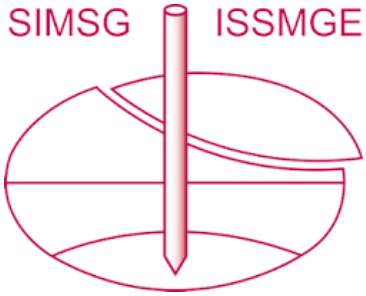
INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)
© 2009 Taylor & Francis Group, London, ISBN 978-0-415-48475-6

Shotcrete excavations for the Munich subway – Comparison of different methods of face support in settlement sensitive areas

J. Fillibeck & N. Vogt
Zentrum Geotechnik, Technische Universität München, München, Germany

ABSTRACT: For the construction of shallow tunnels in settlement-sensitive urban areas it is very important to reduce the settlements and to increase the stability of the tunnel face during the excavation. In the case of shotcrete excavation, the use of different methods of face support has become more and more common. These methods are: ground freezing, pipe roofs, jet grouting and injection support. The paper shows the experience made to due the installation of the above mentioned face supports, especially since the specific focus is related to the arising settlements. If only small deformations are allowed to occur, as the examples show, deformations that have to be considered during the construction process as well as those to establish the bearing load; they could be significant depending on the process. Suggestions have been made as to ways in which the deformations can be reduced by making additional measurements.

1 INTRODUCTION

For the construction of safe shallow tunnels in settlement-sensitive urban areas, it is very important to reduce the settlements and to increase the stability of the tunnel face during the excavation. The use of different methods of face support in the case of shotcrete excavations is becoming increasingly common. These methods are ground freezing, pipe roofs, jet grouting and injection support.

The report presents the experience gained in the installation of the abovementioned working face supports, with particular focus on the induced settlements. Four different projects of Munich's subway are described. After a short project description the results of the measurements are illustrated (geodetic and borehole measurements) and evaluated. With this background, the different methods of face support are compared and the different advantages and disadvantages are discussed. Finally, special attention is focused on the installation process. Proposals are made for the reduction of settlements in future tunnel projects.

2 GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

In the Munich subsoil the quaternary gravels follow under fillings of small thickness. The quaternary gravels can reach a thickness of more than 20 m. They predominantly consist of medium density layers, are laminated and have, depending on the deposit conditions and their age, a differing amount of sand and fine grain. The average permeability amounts to approx. $k = 5 \cdot 10^{-3}$ m/s. Tertiary layers lie below the quaternary gravels. They consist of changing layers of fine- to medium-grained sands with high density and clays or silts in stiff to firm consistency. The thickness of the layers can change excessively within a small distance. The average permeability of the sand amounts approximately from $k = 1 \cdot 10^{-4}$ to $1 \cdot 10^{-5}$ m/s, the tertiary clay and silt can for all practical purposes be assumed impermeable.

The quaternary gravels possess a mostly free phreatic water level, which can reach ground level. There are still confined aquifers within the sand layers with fine-grained cover. The pressure of the groundwater approximately corresponds to that of the free phreatic surface in the quaternary gravels.

3 HEADING WITH GROUNDFREEZING UNDER THE CITY HALL OF MUNICH

3.1 *Construction process*

The extention of the station Marienplatz of the subway lines U3/ U6 under the Munich City Hall was built by the company Fa. Max Bögl GmbH & Co KG. The project was finished in 2006.

Parallel to the two existing platforms, two directly joining tunnels were built in shotcrete method under atmospheric conditions with a vertical distance of

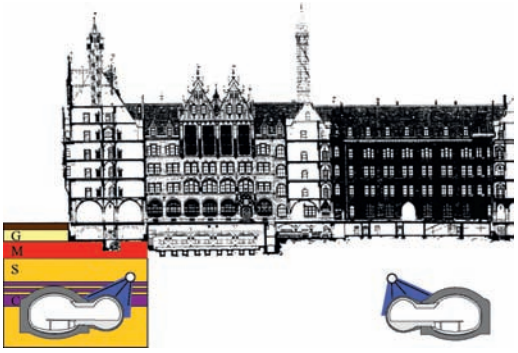


Figure 1. Cross section with City Hall, tunnels and geologic situation.

