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Tunnels of Metro Vienna

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Abstract

Vienna has a long tradition in Metro Construction dated back to the end of the 19th century, when the „Vienna Stadtbahn“ was established, well known for the design of architect Otto Wagner. At the end of the last century the urban traffic increased so heavily that tram and bus couldn’t solve anymore the problems of public traffic needs. In 1970 the first working lot “Karlsplatz” situated in the centre of the city was opened, followed by different working fields along the Metro Line U 1. The tunnels were established by shield machines of that time supported by compressed air and soil grouting to tight up the water bearing sediments of the ground of Vienna. In the following years the Metro Lines U 4 and U 6 where designed to renew the old public system of the Stadtbahn upgrading the stations and running tunnels equipped with new electric traction and operating services. In 1984 the Metro Line 3 the second transversal line was started adopting NATM for urban area, combined with dewatering systems with groundwater wells outside the tunnels and deep excavation between cut and cover walls. Also compressed air and soil grouting was used for tunnelling under densely populated residential area and nearby architectural well known buildings like St. Stefan Cathedral respectively (**1., 2., 3. 11.**).

In the last ten years the metro net was enlarged with extensions of all lines especially of line 1 and 3. During this decade also the underpass tram Line 2 as a halve circle line beneath the “Lastenstraße” parallel to the Vienna Ringstraße was upgraded to the Metro Line 2 starting at the well known Musikverein palace running to the Vienna main stadium. This is situated in the park of Prater where the soccer championship of 2008 took place. The Metro extensions opened challenges for up-to-date soil construction techniques with deep foundation engineering like soil freezing, halve and full crown support by horizontal jet grouting rings, well dewatering for large fields down to ten and fifteen metres limited by tight walls from other Metro Lines interrupting the ground water flow during working period (**10., 11.**).

1. INTRODUCTION

The centre of Vienna has a long tradition of traffic jam. Trams and carts driven by horses in the last decades of the 19th century overloaded the main streets but at that time tunnelling under the water table was too risky and too costly. The government of Vienna at those days decided to follow the trend of London City in establishing steam driven circle lines at the Vienna “Gürtel” avenue and with a connection line between the main railways around the outer districts fulfilling commercial and military needs for transport of fright and troops. The demands of the daily passengers from outside to the central districts and back were more or less neglected in offering railway stations in art deco style by the prominent architect Otto Wagner leaving them alone with later on electric tram in between over crowed roads and lanes (figure 1).

The tunnel engineering design was concentrated on open galleries, for instances along the “Donaukanal”, an old flood regulated side river of the Danube and on open excavations cutting the Gürtel avenue with bridge underpasses at every crossing street. Due to the steam and smoke all of the used cast-iron beams were corroded and the mortar of the stone vaults was destroyed in the following decades. Figure 2 gives an idea of the engineering for that inner and outer city tunnel railway. Sixty years later after two world wars and reconstruction the moderately bombed city of Vienna, traffic jam occurred again causes by private cars. The inner city railway transformed with electrical traction and modern street trams were not able to pick up all public traffic any more. Experiments in the sixties of the 20th century with underpass tram on neuralgic points of the main road net helped only temporary. At the end of the sixties of the last century Vienna City government was forced to settle the design of a Metro Net with 3 or more underground lines connecting the existing Stadtbahn, the state owned main railway stations and the stops of the inner city suburb railways called Vienna Schnellbahn.

Due to the geology the ground of the city area consists mainly of sand and gravels coming from the Pleistozänen and Holozänen period covering the huge sediments of Miozänen silts, clays and fine sands. Both groups of sediments are water bearing with different pressure levels linked with each other but divided with water tight horizons. The dewatering of these aquifers was and will be the main problem for tunnelling construction either by NATM or shield (**4.**).

