns in a three track tube drive with full face excavation, a pipe roof umbrella under an area of skyscrapers and a drive with compressed air up to 0.7 bar. The geological setting is Quaternary gravel with a homogeneous groundwater surface and Tertiary clays, silts and sands with confined water horizons. In this paper the different geological and hydrogeological conditions are presented and the different tunnelling methods are discussed on the basis of the experience gained during the drives. The different methods of dewatering adapted for the tunnelling methods are also discussed.

Résumé: Le système du métro de Munich grandit tous les ans. Bien que les situations géologiques et hydrologiques soient bien connues, chaque autre chantier permet d'apprendre plus sur la construction des tunnels dans les rochers desserrés.

Dans les années 2001 à 2005 le lot de travaux "U3-Nord-1" a été construit dans le nord de Munich. Ici cinq procès différents ont été employés por la construction du tunnel: la méthode "cut and cover"; la méthode NATM pour des tunnels avec une voie; excavation d'un tunnel avec trois voies sous la protection d'un écran soile crete; excavation d'un tunnel au-dessous des tours sous la protection d'un écran de tube et NATM par la pression de l'air jusqu'à 0,7 bar.

Les situations géologiques sont: des graviers quartaires, qui contiennent de l'eau tendue. Des méthodes différentes de drainage vont être discuter.

Keywords: Hydrogeology, overburden, risk assessment, sand, tunnels, water wells.

INTRODUCTION

The construction of the subway system in Munich started in 1965. The first line - U6, running from "Freimann" in the northern part of Munich to "Goetheplatz" in the southwestern part of Munich – was opened in the year 1971. The line U3 to the Olympic area of Munich was opened in the following year. Since 1972 the subway system of Munich has growing year by year. In 2001 started the construction of lot "U3 Nord 1", which is a part of the 4.4 km extension of line U3 towards Moosach in the west of Munich. The construction period of lot "U3 Nord 1", which had a total length of about 2.2 km, ended in 2005.

Five different methods of tunnelling were used in this lot because of different geological, hydrological and topographical settings. Figure 1 shows the different methods. Figure 2 shows the geological and hydrological settings of the different sections.

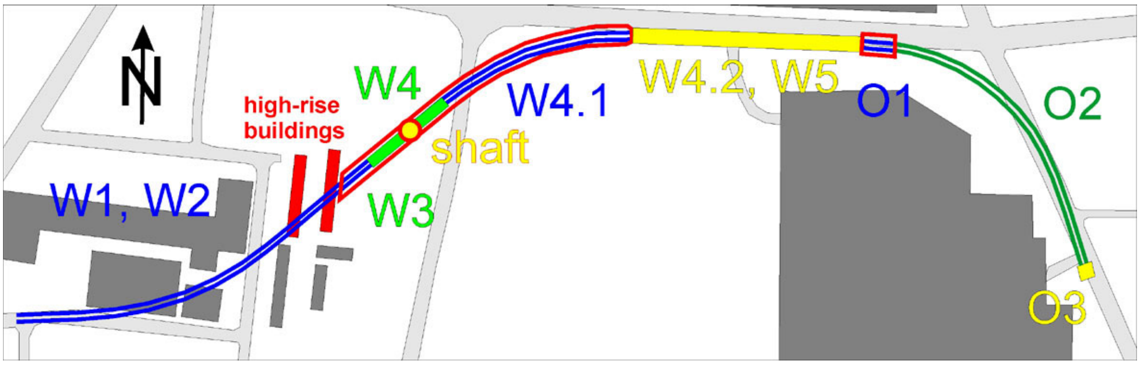

Figure 1. Sketch of lot "U3 Nord 1" showing the different sections.