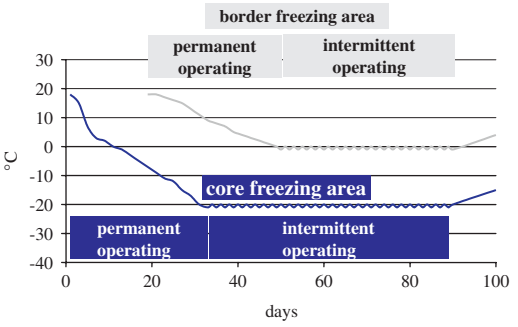


Figure 2. Operating – Control of the artificial ground freezing.

about 10 m to the city hall. In order to avoid damage to the landmark city hall, the deformations had to be strictly limited. The construction company Fa. Bögl, planned freezing arches in the context of an alternate bid, in order to support the crown and to keep the retaining water away from the tunnel face. The freezing arches were provided for through pilot galleries above the crown (Figure 1).

The tunnels are embedded in the tertiary layers (figure 1). The water bearing sand layers had to be dewatered with the help of filter wells.

3.2 *Measurements to reduce frost heave*

For the successful realization of the specific proposal it was crucial to reduce frost heave in such a way that no damage occur to the city hall. Frost heave can be essentially attributed to two reasons:

- homogenous frost heave (Δh_{vol}) because of a 9% increase in volume caused by the changeover from water to ice.
- growing of ice lenses with corresponding frost heave ($\Delta h_{icel.}$) because of the tendency of the soil to draw water near the interface of the frozen to the unfrozen soil (zero-degree-front). This frost heave increases with time.

The frost heave tests, which were performed in the laboratory of the Centre for Geotechnics at the Technical University of Munich (Zentrum Geotechnik, TU München), showed, that in the tertiary fine-grained soils frost heave $\Delta h_{icel.}$ still occurs at load-levels of more than 400 kN/m^2 if water can be drawn at the interface to the permeable sand layers. Therefore the alternating layers of permeable sands and frost-sensitive clays present a critical risk source when frost heave is considered.

In order to reduce frost heave to a minimum the following measurements had to be taken:

- measuring and controlling the temperature in the soil with the help of 5 measuring cross sections per tunnel. Every cross section includes 18 thermo couples.
- reducing the operation time of the frozen arches by dividing the tunnels into 3 different sections: north, middle and south.
- further partitioning within the freezing sections by the installation of groups of freezing tubes with separate control.

In figure 2 the temperature development of a section is shown schematically. Twenty days after starting the freezing process in the core of the freezing body the freezing of the border area started. After the frozen body reached approx. −22°C in the core area and 0°C in the border area, the freezing tubes were operated intermittently, an average of 8 to 24 hours in the core area and 12 to 24 hours in the border area. Due to intermittent handling, the zero-degree-front does not move outside (enlargement of the frozen body), but stays in a narrow zone, which again and again gets frozen and defrosted. Thus frost heave reduces significantly. The operation of one section could be stopped after approx. 90 days. The adjacent defrosting process took about three months.

3.3 *Measuring of the settlements*

The deformations which occurred during the construction process were measured by a geodetic precise levelling system on the surface and a closed water levelling system in the 2nd basement of the city hall.