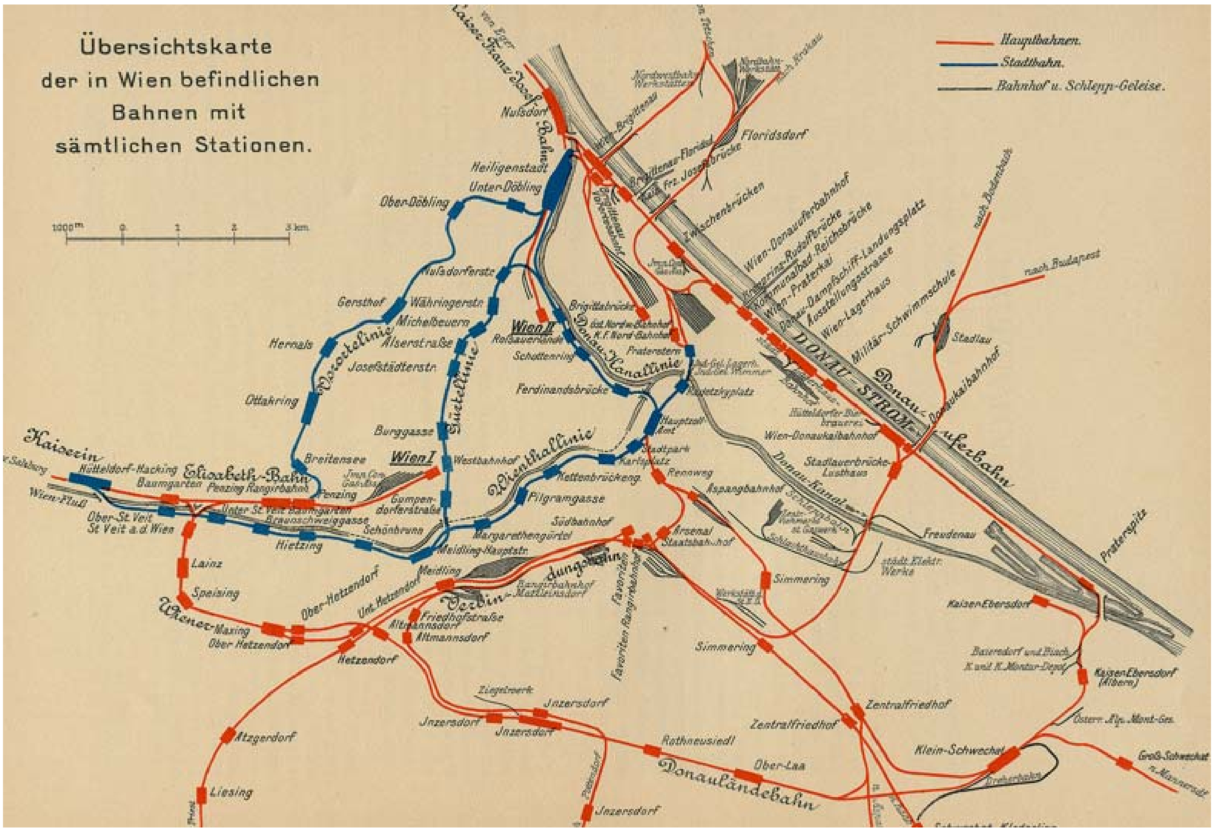

Figure 1. State owned Railway net in red colour, city railway with blue lines at the end of the 19th century

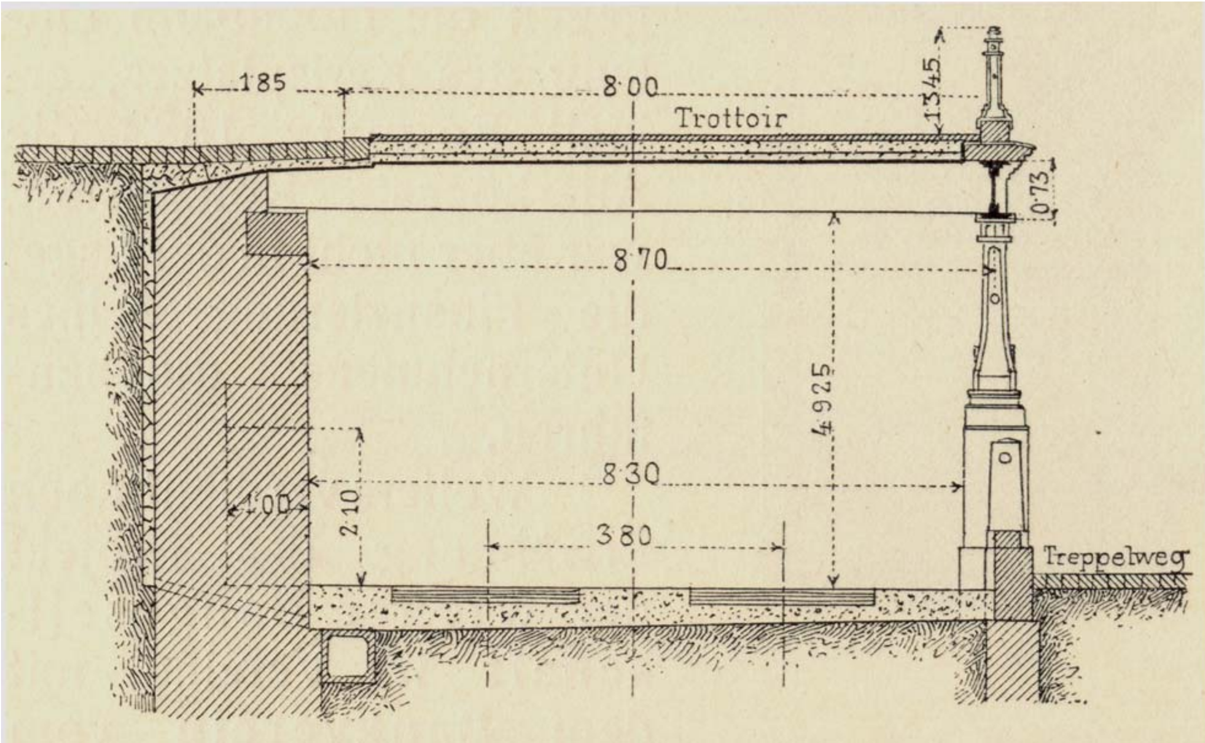

Figure 2. Details of the gallery of the city railway line at Donaukanal Quai.