The station "Olympiapark Nord" (section W4.2, W5; l = 360 m) was built by the cut and cover-method with treated walling and concrete top. The section O1 consists of two single-track tubes (each 42 m²) with a length of 50 m in

NATM within a trough structure of bored piles. Section O2 (l =400 m) consists of two single-track tubes (each 42 m^2) in NATM with support of compressed air with pressure of up to 0,7 bar. The section was connected to the existing station “Olympiazentrum” through a trough structure of bored piles (O3, l = 70 m). The 250 m long section W4.1 to the west of the station “Olympiapark Nord” consists of two single-track tubes (each 42 m^2) in NATM within a trough structure of thin diaphragm walls. In section W4/W3 (l = 145 m) a triple-track tunnel with a cross-sectional area of 170-200 m^2 was build in NATM within a trough structure of thin diaphragm walls. In the middle of this section the 25 m deep shaft (diameter of 25 m) is located from where the driving W3 and W4 started. Section W2 also consists of two single-track tunnels in NATM (l=95m). One part of this section is located within a trough structure of thin diaphragm walls. The other part of this section crosses beneath, at a safety depth, a high-rise building with up to 14 floors. The two single-track tunnels of section W1 (l = 510 m) were built with NATM. The western sections W3/W4 and W2 were difficult referring to risk management during the period of construction. Therefore, they will be a main topic of this paper.

GEOLOGICAL SETTING

The subsurface of Munich is divided into two different geological layers (Gebhardt 1968). The upper one is composed of Pleistocene gravel deposits resulting from different ice ages. The lower one consists of clay, silt, marls and sand of Miocene and Pliocene age. An unconformity is the boundary between the two strata.

The Quaternary gravel deposits have varying thickness of a few metres up to some 20-30 m. They build up the so called “Schiefe Ebene” of Munich, which is an outwash plain to the north of the Alps resulting from the Würm (Weichselian) and Riss (Saale) ice ages. So, you can find different gravel deposits with varying amounts of components from different parts of the Alps as well as different sand and silt deposits. The deposits are well bedded and of medium to high grade of compactness. In the project area the gravel deposits have a thickness of about 10-15 m.

The Tertiary sediments consist of stiff to firm clay, silt and marls as well as sand deposits with varying amounts of mica. Because of the mica-bearing deposits, the Tertiary deposits are locally called “Flinz”. The Tertiary deposits have a thickness of several hundred metres. The sequence of the Tertiary deposits in the project area is as follows: 15-25 m thick interbedded strata of clay, silt and marls with some lenses and layers of sand; 10-15 m thick stratum of sand; >20 m thick interbedded strata of clay, silt and marls with some lenses and layers of sand.

In the subsurface of Munich several levels of groundwater can be divided. The upper one is that within the Quaternary gravel deposits. This aquifer has a high grade hydrological conductivity horizontally ($k=5x10^{-3}$ m/s) and a medium grade hydrological conductivity vertically ($k=5x10^{-4}$ m/s). The distance of the water level from the surface is about a few metres in the northern part of Munich and about 18 m in the south-western part of the city. The deeper groundwater is contained in the Tertiary sand lenses and sand layers. This is mostly confined groundwater with levels of pressure equal or similar to that level of the Quaternary groundwater. The hydrological conductivity of the sands is about $k=5x10^{-4}$ -$5x10^{-5}$ m/s). Figure 2 shows the geological and hydrological setting in the project area.

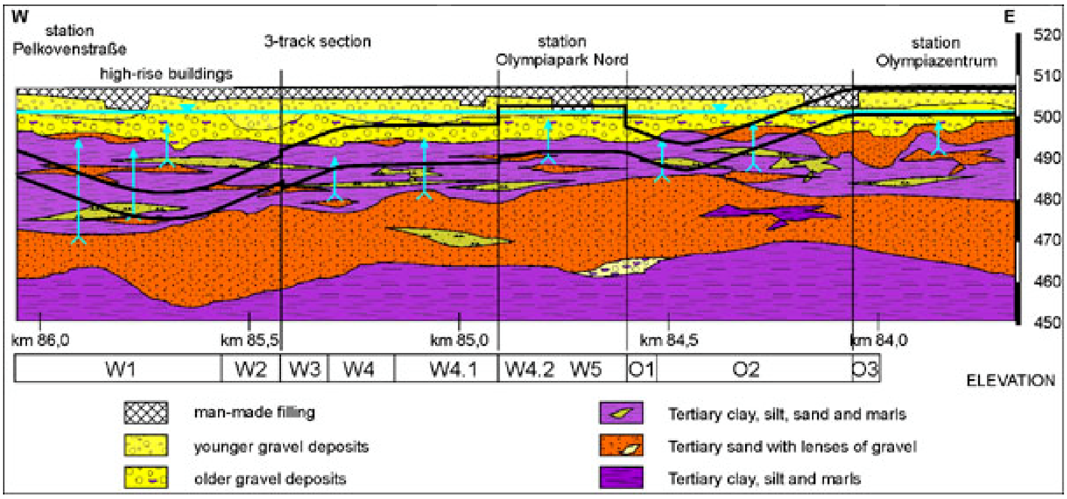

Figure 2. Section of the geological and hydro geological situation of lot “U3 Nord 1”.