The closed water levelling system consisted of 10 measuring points with a resolution of 1/10 mm. The measuring results could be checked online at all times. Figure 3 shows the location of the measuring points S03, S06 and S09 of the closed water levelling system as well as the development of the settlement and heave

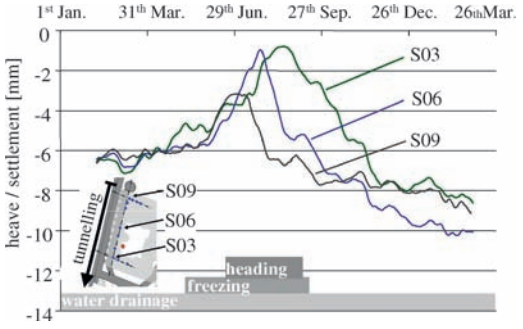


Figure 3. Vertical displacements of the measuring points S03, S06 and S09.

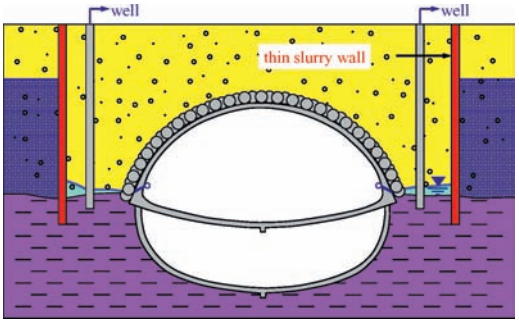


Figure 4. Heading W3 and W4 with jet grouting cover.

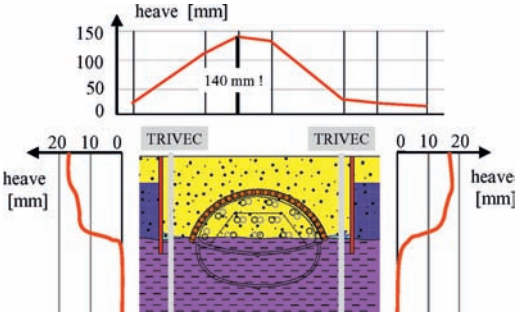


Figure 5. Deformations in cross section MQ 8 after construction of the jet grouting cover.

depending on the time. The three measurement points were situated in the sections north, middle and south.

The settlements at the beginning of the freezing process result from groundwater drawdown. At the onset of freezing the expected frost heave started. It reached a maximum value of 3 to 5 mm. The settlements due to the tunnelling process occurred after the heading had passed the measuring points and they still continued after the freezing process was stopped. The settlements slowed down continuously and stopped 3 months later with a maximum settlement of about 10 to 12 mm.

Figure 3 clearly shows the temporary displacement of the settlements according to the heading. The drive reached the measuring points in descending order, resulting in them reaching the maximum heave successively.

The measured deformations were approximately the same as the calculated ones. Thereby half of the settlements could be attributed to dewatering measures, which lead to large area settlements and correspondingly low differential settlements. Furthermore, no settlement damages were determined at the city hall, so it can be assumed that the heading was very successful. It was essential that for the success of the project, larger frost heave by ice lenses could be avoided by applying the above mentioned measures. Frost lenses would otherwise have led to a softening of larger soil areas and therefore to larger settlements and settlement differences.

4 JET GROUTING COVER FOR A LARGE CROSS SECTION FOR U3 NORTH LOT 1

4.1 *Construction process*

The consortium Ed. Züblin AG/Max Bögl GmbH & Co KG carried out the construction of the subway lot U3 North – 1 in the north of Munich. The works were completed in 2006. The shotcrete headings with a total length of around 1950 m were driven with and without compressed air support and with several methods of crown support which will be introduced hereafter.

The headings W3 and W4 with a cross section area of up to 200 m^2 began from a starting shaft with a top heading. First watertight pits with thin slurry walls were produced (figure 4) in order to lower the groundwater table. The safety of the excavation face was increased by 13 jet grouting covers (total length of about 15.5 m each, overlap 4.3 m) as well as further jet grouting piles in the face of the crown.

The quaternary gravels were cut with suspension (simplex – method) at a pressure of up to 400 bar at the cone. At anytime during the making of a jet grouting pipe a controlled outflow of the suspension is required, assuring that the pressure does not lift the soil. The top heading followed after the installation of the jet grouting took place. The heading of the bench and invert began on finishing all top headings.