Figure 3 illustrates the 3 construction periods between 1969 and 2010 already finished. A 4th extension program is in preparation and the lines will be design and realized in the coming ten years.

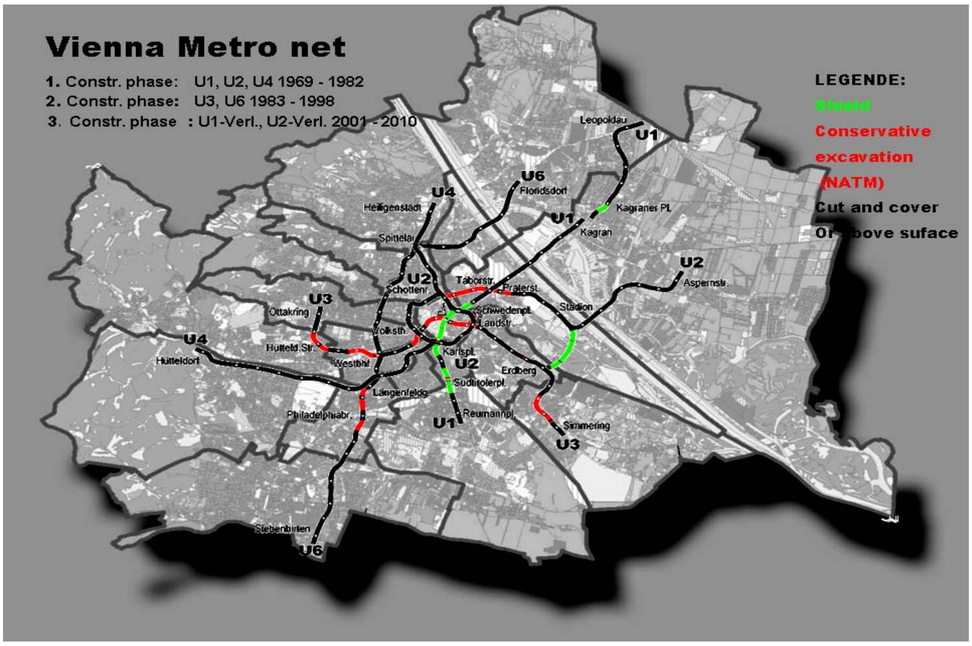

Figure 3. the existing Metro net with 3 construction phases for the Lines U1, U3, U4 and U6.

Before you start with a Metro System you have to collect all existing infrastructure, as sewers, pipes for gas & water, cables of all infrastructure suppliers. The Metro Lines have to connect the

residential areas of the working population with their working places. You have to decide the possible emissions of noise and durst from Metro construction and operation of the designed rolling stock. Due to these influences combined with the necessity of need of new infrastructure the design of the alignment for tunnelling or above surface is to decide. An example for of coarse expensive shield tunnelling gives the Metro Line 1 beneath Kärnter Straße in the inner city of Vienna.
Figure 4 and 5 show the overwhelming change from traffic overloaded Main Street "Kärnter Straße" to pedestrian precinct after finishing the running tunnels. The result were big steps into better quality of live for recreation before and after shopping, paying back the enormous costs of the chosen tunnelling construction system.

Figure 4. Kärntner Straße in the 60th of the 20th century

Figure 5. Kärntner Straße now

2. 1st CONSTRUCTION PHASE

In the years of 1969 to 1982 there was an enthusiasm in the population of Vienna to watch and to visit the construction fields of the Metro. Only few lawyers realized the possibility to get more financial compensation by raising an objection against metro construction. The older the buildings above the designed tunnels the more precise the hearings and the evidence of the main construction and the chimneys were necessary. The figures 6 and 7 will give an impression of the inventory of building defects outside and in the foundation construction.

Figure 6. observation of destructions outside

Figure 7. rotten wooden piles in foundation

Start of shield tunnelling for running tunnels and station was at Kalsplatz with Bade shield in open mode under compressed air. The tunnels were shaped with cast iron segment rings with lead in the joints. The shield for the central station “Stephansplatz” for instances had two platforms to excavate the stiff clay and sandy silt (figure 8) by hand-mining. Soil mechanic research of the material properties was done at the excavation face before starting the shield machine compared with the results of laboratory tests (figure 9).

