"SOFT GROUND TUNNEL FOR THE MUNICH METRO"

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Munich Metro, Section 9/18.2

In this lecture, I would like to inform you generally as to extension of Section 9 of the Munich Metro located at Sendlinger Tor Platz in downtown Munich.

The basic requirements on the application of the method of construction we selected for Section 9, also apply to the following Section 18.2 connecting up the main-line station.

In September 1973 we were contracted by the joint venture for Section 9 to work out alternative proposals for advancing the various tunnel tubes in accordance with the New Austrian Tunnelling Method. Full scale advancement was started in spring of 1974 and is still going on.

Location

The metro line 8/1 und 6/3 intercept at Section 9, the platform 1 and 2 mainline station tubes of Section 9 connecting the Sendlinger Tor Platz station at right

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angles, the latter having been operational for quite some time. This station was completed at the end of the sixties in open-type construction, the station tubes being connected to a 200 m long, two-line siding and the neighbouring section 7/1 in the south-west through a single line tunnel section. In the north-west, the station connects Section 18.2 which has been extended in the mainline station area from a two-line tunnel section to a four-line switch point section.

Fig. 1  Layout Survey of Section 9
The particular characteristic of this section is the repeated change from single and two-line tunnel tubes in relatively short intervals, further featured by the flared extension where the platform 2 station tubes meet the connecting track and the single line tunnel tube of the neighbouring Section 7/1 as well as the connections to the existing station.

Due to the total loads acting on the station outer walls being transmitted to the tunnel tube below, connecting platform 2 necessitated a temporary opening-up of the station section from approx. 75 m² to approx. 150 m². In addition, the tunnel is advanced under built-up area involving seven-story high risers in part with little distance between the foundations and the roof (approx. 4.0 m).
MUNICH METRO

Geological Conditions and Geotechnical Problems

**Fig. 2** Authoritative geological section of the test route

Munich City is founded on layers of two geological formations.

At the top we have quaternary sediments with tertiary sediments underneath, the ice-age and post-ice-age changes from gravel formation and erosion having formed various terraces.
Section 9 is on the boundary between the Talaluvium of the Isar and the step of the old part of the town.

The quartery layer is mainly made up of fine and coarse grades of gravel and partial deposits of quartery fine and coarse sands and clay deposits. In addition, we have to deal with deposits of building rubble, humus, etc., in age-old channels.

The tertiary layer, the actual layer in which the tunnel is advanced, is generally made up of the top layer of flaky sand covering a layer of flaky marl; in Section 18.2 the tunnel is advanced through changes of the above-mentioned layers.

The flaky sands are deposited dense to highly dense and constitute fine to medium grain quartz sands containing mica and feldspar. The flaky marls generally constitute tough, hard to very hard clays.

The geotechnical problems resulting from the above-mentioned engineering and geological conditions involve best-economy advancement in an unstable environment through a variety of cross-sections overshadowed by the paramount requirement of ensuring minimum subsidence especially underneath the structure.
Ground Mechanics, Design and Engineering Planning
Consideration

Fig. 3  Control section in accordance with the
draft of the Invitation to Tender and the
alternative proposal

The above figure shows the original control sec-
tion and the new one and thus the basic difference
regarding the geomechanics of the previous technique
and that of the special proposal.

This difference of opinion makes itself apparent
in the choice of curvature thickness in the design
shown here for the sake of comparison, the one
constituting a construction subject to external earth
compression forces usually involving high-bending
moments contrasting to appreciation of cavity relaxa-
tion and the interaction between the ground and the
structure.

The extremely rigid structure is a clear indication
of intending to completely eliminate surface subsi-
dences, an intention which is also obvious in the
actual progress and selected individual procedures of
the advancement.

Our alternative proposal avoided considerations of this
kind right from the very beginning in the sure knowledge
that subsidence can hardly be avoided and that defor-
mations to mobilize the supporting capacity of the
environment itself are certain to occur in the course
of force displacement. Cavity relaxation is simply not
possible without deformation.