CONSTRUCTION OF THE STATION, THE SECTION O2 AND THE SECTION W4.1

Station building W4.2/W5

The station “Olympiapark Nord“ was built using the cut and cover method using treated diaphragm walls and concrete top. The slots of the diaphragm wall had a thickness of 1 m. The excavated lamellas had a breadth of 2.6-6.35 m and were 15-18 m deep according to the elevation of the building and to the geological setting. The lamellas of the diaphragm wall build up a sealed trough structure within the Quaternary gravel deposits. This trough structure is the station building itself. During excavation the slots were supported by a slurry containing bentonite. The gravel was excavated by clamshell. The Tertiary sediments were excavated by cutter without any problem. However, problems occurred during excavation of the gravel deposits. Here, the slot collapsed sometimes, when unexpected man-made cavities – such as old sewers - were encountered during excavation and the slurry flushed out of the slot into the cavities. Collapses as a result of geological phenomena – such as layers of well sorted gravel of one single grain size - did not happen.

The dewatering system was started before excavation. It consisted of wells within the trough structure for dewatering the gravel body within the building and wells out off the trough structure for dewatering and pressure reduction of the Tertiary groundwater.

Because of dislocated water bars gaps occurred between several lamellas during excavation. So the building was not watertight. Therefore, excavation was stopped. After an investigation of the problem it was decided to seal all the contact zones between all lamellas on the southern side of the building by jetted soilcrete columns before excavation. The southern side of the building is located in the upstream flow of Quaternary groundwater.

Section O2

In section O2 NATM-drives supported by compressed air with pressure level up to 0.7 bar were performed in the Quaternary deposits and in the Tertiary deposits. Figure 3 gives an idea of the geological and hydrological setting as well as of the support measures.

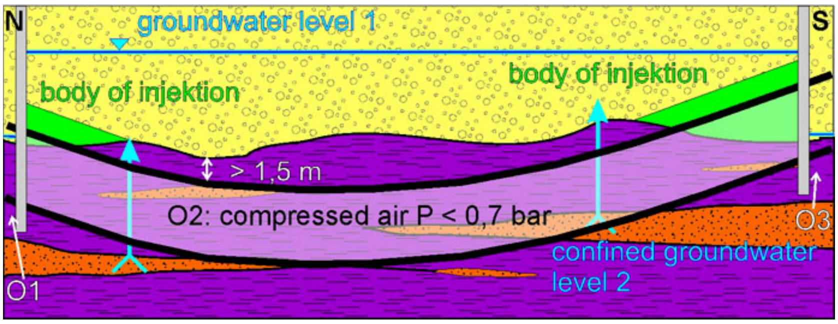

Figure 3. Section with the geological and hydrological situation of driving O2 with sealing injections.

The Quaternary deposits are of high conductivity concerning water and air. Therefore, the support by compressed air was not possible without sealing the gravel deposits by injection or jetted soilcrete bodies. The conductivity of the gravel deposits had to be reduced to $k=5x10^{-5}$ m/s. In this section the air pressure had to be higher than the water pressure at the base of the Quaternary groundwater horizon. The pressure of the compressed air had also to avoid hydrological induced collapses of the invert. To reduce the required air pressure the pressure of the confined water within the Tertiary sand had to be reduced by wells.

The Tertiary deposits are of low conductivity concerning water and air. Therefore, the support by compressed air was possible without sealing the gravel deposits as long as the tight roof between the tunnel and the Quaternary groundwater was larger than 1.5 m. It is well known from other case studies that the Tertiary roof of Tertiary sediments can be weakened by different phenomena, which are as follows:

- jointed clays and marls, which are unstable,
- slickenside surfaces within the stiff to firm clays and marls,
- locally developed erosion channels filled with Quaternary gravel,
- vertical orientated rifts, which are filled with sand.

