SHALLOW TUNNELING IN URBAN AREAS

Some Special Aspects

by
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Introduction

Tunneling in urban areas with high ground water level requires special care, skill and responsibility! It starts with the design of the underground alignment, its space and shape. This should address not only politics and traffic needs but also geotechnical facts. Long tunnels with one continuous cross-section in uniform ground conditions are competitively bored by today's available machines. It is the changing factor in size and shape not only of the client but also of the structure and the ground conditions that still causes problems, frequently resulting in time and cost overrun.

Short underground bores, especially twin tunnels with underground branches, mined stations, cross-over chambers, shafts, escalator tunnels, additional electrical and mechanical caverns and widenings along tunnels and other auxiliary space which needs to be mined, require an easy to handle, flexible construction technique, that can cost effectively adapt to unforeseen conditions.

The so called "New Austrian Tunneling Method" (NATM) has proven worldwide to be one of the most economically adaptable and most responsive excavation and support methods, which can be used in virtually any kind of ground. This shotcrete tunneling or sequential support technique has also successfully been applied in the rehabilitation of underground structures of all kinds.

Brief History

Although NATM was originally developed for tunneling through the Alps in Austria, its main support element - the shotcrete - was invented and patented at the beginning of this century here in the US (1912, Allentown, PA). In the meantime, it has developed a long and well-established history of application to mixed ground conditions in an urban environment.

Sprayed concrete (shotcrete) was used for the first time in 1954 to stabilize squeezing ground in a 8 m diameter diversion tunnel for an Austrian power plant. After a number of successful applications for further water-, rail- and road tunnel projects, this method was adopted for the first time in urban areas in soft ground for a section of the Frankfurt Underground Scheme. The construction took place in Frankfurt clay in 1968. Because of its obvious flexibility, economic and safe performance, more than two thirds of Germany's urban mass transit tunneling in more than 10 major cities were carried out using this method by the 1970's. These tunnels were constructed in all kinds of soft, mixed and hard formations such as: clay, silty clay, silt and soft marl, brittled to solid basalt and granite conditions, etc.

In the meantime, many large cities around the world, e.g. Algier, Brasilia, Copenhagen, Dallas, Essen, Frankfurt, Geneva, Helsinki, Istanbul, Jerusalem, Kyoto, Lisbon, Madrid, Nürnberg, Ottawa, Paris, Quebec, Rome, Sao Paulo, Seattle, Seoul, Tokyo, Udine, Valparaiso, Washington DC, Zürich, among many others, have taken advantage of this method.

Combined with compensation grouting, even old historic buildings in Athens, London, Vienna and elsewhere remained undisturbed while mining underneath them.

Basics

Geological formations can be compared to a highly viscose anisotropic discontinuum with cohesion and internal friction. It provides a more or less limited stand-up time when excavated which leads to some basic requirements for its application:

- The excavated cross section should follow an ovoid shape (no vertical sidewalls!).
- Immediate, continuous, smooth support around the tunnel perimeter (and, if required, also to the face) is a significant factor to minimize initial movement in the surrounding ground.
- In soft ground conditions, the supporting ring (shotcrete) needs to be closed as quickly as possible within one tunnel diameter from the advancing face.
- The 3-dimensional stress redistribution around the tunnel depends upon geometry and time. This must be carefully considered, particularly where multiple openings are planned. It will also govern the progress of tunneling with respect to stress redistribution, soil-structure interaction and curing of the shotcrete support.

Continuous (and, if feasible, symmetric) excavation of multiple drifts avoids irregularities in stiffness of the initial lining, changing load conditions and, therefore, provides smooth stress redistribution in both lining and the surrounding ground.

NATM is said to be an observational method. Therefore, monitoring (in-situ measurements) of deformation in the ground and opening and stress development on and in the initial lining (shotcrete) is recommended. Any remedial work caused by violation of material specification, misalignment, other construction errors and errors due to unforeseen conditions must be carefully designed and follow the same step-by-step approach as adopted for the main design work.