The anticipated subsidence, especially its magnitude
was thus one of the major considerations in the frame-
work of the contract awarding negotiation. Since no
experience in using the new Austrian tunnelling method
in sandy and marly ground in section of this kind at
the time of Contract Award, it was extremely difficult
to forecast anticipated subsidence. It was thus agreed to drive an approx. 60 m long trial tunnel underneath a non-built-up area to gain an insight into anticipated subsidence behaviour.

Demonstration was required that the new method would not result in any damaging subsidence.

Fig. 4 Side Headings with Final Outer Side Walls
Advancing the tunnel in soft ground usually requires opening up the heading step by step. In our case, confronted with two-line tunnel tubes of approx. 75 m² sectional area involving a horizontal, elliptical shaped structure and with relatively little overburden to the surface, progressing had to be carefully selected to fully meet the requirements of minimum subsidence.

Whilst heading of the single line section having a cross-section of only 35 m² involved subdividing operations into roof section heading quickly followed by core excavation including excavation of the bottom curvature, the two-line tube was executed by first driving and securing the two side headings (see Fig. No. 4) followed by the roof section excavation prior to finally excavating the core including the bottom curvature.

The following illustration (Fig. No. 5) is a schematic representation of the sequence of excavating the two-line cross-section:
Fig. 5  Schematic Representation of the Excavation Sequence in Providing the Two-line Cross-section

- First phase  Parallel advancement of the side excavation headings with anchoring the final side walls

- Second phase  Advancement and supporting the large excavation roof section excavation in flaky sand
- Third phase excavation

Excavation of the core including the inside side walls of the side headings and simultaneous bottom excavation in flaky marl

Both methods are based on the prime requirement of resulting in minimum subsidence. Floor excavation follows very quickly the excavation and support of the roof section in the case of the single line tunnel tube, with which the full excavation resistance of the outer ring is obtained.

In this way, very little time is left for subsidence movements.

Fig. 6 Side headings and single line tunnel tubes
With the two-line tubes, the advanced side headings permit advance excavation and support of the final side walls of the large section, the side headings thus producing a stable support which is more or less insensitive to subsidence for later excavation of the roof section. The large roof section is the most sensitive part of the tunnel section. The springer loads flow out of the roof section, so to speak, as if transported by wide footings into the ground underneath the bottom of the tunnel, a certain proportion being transmitted to the surrounding ground by friction in the shotcrete ground contact surface interface.

Aside from this, the side headings act as large drains, which completely lead off the residual water resulting from lowering the ground water level out of the roof section. Due to their height, the side headings or the already completed side walls act as load distributing supports via a number of rings in the longitudinal direction during excavation and providing the tunnel bottom.

When the roof section is advanced ahead of a few rings, an intermediate connection to the bottom is provided via the existing side headings together with the core remaining in between.
Fig. 7 shows the status of the test tunnel as has since been attained which was kept for more than a year for technical reasons and which is a very good representation of excavating progress actually achieved.
The necessary lining resistance of the final status is achieved by means of a two-shell structure comprising the outer shotcreted ring already described and an inside ring of in-situ concrete.

The outer ring having a shotcrete thickness of 25 to 30 cm also includes system anchoring of SN-anchors, TH ribs and two layers of wire mesh. The anchoring ensures intimate contact with the surrounding ground requiring the latter to provide a great share of support resistance.

For most of the time required for tunnelling, the outer ring provides support of the tunnel cavity and has to absorb deformation resulting from the stress rearrangement subsequent to excavation.

When finished, the inside ring is required to take the pressure of the ground water and the surrounding ground resulting from any later creeping loads of the ground.

**Structural Analysis**

Since the new Austrian method as applied to Section 9 was being used for the very first time in the Munich area, structural analysis according to geomechanical
considerations had to be demonstrated to the Authorities for permission.