For safety reason the air pressure had also to be higher than the water pressure at the base of the Quaternary groundwater horizon. The pressure of the compressed air had also to avoid hydrological induced collapses of the invert. To reduce the required air pressure the pressure of the confined water within the Tertiary sand had to be reduced by wells. The driving was performed without major problems.

Section W4.1

The two single-track tunnels of section W4.1 crossed the Quaternary gravel deposits with its groundwater and also Tertiary sediments in the invert. Because the Quaternary deposits are of high hydrological conductivity a sump drainage is efficient if the water level has to be reduced for 1-2 m. If it is necessary to reduce the water level more than 2 m, a tight trough structure has to be built. Within this trough structure the Quaternary water level can be reduced efficiently by wells. Figure 4 shows the geological and the hydrological setting as well as the measure of dewatering.

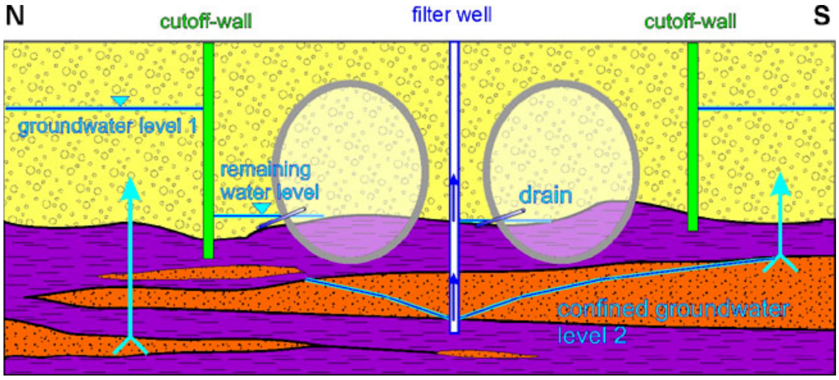

Figure 4. Single-track tunnels of section W4.1 with cutoff-walls and arrangement of wells.

In section W4.2 the trough structure consisted of thin diaphragm walls (slurry of bentonite-grout). The wells within the trough structure had to dewater the Quaternary groundwater as far as possible. They also had to dewater the Tertiary sand lenses or to reduce the pressure of the confined water within the sand lenses to avoid hydrological induced collapses of the invert. Though the overburden is less than 5 m – as shown in Figure 4 – it was not possible to build this section by the cut and cover method because the tunnel line crossed a main road with a high volume of traffic. The NATM driving of the two tubes with a cross-sectional area of 42 m² was supported ahead by steel plates of 4 m length, which were driven in the gravel in shape of an umbrella.

All the trough structures in the lot have a total length of about 900 m. So, they dam up the flow of the groundwater. To avoid this, several siphons are situated along the building to manage the communication of groundwater flows.

TRIPLE-TRACK TUNNEL W3 AND W4

Starting at the shaft the elevation of the alignment decreases with 4 % towards west and rises with 10 % toward east. Therefore, the overburden is in the eastern part of the section about 6 m and in the western part of the section about 16 m. The triple-track tunnel crosses the Quaternary gravel deposits as well as the Tertiary deposits (see Figure 1). This tunnel was also located within a trough structure, which consisted of thin diaphragm walls (slurry of bentonite-grout) within the Quaternary gravel deposits. The distance between the tunnel tube and the cut-off walls was about 6 m. The wells within the trough structure had to dewater the Quaternary groundwater as far as possible. They also had to dewater the Tertiary sand lenses or to reduce the pressure of the confined water within the sand lenses to avoid hydrological induced collapses of the invert (similar to Figure 4).

The tunnel was performed with separate top heading and separate bench/invert in NATM. As support ahead the face an umbrella consisting of jetted soilcrete columns (l = 15 m) was used. In addition, the tunnel faces were supported by 15 m long jetted soilcrete columns, whereas in the Quaternary sediments more columns were necessary than in the Tertiary sediments.