Content of Presentation

There will be examples of underground structures, such as under/over tunnels, underpasses of buildings, tunneling at airports, typical excavation and support sequences in difficult ground conditions. The presentation will provide a glimpse into the theory of stress redistribution during excavation and its monitoring. It will introduce modern ground improvements and construction methods [e.g. face stabilization, spiling, grouting, freezing, horizontal jet grouting, compressed air, Barrel Vault Method (BVM) and Doorframe Slab Method (DFS), etc.]. Multiple drifts are used to construct larger openings in soft ground, such as large tunnels, stations, parking garages, caverns, etc. Modern techniques for construction of twin tunnel structures and step plate junctions will be explained. New waterproofing techniques and their consequences will be presented along with some final examples from projects all over the world. Success of this flexible tunneling method relies on (as it does for most of what society is producing) quality planning, trained execution, overseen by responsible and skilled supervisors!

1 Excavation in Hard Rock and Soft Ground

2 After installation of initial lining, both underground caverns are looking more or less the
same, regardless of whether it is hard rock in Washington, D.C. or mylonitic sand in Austria.
3 Road tunnels need u-turn widenings in regular distances, and urban tunnels often have to be
constructed with changing cross-sections on over/under schemes. One of the latter has just
4 recently been built in Washington, D.C. Sometimes, underground branches and station
5 tunnels need to be constructed underneath tall buildings like churches or skyscrapers, as well
6 as under historic structures, like "The Old Römer" at Frankfurt. Airport links, like Heathrow
7 Airport, where we did the trial for the new heavy rail-connection into London, are becoming
an increasing transportation issue. While long running tunnels which are uniform in size and
8 uniform in geology (e.g. in Dallas, Texas) are being built competitively using modern and
9 effective TBM's, some shorter rock tunnels are still being built using drill and blast
techniques like B10 and 11 in Washington, D.C. or a road tunnel near Algeria.

A Glimpse into Theory

The effect of shotcrete as initial support has been discussed in the last few decades at length.
A short summary is shown in the two graphs: It is the basic stability issue in NATM, the so
10 called "Jerry-Stone Effect", and the major advantage in using shotcrete is the "immediate
11 blocking of initial raveling and movements". As mentioned before, a key to NATM's success
is competent monitoring! Its result, however, does not always reflect what the theory would
12 expect. This happened to my research work at the University of Karlsruhe, Germany. I had
started with in-situ measurement on a twin track cross section in Frankfurt while under
13 excavation and after obtaining unexpected results, such as wave like stress redistribution, I
had to reproduce them in model tests. Fortunately, it turned out to be a success. By accident,
14 I spotted some results of in-situ measurements from non-tunnel expert colleagues, showing
15 their findings with advanced instrumentation, and I could project them onto my own findings.
The final outcome was a wave-like stress pattern around the tunnel which produced some
confusion among theoreticians but has been adopted by the alert industry immediately.

Ground Improvement and Additional Support Means

16 Face stabilization with earth wedge or shotcrete is successfully used today, as well as spiling
17 in brittle and soft ground which recently has been used at many of our Metro tunnels and
some hundred tunnels of the high speed rail link in Germany. In even softer and sandy
18 ground, however, grouted pipe spiling and grouting was and still is the standard answer.

The under-passing of buildings or even vaults, like the one of the "Hardy-Bank" in Frankfurt,
requires carefully grouted slabs above the to be built tunnels. What has been developed in
19 urban tunneling in the last thirty years is the "Ground Freezing" method. This concept has
been successfully used on several projects, among them Zürich which is one of the most
spectacular ones with a cross-section of some 36 feet in diameter.

20 Horizontal jet-grouting has been developed in the last twenty-five years; although using
21 compressed air in underground tunneling is an old means of temporary support, it is now
used in conjunction with shotcrete. Its economic success, however, remains at air pressures
22 below 14 psi. The "Barrel Vault Method" (BVM) is one of the most cost effective methods
23 to underpass railway or Autobahn embankments with a very high proven safety factor. This
24 had already been demonstrated on some projects in Europe in the past but has now also been
shown here in the United States (e.g. near San Francisco) as well as other locations.

25 A semi cut-and-cover method recently developed is the so called "Doorframe Slab Method"
(DSM). Its advantages are the very temporarily open cuts in busy streets (approximately 300
feet in one or two weeks). During this period, the concrete slab is poured, some spile side
wall reinforcement is driven into the ground, and the street is restored. After this, the
underground excavation beneath the protective slab can commence. We are currently using
this method on a job at the North Station in Boston.