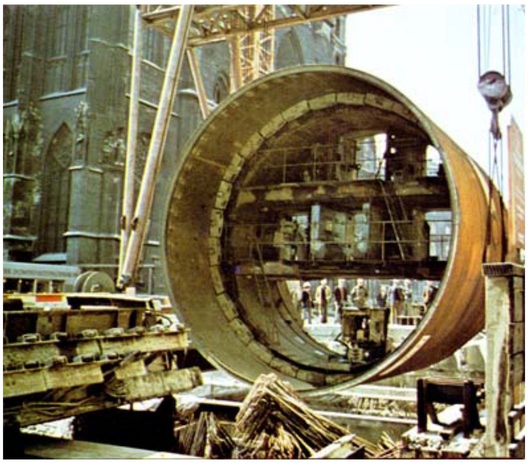

Figure 8. Open shield with two digging-platforms

Figure 9. soil mech. research in clay & silt

Some running tunnels were too short to be excavated by shield. In these cases the first time in Vienna NATM was tested successfully similar to Frankfurt and other German cities, combined with soil grouting in the sandy gravels of the alluvium from the River Danube (**3**.). At that time chemical grouting was used based on cement-bentonit, sodium silicate and ultra fine-cement in sandy silt and gravel (figure 10).

Figure 10. Chemical grouting in sandy gravels

Figure 11. NATM excavation in silt and clay

NATM in modification was the only way of successful tunnelling passing beneath the wooden foundation of the bed of River Wien, used as part of an open sewerage system at the end of the 19th century (figure 11). Still now wood is a serious handicap for modern tunnelling machines.

3. 2nd CONSTRUCTION PHASE

2nd construction phase started in 1983 with the opening of the workings lots on Line 3, crossing the central part of Vienna rectangular to Line 1. Requirements were given to open the pavement of streets and squares as little as possible, especially in the inner districts of the city. NATM was adopted for city area with the task to minimize settlements, roar and dust for local residents and tourists. The environmental tunnelling concept included to avoid any chemical grouting liquids, despite of cement-bentonite and in some cases sodium silicate with soft hardeners. To tighten the open excavation compressed air was necessary again. The former grouting fields on the pavements were reduced to shot Crete shaped shafts from where some thousand meters inclined borings were drilled up to 40 m length to grout gravel and sand horizons under flat foundations and to tighten the groundwater ingress as good as possible. The Metro stations constructed under city main points and Metro line crossings consisted of pile or diagram-wall shafts by cut & cover method for stair houses, lifts, elevators and infrastructure supply. The station tunnels and the running tunnels were excavated due to NATM but equipped with additional steel bars and ribs to prevent relaxation of soil in front of excavation followed by settlements on the surface (figure 12). Geotechnical measurements were establish consequently as there are pressure cells, extensometers, sliding micrometers (figure 13), convergence bolts in the shot Crete etc., installed before or directly after excavation.

Figure 12. NATM under heavy overburden

Figure 13. sliding micrometer

Due to the pressure of different groundwater levels most of the excavation has to happen under compressed air up to 1,50 bar to defend hydraulic uplift, suffusion or fine sand erosion. Special finite element calculations were created based on the results of the geotechnical measurements. With a number of nearly 400 measuring results a constitutive law related to the well known cam clay model was developed to recalculate numerically the deformations of the tunnelling under heavy overburden and under historical buildings. This model could solve the plastic behaviour of the Viennese clay and silt satisfactory showing a small extension cone due to cohesion. Calculation and reality were good comparable as demonstrated in the figures 14 and 15 (**7.,9.**).