To solve this really delicate problem, we used the method of finite elements to establish approx. the stress relationships around the cavities, the deformation, plastic zones and shear forces resulting in the outer and inner shells in the course of tunnelling progressing and to be on the safe side.

Section 9 computations were carried out by the Technical University in Zürich, Section 18.2 computations by the Technical University in Innsbruck once the material characteristics had been established in agreement with the City Inspectorate with due regard to the first-time application of the Austrian method of tunnelling and the multi-layer nature of the ground of differing strengths.

The following illustration shows an excerpt of the results of computation indicating really useful values. This shows the distribution of bending moments and normal forces in the outer ring in finished condition for symmetrical loading and lowered ground water.
Fig. 8 Computed distribution of bending moments and normal forces in the outer ring with ground water lowered. The predominance of normal forces is clearly indicated, the bending moments merely constituting the deformation of the lining and thus to be understood as moments of restraint.

The following figure (Fig. No. 9) shows the stress plot and the plastic zones of the outer ring (AR) in the finished condition.
Fig. 9 Stress pattern and plastic zones around the outer ring with ground water lowered

The information provided by these figures and the numerical results tend to prompt utilization as a basis for dimensioning. It must be remembered, however, that the results are the exclusive product of the input figures and the degree to which the
method of computation agrees with actual conditions.

And thus the civil engineer has no other option but to also reinterpret the results of exhaustive electronic computations according to his experience and any test data available for agreement with practical findings.

**Work Progress**

Work has progressed highly satisfactory to date and no exceptional problems - apart from some trouble here and there with residual water or water blisters - have been experienced.

Advancing sometimes proved to be a nuisance and muddy due to tunnelling along the boundary between the flaky sand and flaky marl, in other words, between the ground water carrier and ground water accumulator horizontal at half height through the side headings. By shortening the depth of cut in geomechanically weaker areas, these areas proved to be no problem.

Advancing to various cross-sections was partly done by cutting, partly by excavation, removal of excavated material being carried out centrally through the removal shaft where an electric crane loads the material on to the waiting trucks.
Measurements

It is mandatory with the new Austrian tunnelling method to carry out test measurements as to cavity deformation, loosening and pressures present in the lining and in the contact surface to the surrounding ground.

Behaviour of the resulting cavity is continuously checked by a system of measuring sections which are differently equipped.

Fig. 10 Extensometer - E 2
Subsidence as a function of time and distribution over 4 levels
The following refers to the major measuring section in part as shown in the following figure, this being the test section MQ₄ taken from the test tunnel of Section 9 which mainly is concentrated on the magnitude of subsidence above the tunnel.

This figure shows the results obtained over the tunnel axis using the multiple extensometer E 2 to establish absolute subsidence movements in four levels, E 2 - 1 attaining more or less the tunnel roof top. Subsidence measurements were carried out at the same time as ground water was lowered, long before advancement was made in the test section MQ₄.

This resulted in also the amount of subsidence resulting from ground water lowering being obtained which here amounted to approx. 50 % of total subsidence.

The curve profiles clearly indicate how excavating the large roof section affects subsidence.

This is where subsidence is most accelerated, all other advancement procedures such as step-by-step excavation of the side headings and removing the core and curving the bottom having little or no effect
on subsidence movements. The reason for this, is the standing geometrical shape of the side headings favouring in particular horizontal convergence and the firm support of the roof section by the finished side walls when excavating the core and tunnel bottom.

Subsidence amounted finally to approx. 20 mm, 50 % being due to lowering ground water and 50 % to actual tunnelling. This figure was confirmed by all other two-line cross-sections. The single line tunnel tubes exhibit a similar behaviour with time but with reduced subsidence. The good progress made in advancing tunnelling, confirms the system as the correct choice and until now there has been no reason to doubt the continued usefulness of the system.

And now at least an economic aspect: the different on construction cost's between the draft of the Invitation to Tender and the alternative proposal is more than 30 %.

It means we saved 30 % for the owner!