4.2 *Heave during the installation of the jet grouting cover*

Figure 5 shows the deformation in the cross section at a distance of 50 m away from the starting shaft directly after the installation of the jet grouting cover.

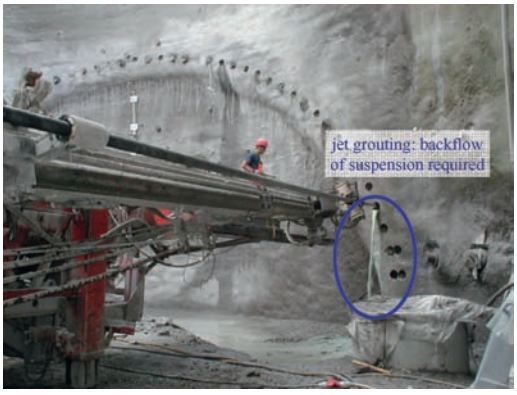


Figure 6. Required suspension backflow during jet grouting.

The heave above the crown reached in MQ 8 about 140 mm and in total a maximum of 250 mm. At first, the heave was deemed uncritical because there were no buildings close to the tunnel, however they result particularly in soil strains in a narrow band directly above the interface to the tertiary soils. Because of the proximity of the thin slurry wall to the jet grouting cover, the heave led to a crack in the thin slurry wall, making the wall permeable.

The heave results from the fact, that the outflow of the suspension in the annular space of the jet grouting piles, which are faced upwards, can not be controlled in a suitable way (figure 6). Owing to the lack of backflow in the layered soil with strongly differing conductivity the overpressure spread over a greater area, resulting in a rising of the soil above the jet grouting cover.

The large heave could only be limited by reducing the overpressure through the installation of further boreholes from the ground level, resulting in high costs.

With increasing soil cover the heave reduced because of the increasing load. However, even under more than 12 m of soil cover and the installation of the jet grouting cover in tertiary clays, the heave still amounted to approximately 20 mm.

For further projects, where only very few deformations are allowed during the installation of the jet grouting cover, sufficient attention should be paid to the control of the suspension backflow during grouting. This problem could for example be resolved by improving the technique of the grouting machine or with the help of a double tube, which is pulled a little ahead during jet grouting or likewise with the help of special valves which control the pressure of the backflow.

If the pressure gets to high during grouting, heave can be avoided or at least reduced by additional horizontal or vertical arranged boreholes.

	U5/9 Ostbahn-hof	U5/9 Theresien-wiese	U3N1 W4 / W3
tunnelling cross section			
cross section area [m²]	200	175	170 - 200
covering [m]	9,3	9,6	6,5 / 11
max. settlement [mm]	36	38	26 / 40

Figure 7. Comparison of settlements of different shotcrete tunnels, driven under atmospheric conditions.

4.3 *Settlements during the heading*

After the installation of the jet grouting cover, the top heading with temporary shotcrete invert followed step by step, over the whole heading distance. After this the heading of the bench and invert followed. The settlements which occurred during the headings amounted to a maximum of 26 mm in cross section MQ 8 and 30 to 40 mm in the area with larger soil cover.

In order to be able to judge the results, in figure 7 the above mentioned measurements are compared with those of atmospheric shotcrete headings having nearly the same soil cover but were driven in partial face advance without jet grouting cover.

Overall maximum settlements were measured as almost the same size, which means that the jet grouting cover does not reduce the settlements, in comparison to tunnels driven in partial face advance. As the sliding micrometer measurements show, the forces which were taken from the jet grouting cover, lead to concentrated high stresses in the small bedding area of the jet grouting cover. This stress concentration leads to comparatively high compressions and settlements. On the other hand partial face advance leads to less stress concentration, however the different delayed headings lead to multiple load rearrangements and therefore the surface experiences approximately the same settlements.