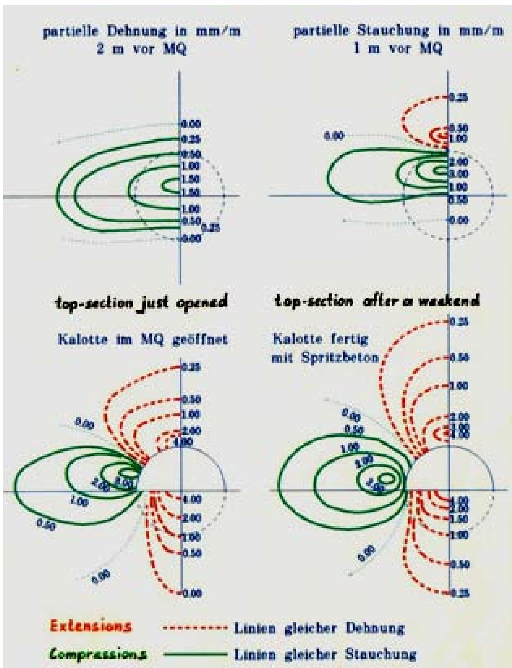

Figure 14. differential extensions and compressions

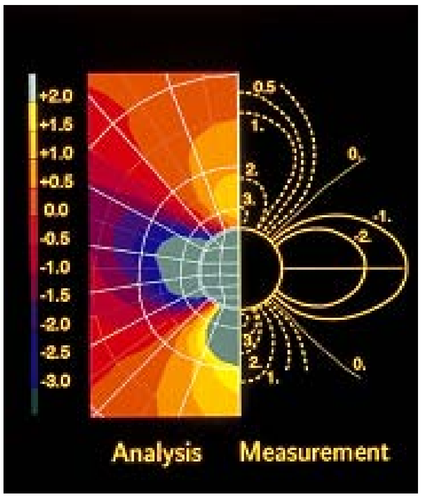

Figure 15. comparison of calculation at excavation steps before of and after tunnel face opening and measurement

These intensively worked out geotechnical measurements opened a much better understanding of the change of earth pressure from vault distribution in front of the tunnel excavation to a three-dimensional ring bearing ground. In figure 14 the differential vertical deformation sequences in mm/m of measuring cross-section with two and one meter in front of the face opening will find compression of soil around the coming tunnel, removed by extension at first in the top section. When the top section is opened fully the extension develops intensively both in top and in bottom at the same time. When the tunnel is opened completely you may realize in figure 15 the compressions on both side walls in the tunnel lining of the shot crete and big extensions beneath the tunnel, similar to the wide sprayed extension above the crown. The amount of vertical partially deformation was fond in the range of 3 mm/m vertical compression up to 2 mm/m vertical extension. These orders of magnitude must be calibrated to tunnel diameter of about 6 m and the semi hard stiffness of the researched silts & clay of Vienna (**4., 9., 10.**).

For opening of large excavations and in case of loose soils stabilizing canopies were formed to support the crown of the top section. These canopies consisted either of rings of drilled steel tubes for low pressure soil grouting with cement suspension or with jet-grouting columns forming horse shoe shaped vaults. The grouting (tube-a-manchette) and jet-grouting technology were a real help in sandy gravel and in loess to reduce soil extension but sometimes the grout was found in the basements of the buildings above due to fissures opened by grouting pressure.

Further more jet-grouting columns were used at the tunnel face in horizontal direction to stabilize the opened ground against sliding and horizontal extension before shot Crete was able to close the space. This cheap investigation in conventional NATM tunnelling was able to keep settlements in the limits of 10mm to 30 mm for tunnel faces up to 150 m2 area in cases of few meters overburden (figure 16 and 17).

Figure 16. jet-grouting canopy for large excavations

Figure 17. face stabilization by horizontal jet-grouting columns

The Metro tunnels at that time got normally an outer lining of shot Crete, enabling the bearing of earth- and groundwater pressure during construction, followed by an inner lining of reinforced concrete shell elements with 8 m to 12 m length able to bear all loads and additionally to guarantee the an absolutely watertight tunnel surface combined with the task stopping the emissions of vibrations by the rolling stock to buildings above.

In 1998 the Metro Line 3 was opened from the north-western district Ottakring to the south-eastern district Simmering over a distance of nearly 20 km with a travelling time of less than 35 minutes, running all 5 minutes.

4. 3rd CONSTRUCTION PHASE

In between the years 2001 and 2008 extensions of the existing Metro Line 1 and 2 were designed, let to contract, constructed and finished few weeks before the European Socker Championship in Vienna in May 2008 started. The construction time for the 6 and 4 km distances was reduced to 5 years, including ground exploration, soil mechanic reports for all working lots, public invitation to tenders and realization of the construction work in the ground and above surface. Especially extension of Line 2 crossed River Donaukanal with station tunnels and passed the mostly under closely situated buildings of the inner districts and main squares. Most challenging was the underpass of River Donaukanal, a former arm of River Danube with the Metro station “Franz Josefs Kai” including the connection to existing Line 4. It was impossible to interrupt the Donaukanal for Tourist boats and other ships and to divide the river into two joined excavation pits, due to the high speed of the water of up to more than 2 m/sec flow velocity. Crossing the fully straightened river includes he underpass of a sluice, called “Kaiserbad Schleuse” of 15 m width and the River Donaukanal of 70 m width with an alignment diagonally of 40° horizontal inclination to the river.

The Donaukanal and the neighbourhood were partly destroyed during many air raids in Word War II, leaving a destroyed foundation of the sluice and a lot of unknown bomb craters in the river and besides. The design asked an overburden of less than 4 m for the station tunnels in clay and silt with water bearing sand lenses. The alignment was shallow enough for toughing a badly filled up bomb crater. So it was decided to freeze the silt and the unknown fill and to dig out the station tunnels between the two working shafts, situated on both sides of the river. The freezing concept consisted of a canopy of freezing pipes for liquid nitrogen (LN_2) in the crow section and a full ring of freezing borings around the tunnels using freezing brain (Na/Mg Cl_2) including a sufficient mass of frozen soil against uplift.