26 Subdivision of cross-sections is a proven method to enhance safety in soft ground tunneling.
This includes tunnels as shown at London Bridge or in a center-platform station in Essen,
27 Germany. Cross-sections in soft ground up to 65 feet and more have been successfully built
by using side wall drifts and consequent widening to the full extension of the cross-section.

The originator of the main element of what I have been introducing as initial and/or,
sometimes, final support means is not very well known. The so called "Shotcrete" was
invented by a taxidermist named Karl Acly in Chicago in 1908. The first shotcrete machine
was patented and built in 1912 in Allentown, Pennsylvania, which is where we finished our
first highway tunnel on the Pennsylvania-Turnpike a few years ago, in 1995. With this
28 method, we have been able to build underground caverns, like parking garages - here an
29 example of Landsberg - , shafts, adits on running tunnels, as shown on examples of
30 Washington, D.C., or escalators and station tunnels in Dortmund, Germany, or the Wheaton
31 station in Maryland. A large twin tunnel, using an old shut-down railway tunnel to construct
32 the center pillar section, has been built in Wuppertal, Germany, with success.

Waterproofing

Most of the underground structures are producing ground water, and if no sufficient
34 precautions are successfully applied, the underground structure starts to deteriorate
35 substantially. Approximately 30 years ago, beginning in Switzerland, the "Membrane
Waterproofing" has been developed and is now standard in Europe and in most of the traffic

36 tunnels in the world. A comparison at the Silver Spring, Wheaton, job demonstrates the
37 difference between a non-waterproofed and a properly waterproofed tunnel. Waterproofing
is currently installed at some cut-and-cover stations and adjacent structures at the
38 Washington, D.C. Metro.

Rehabilitation

More and more underground structures need to be refurbished, mainly because of no or
insufficient waterproofing. One of our first jobs in this respect was the "Felbertauern Tunnel"
39 in the Austrian Alps, followed by the old "Lehigh Tunnel No. 1", built in 1956, at the
Pennsylvania Turnpike. Both are now finished, and a comparison between the old and the
40 new appearance is self-explanatory. In joint venture with a local contractor, we just recently
41 widened a some 150 year-old railway tunnel in Pittsburgh to a modern road tunnel. Some of
you have probably visited it already.

42 But one of our most prestigious jobs was the rehabilitation of the very first underwater brick-
work tunnel, constructed using a rectangular shield. This was the "Thames Tunnel" in
London, built by Sir Isaac Brunnel in the beginning of the last century. The tunnel was
entirely deteriorated, and riverbank investigations were showing some exposed tunnel
structures. This made the tunnel highly accessible to scratches from ship anchors, or even
worse, it made the tunnel vulnerable to attacks by their good friends from the Western island.
43 If it had collapsed, it would have flooded the Southern part of London. Now, refurbished
with a reinforced two-shell system which was actually designed for dynamic impact, its
44 interior has the same pattern as the old tunnel. So everyone is happy now and feels safe, as it
45 is the case on other finished jobs at Wheaton and Frankfurt or with the running tunnels in
Germany and Texas.

Cost and Contracting

46 The good news is that tunnel costs have been reduced during the last few decades, more or
less consistently. We are currently calculating cubic yard costs of finished tunnels including
waterproofing and final lining in the range of $180.00 to $280.00 depending upon various
factors. This leads to tunnel cost for single track tunnels in the proximity $3,500.00/lft and
double track or two-lane road tunnels of $6,000.00/lft.

One of the reasons for this decrease is the improved tunneling technology but also the introduction of flexible contracting. This, however, requires competence on both sides at the level of decision makers, just as everything else does in this world!

Design-Build by the contractor is used in the private industry to a great extent. It has been increasingly used in tunneling in the public sector in Europe for over thirty years. The percentage of the client's engineers pre-design may vary between 30% to 70%, depending on the complexity of the scheme but also on the skill of local industry.

47 Another, even better, news is the fact that NATM does not require costly investments in plants and machinery. Besides construction materials, good local labor with some expert training and supervision, constitutes the main cost factor on the job.

The initial success of the NATM approach in urban areas, as mentioned before, was reflected
47 in a rapidly increasing use in many German Subway Schemes built in the seventies and eighties. Nowadays, it has been adopted worldwide for urban tunneling to a great extent.

48 Ladies and Gentlemen, thank you for your undivided attention.