Because of the large cross-sectional area of 170-200 m² this driving had to deal with four hazard scenarios, which are displayed in Figure 5. These hazard scenarios were:

- leakage of the cutoff-wall / diaphragm wall – this mostly affects the top heading,
- collapse of the face in the gravel deposits – this mostly affects the top heading,
- subsidence because of soaked and weakened foundation of the top heading,
- undetected layers of sand which are hydrological connected to the Quaternary groundwater -– this mostly affects the driving of bench and invert.

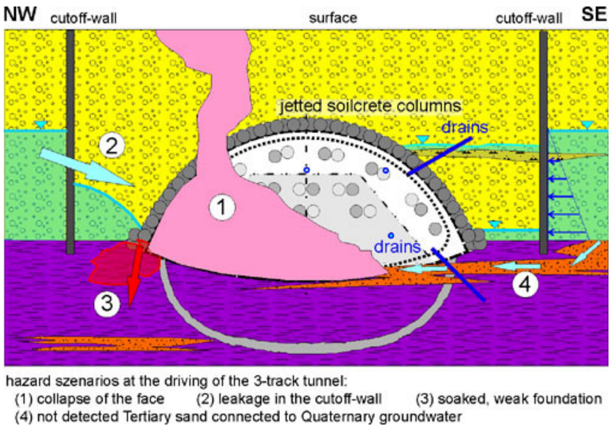

Figure 5. Hazard scenarios at the heading of the 3-track tunnel

The hazard of a leakage in the diaphragm wall was very probable. If the diaphragm wall was constructed in the right way, such leakages were not probable. However, if large movements and transport of sediments occurred within the gravel deposits – especially if you think of jetting soilcrete columns – the risk of a leakage is evident. Indeed, such leakages occurred during jetting the soilcrete columns in W4. During jetting the first umbrellas too much soil flushed out of the drillings so that the loss of material in the subsurface lead to subsidence at the surface. Thereby the diaphragm wall was not damaged. The damage to the diaphragm wall occurred as a result of positive displacement. The positive displacement of up to 300 mm at the surface happened because the pressure of the jet grouting was too high within the soil so that layers of soft silt within the gravel deposits were forced open while grout shot in to the fissure and built up extensive layers of cement of 50-150 mm in thickness. The problem of high pressure within the soil could be solved by additional drillings, which could reduce the pressure of the grout. These pipes were drilled from the surface in the area of the future soilcrete columns. This system worked very well and helped to improve the shape of the soilcrete columns. The hazard scenario of leakage and the incident were controlled by detailed exploration, additional drilling of wells, additional drains drilled from the tunnel face, intensive observation of the groundwater levels and tracer tests.

The risk that the hazard scenario of a collapse of the face could happen was minimised by conditioning the ground ahead the tunnel with a large number of soilcrete columns and careful excavation of the face step by step in small areas. The risk of the hazard scenario of subsidence as a result of soaked and weakened foundation of the top heading was minimised by intensive dewatering.

During the driving of the bench and the invert a detailed additional exploration of the ground was done to detect layers of sand which were hydrological connected to the Quaternary groundwater. To control the groundwater situation additional observation wells were drilled. A large number of additional drains charged with vacuum were completed from the invert of the top heading. These and other drains had to dewater the lenses and layers of sand in the area of the bench and the invert. The bench and invert were excavated carefully step by step in small areas and supported immediately. In this way no problems occurred during excavation. Figure 6 shows all additional measures of ground exploration and control of ground water in the east part from the shaft.