There was much experience on freezing technology, for it was used in Vienna sometimes before. According to the necessary geotechnical control more than halve a dozen chains of temperature gauges were installed drilled through the designed freezing bodies completing the more than 40 freezing borings for both freezing systems and the relief borings in the central parts of the excavations (figure 18, 19 and 20).

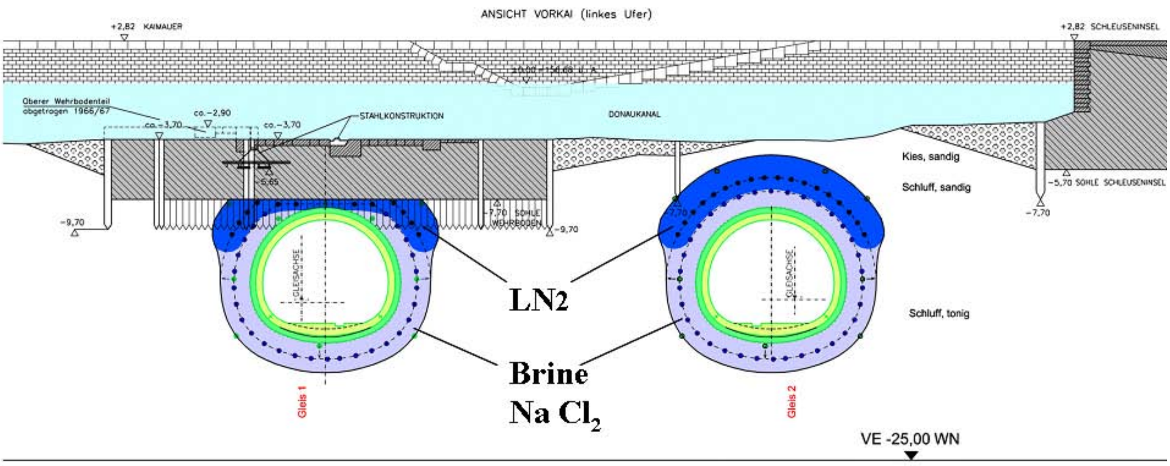

Figure 18. Cross section of the station tunnels under River Donaukanal

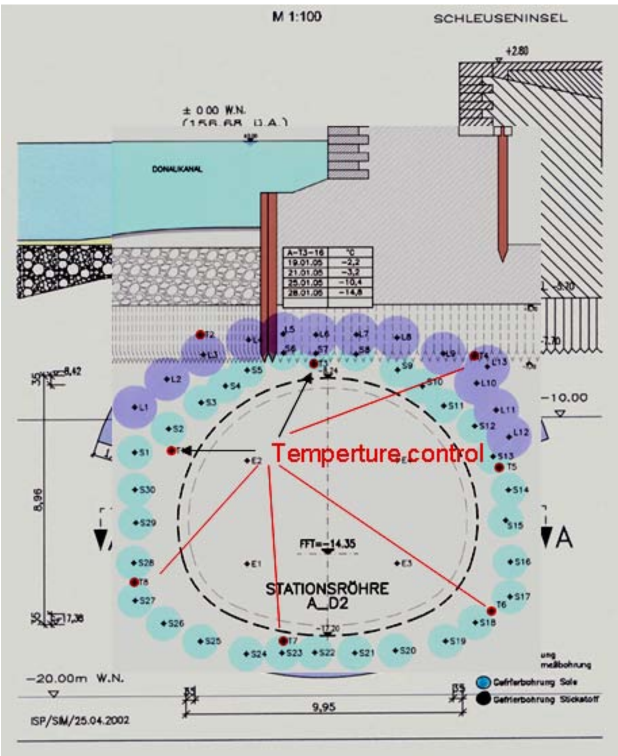

Figure 19. Cross section of the freezing systems

Figure 20. Relief borings to drain soil

During drilling all freezing borings were adapted with preventions against water ingress when passing through ground and fill, justifying the decision to employ LN_2 additional to the brain technology, which will have not been able to freeze the warmed up ground water up to 12°C all the year under the river bed. Frozen soil was excavated by a rotating mining machine cutting it into small ships (fig. 21 and 22). Freezing method pays economically if freezing design starts from the beginning of the tunnelling construction (**10.**).