Finally it can be concluded that with the jet grouting cover the settlements are not reduced in comparison to those caused by partial face advances. However, the face stability clearly increases by using a jet grouting cover.

5 PIPE SCREEN COVER FOR THE UNDERPINNING OF A BUILDING IN U3 NORTH LOT 1

The two shotcrete headings of section W1 in the above described subway Lot U3 North-1 in Munich had a cross sectional area of $A = 41\ m^2$ and were driven in the tertiary soils under atmospheric conditions with the help of wells, dewatering the tertiary sand layers.

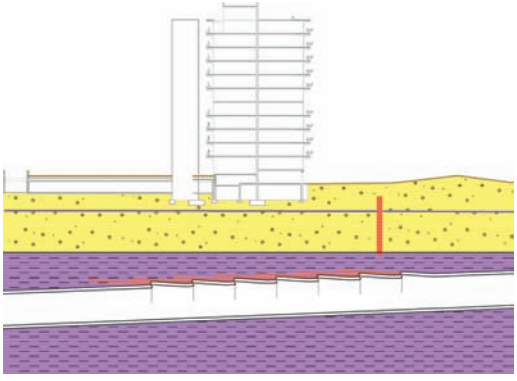


Figure 8. Crossing the building Werner-Friedmann-Bogen, longitudinal section.

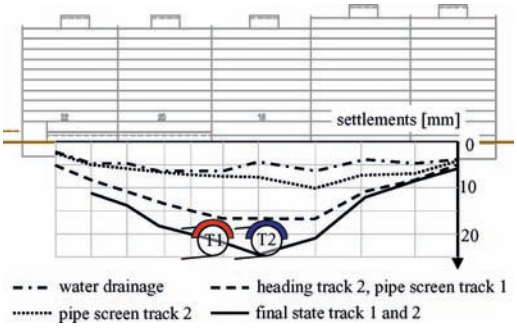


Figure 9. Settlements of Werner-Friedmann-Bogen during tunnelling (cross section).

In this section the underpinning of the Werner-Friedmann-Bogen, a building complex with 12 floors, is of special interest. The foundation pressure of the 3 m wide strip foundation, which lies in the centre of the building and carries the main loads, amounting to nearly 300 kN/m^2.

At a vertical distance of approx. 12 m between the foundation and the crown, a pipe screen cover was planned as an additional measure of protection (figure 8), because the tertiary soil cover amounted only 4 m and full water pressure was acting from the quaternary to the surface of the tertiary soils. At the southwest side of the Werner-Friedmann-Bogen an underground garage follows.

For every pipe screen 38 pipes were installed. The length of the pipes amounted to 12 m with an overlap of 4 m. The bore diameter amounted to 146 mm with a 6 mm annular space.

In figure 9 the settlement trough along the Werner-Friedmann-Bogen is shown as dependent on the development of the heading.

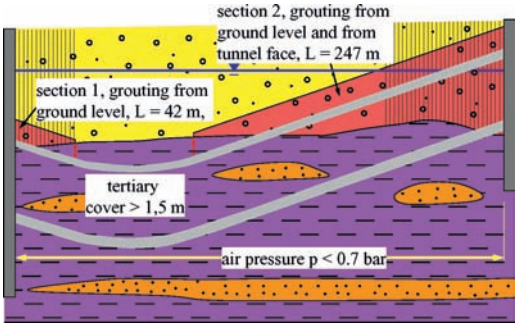


Figure 10. Longitudinal section of the grouting section O2.

Due to the dewatering of the tertiary sand layers settlements of 5 mm to 7 mm were recorded. The installation of the pipe screen and the forward directed settlements of the heading of track 2 increased the maximum settlements to approx. 10 mm. The largest settlements resulted from the 2 headings. Finally the maximum settlements amounted to 25 mm.