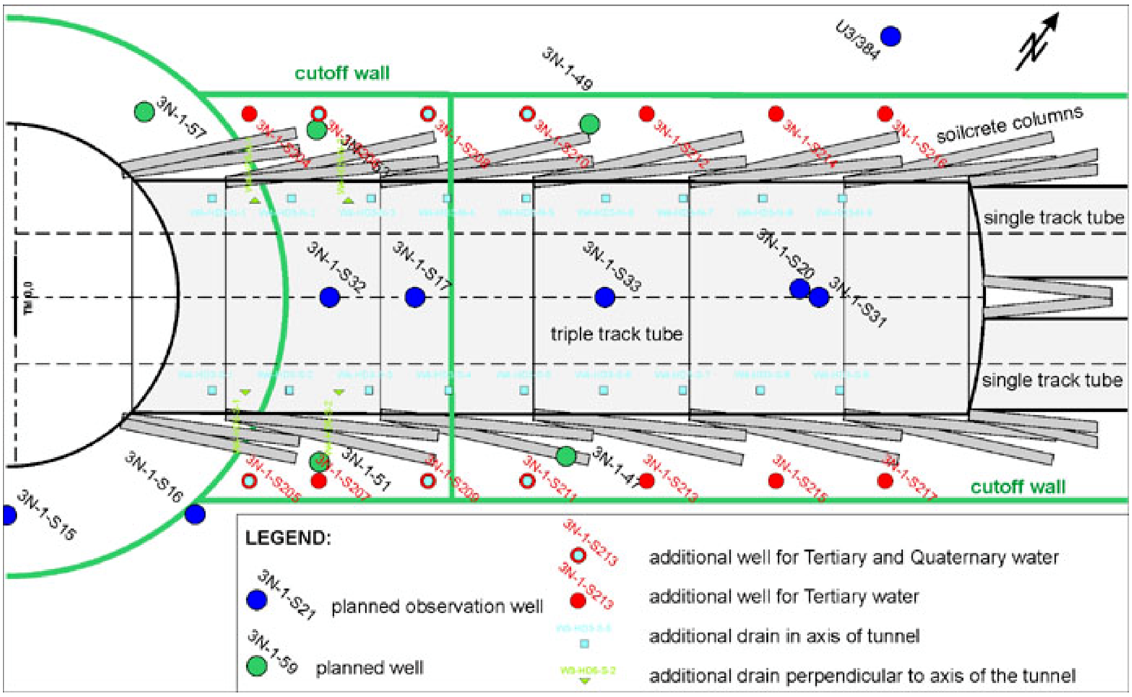

Figure 6. Measures of ground exploration and control of groundwater in the east part from the shaft (W4).

W2 – TUNNELLING BENEATH A HIGH RISE BUILDUNG

The difficulty in crossing beneath the high rise building was induced by the groundwater situation. As shown in Figure 7 the Quaternary groundwater level was located about 7 m above the Tertiary sediments, which is about 15 m above the crown of the tunnel.

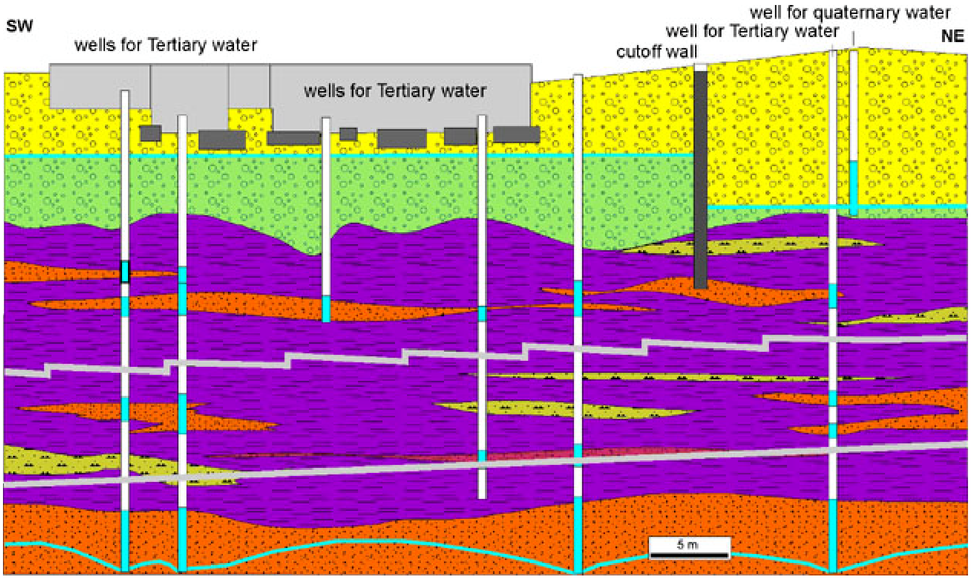

Figure 7. Geological setting and heading with steel tube umbrella under the high-rise building.

The major hazard scenario was that of Quaternary gravel breaking into the tunnel. This could happen if unexpected or unexplored layers of Tertiary sand, which were connected to the Quaternary groundwater, were encountered in the face. Beneath the high rise-building even a small loss of gravel would lead to a large damage of the foundation of the building. Another reason for such an incident could be old bore holes, which were not sealed in the right way.