Figure 21. silt & clay excavated by rotating mining machine

Figure 22. frozen clay in ships

The second method of dewatering ground employed for Metro extension Line 2 was the installation of a huge number of wells working on gravity or under vacuum reducing the water table beneath tunnel invert and vacuum lances to stop water ingress coming from water bearing sand horizons form the open face. The technology of wells and lances has long tradition in Metro construction in Vienna considering the well known filter laws according to corn size distribution of the silt, sand and gravel. By help of vacuum it is possible to stop sand and coarse silt ingress into the filter of the steel tube of the wells as apart of the fine sediments. Such bored or spoiled wells will filter the fines of the water bearing ground during tunnel excavation time sufficiently. Although you will find bleeding water with silt and clay including.

Figure 23. bleeding of silty sand horizons

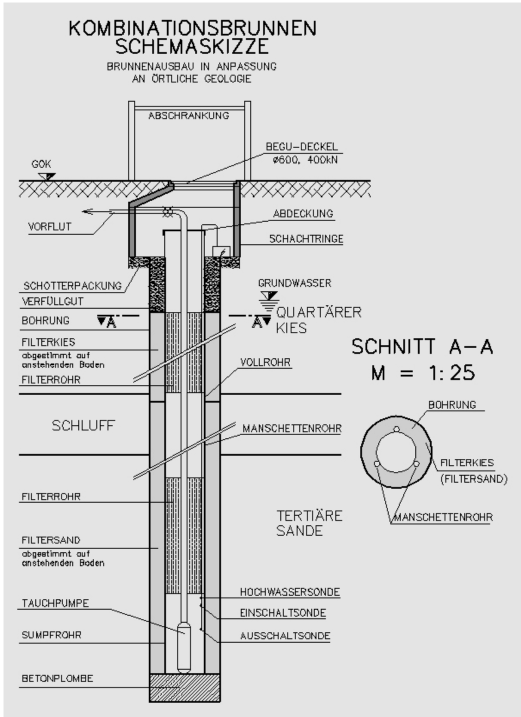

Figure 24. vertical and cross section of a gravity well dewatering to aquifers

Clay and fine silt will not be filtered out of the groundwater due to its small sizes. In tunnelling by sequential excavation method (NATM) bleeding water of fine sand horizons at the open face will be a real challenge for the miners to stop hydraulic uplift (figure 23). Figure 23 show the beginning of erosion which must be stopped immediately to excavate ground safely and to keep the equilibrium of the upper soil layers intact avoiding settlements later on. In the district Leopoldstadt between the regulated River Danube and the Donaukanal ground is build up by two water aquifers. The first and upper one consists of the alluvium of the River Danube; the second and deeper one is build up of series of silty clay and water bearing silty sand. The design of dewatering opened the possibility with one well drilling only to dewater both aquifers, which works quite well. Figure 24 gives a system sketch of these wells working with or without vacuum assistance (**6., 8., 11.**).

In sediments with sandwich layers of fine and coarse grain distributions wells bored from surface will not be able to dewater every layer completely, because of the often too long distance between the wells determined by the existing space between the buildings and the public infrastructure. It is necessary to adopt additional dewatering with vacuum lances from the tunnel face and the shot Crete sealed excavation. At the bottom of the excavation face a row of vacuum lances may stabilize the infiltrating sand and stop the water. The lances can be installed by a skilled crew of miners as shown in figure 24. Don't forget to remember that vacuum lances will filter the fine particles only for a few hours, because of its given size of slots, which will block up water or give way to unacceptable erosion. The lances have to be renewed if they shall work longer on. A better way to get ride of groundwater will be to drill canopies of vacuum lances around the tunnel vault, if soil conditions are appropriate, i.e. silty sand layers of more than few meters thickness. This system was developed in Vienna and accelerated the tunnelling progress significantly (figure 25).

Figure 24. vacuum lances in the bench drilled with water spoil on site

Figure 25. canopies of vacuum filter lances prepared from the enlarged tunnel face

Parts of the Metro extensions Lines 1 and 2 were predestined for shield driving, especially the two 400 m long running tunnels beneath a densely populated residential area in the outer district "Kagran" in sandy and silty gravels in the bottom of the alignment, saturated with water. To dewater the alluvium completely would have been not possible for conventional tunnelling due to residual ground water (figure 26) in that case. A second opportunity of shield drive was designed for the service running tunnel from the operational station of Metro Lines 2 and 3 to the Metro station "Stadion" of Line 2. This shield drive passed under the River Donaukanal in the south-east of Vienna, partially with an overburden of less than 3 m in alluvium. Even for a shield machine this overburden has to be strengthened by loading up the river bed with a 4 m thick layer of stones and blocks to support against uplift and blow out of the bentonite suspension of the slurry shield (figure 27). Even slurry shield was difficult to operate in open gravels with few meters overburden because of loosing suspension. Handicaps appeared also when working in silty clay due to adhesion of the soil on the steel plates at the cutting face and on the breaker in the excavation chamber of the shield (**10.**).