As a comparison with measuring of further cross sections without pipe screen shows, the maximum settlements were measured under the Werner-Friedmann-Bogen. It is clear that the foundation loads lead to higher settlements and because of the smaller soil cover only limited arching develops. Furthermore, installation also cause settlements. However, it is crucial to settlements, that the pipe screens as well as the surrounding soil layers experience some deformation, before the system can carry the expected load in both the longitudinal and lateral directions. That is why the predominant settlements respectively occur shortly before and directly during the heading.

It can therefore be concluded, that the pipe screen primarily increases the safety of the tunnel face. For the installation and formation of the bearing effects, deformations are however necessary, which lead in this case to settlements of 25 mm. Pipe screens are only applicable for the reduction of settlements, if substantially higher settlements are expected without them.

6 HEADING WITH COMPRESSED AIR SUPPORT AND GROUTING IN U3 NORTH LOT 1

The geological conditions in the section O2 of the subway lot U3 north-1 are shown in figure 10. In this section a shotcrete heading with compressed air support was provided for. If the thickness of the tertiary soils above the crown reached less than 1.5 m, the overlaying quaternary gravels were grouted. In the grouting section 1 with a length of approx. 40 m the gravels were grouted from the surface. In section 2 the surface was not accessible. The gravel was therefore grouted from

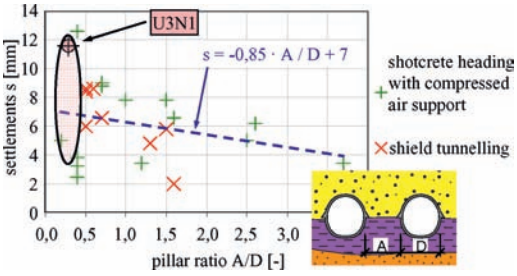


Figure 11. Surface settlements due to shotcrete tunnelling using compressed air in Munich with dependence on the pillar ratio A/D.

the tunnel. At the end of the heading the grouting was done again from the surface.

The aim of the grouting was to reduce the permeability of the gravel to $k \leq 5 \cdot 10^{-5}$ m/s. This was controlled by permeability tests in the bore hole.

After the grouting activity the heading followed in shotcrete method with compressed air support with a maximum overpressure of 0.7 bar. Settlements were measured between 3 mm and 11 mm (without considerating of settlements due to water drainage). In order to assess this result, the results of settlement measurements of headings in Munich, with compressed air support and without grouting (shield tunnelling and shotcrete method) depending on the pillar ratio A/D are compared with the abovementioned result of the U3N1 measurement in figure 11.

It can be seen that the settlements measured if grouting was applied do not differ from those without grouting. It appears that the grouting did not reduce the settlements.

Overall, the results confirm, that shotcrete headings with compressed air support lead only to very small settlements with small tangential inclinations, which cause no damage to conventional buildings.

Considering that the measured compressed air consumption was almost just as small as the calculated value, the very extensive grouting measure (21500 m grouting boreholes with more than 43000 grouting sleeves have been installed) can be determined as very successful.

7 CONCLUSIONS AND FINAL REMARKS

In order to construct shallow tunnels in settlement-sensitive urban areas with the shotcrete method, measures have to be taken to increase the face stability and to reduce the settlements.

Besides the common measures (for example reducing the length of the advance step, etc.) special crown support measures are often used for this purpose. In this paper, the experiences of the authors demonstrated the purpose of using a frozen cover, a pipe screen cover, a jet grouting cover and a grouting cover. It has been shown, that the installation of crown supporting measures can have an extensive influence on the appearing deformations

As the settlements caused by shotcrete headings with conventional cross sections (approx. 40 m^2) in the Munich underground are comparatively small (smaller than 20 mm to 25 mm for atmospheric headings and smaller than 10 to 20 mm for headings with compressed air support), the crown supporting measures do not have, as the examples show, decisive advantages regarding the deformations. However, if the crown supporting measures are used in a adequate way, a considerably higher safety potential occurs. This has to be considered if a decision has to be made, as to whether or not crown supporting measures are necessary in difficult sections.