To reduce the settlement beneath the high rise building NATM with additional measures was chosen as the method of driving. The additional measures were: intensive additional geological and hydrological exploration during the construction period, drainage and additional support of the tunnel. The additional support was a steel tube umbrella as support ahead the tunnel. The length of the tubes was 12 m whereby the overlap was 4 m. The tubes were drilled with air flush because water flush would have weakened the Tertiary sediments ahead the tunnel drive.

The detailed additional exploration started during the regular boring campaign for wells and observation wells. The additional exploration became necessary because of some results of the regular boring campaign. One intention of the additional exploration was to identify deep erosion channels within the surface of the clayey Tertiary sediments. Figure 8 shows a map of the surface of the clayey Tertiary sediments as a result of the different exploration campaigns. The other intention of the exploration was to detect layers of sand nearby the tunnel and layers of sand, which were connected to the Quaternary groundwater. These layers of sand had to be dewatered or the pressure of the confined groundwater within had to be reduced. These intentions were reached by a large number of exploration drillings and wells.

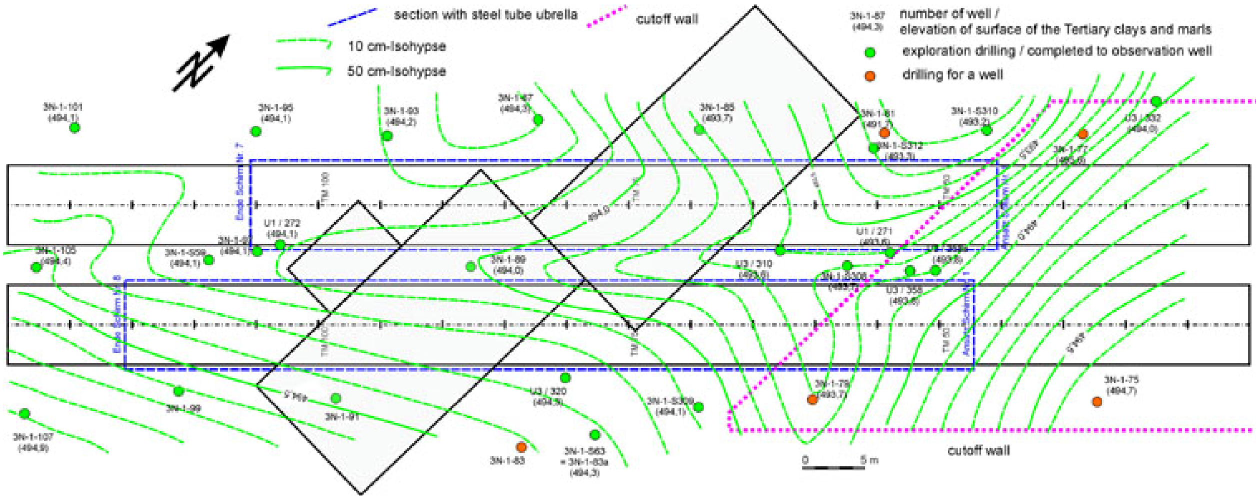

Figure 8. Measures of ground exploration and control of ground water in the area of the high-rise building

In the area of the high rise building it was not possible to perform enough exploration drillings from the surface so that exploration and drainage drills were performed from the face of the driving. Thereby, it was not allowed to drill into to the Quaternary gravel deposits, because of the high risk of a hydrologically induced collapse.

The measured settlement of the high rise building induced by the tunnel drive was in maximum 30 mm within a widespread depression of settlement. So the driving was successful.

FINAL REMARKS

The driving of the triple track tube in the Quaternary gravel deposits and the crossing beneath the high rise building within the Tertiary clays containing water filled layers of sand were performed with the required level of safety and with the expected level of efficiency. In both cases the hazard scenario "groundwater" was eliminated in the same way: exceptionally detailed exploration during the period of construction on the one hand and a strictly controlled effective drainage on the other hand. The system used in other major tunnel projects for risk management (Kovari & Bosshard, 2003) containing hazard scenarios, risk and safety plans as well as the strict site supervision, proved itself during the construction period of lot "U3 Nord 1".

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