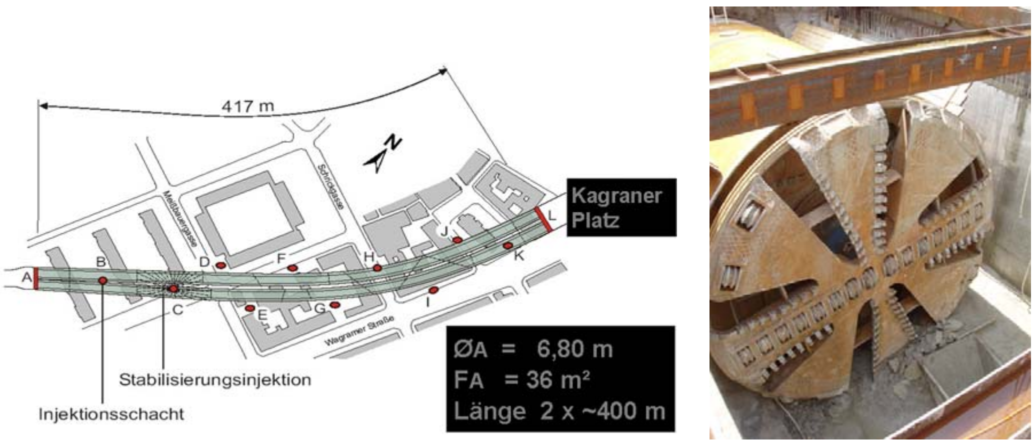

Figure 26. shield drive in district Kagran for extension line 1; slurry shield arriving at the target shaft

Figure 27. supporting the overburden for under-supported with polypropylene fibres

Figure 28. concrete tubing lining pass safely with service tunnel

According to the danger of burning rolling stock the concrete of the service tunnel and the station tunnels was mixed with 1,5 kg/m3 polypropylene fibres, tested intensively in the years 2000 to 2002 in the department 39 of the government of the City Vienna (figure 28). The figures 29 and 30 demonstrate the big difference in destruction with and without polypropylene.

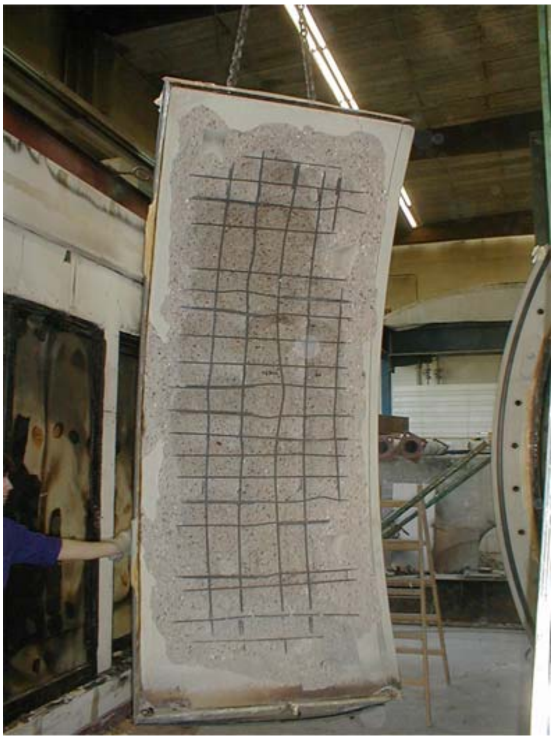

Figure 29. tubing after heat test without PPF

Figure 30. Concrete with polypropylene fibres

The tests on concrete sections for tubing and on inner lining were executed under load conditions similar in stress and strain conditions of tunnels in ground. The used characteristic line of temperature for the development of maximum heat and heating endurance of Metro stock was coordinated with STUVA e. V. in Köln (Germany). Tunnels and deep excavation shafts are used nowadays for receiving geothermal heat. On extension Line 2 the shafts of the stations were equipped with tube rows in the basement protecting stair houses and entrance pavement against ice and snow (figure 31 and 32).

Figure 31. Geothermal tubes in Metro shaft

Figure 32. Metro entrance with heating pipes

5. CONCLUSION

Starting with 2010 the 4th construction phase of Metro Vienna will be designed and announced. It will be an extension of Line 1 and Line 2 to the south of Vienna in the district "Favoriten". According to the soil exploration in the years 2007 to 2012 and the deep alignment under passing the Laaer Berg, a smooth hill in the Vienna the ground will consist of Pleistocene sandy gravels in the tectonic pockets of Miozäne silts and clay interrupt with groundwater filled silty fine sand. The challenge of construction will be dewatering the sand horizons from the surface and from the excavation face with a minimum of disturbance of public traffic and settlements on streets, infrastructure and adjacent buildings. Vienna needs the Metro extensions and the Metro lines have to consider environment and public demands. Economic tunnelling and convenient and safe metro service for the growing population will determine the future of Metro construction in Vienna (**11.**).

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