TUNNELING…..AND BEYOND

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Abstract: “More skill is needed to avoid rather than to handle heavy ground loads.” This finding, from a tunneling engineer of the nineteenth century, is still relevant today with all advanced sequential excavation and support methods available whether they are applied in the vertical or horizontal direction. Balanced contractual documents provide the spirit and climate at site. This publication aims to describe the means and measures for ‘hand mined’ shaft and tunnel support as they are available today. Some recent developments in special construction elements and methods provide flexibility to avoid getting stuck in conservatism are presented as well. If we don’t allow new methods, means and measures we may end up with the famous quote “Only women who have already proven they are able to give birth to a healthy baby are allowed to become pregnant!”

I TUNNELING

Ground, especially soft ground, does not like to be disturbed. So, if you have to do it, do it tenderly, with caution and provide immediate support wherever the in-situ state has been distorted. “Greater skill is needed to avoid (minimize) ground load than to resist it” (Rziha, 1872). This is the fundamental philosophy of the technique commonly referred to as NATM (New Austrian Tunnel Method) used for construction of subway stations, shafts and tunnels.

Tunneling today is based on two main streams of available techniques.

- The fully mechanized tunneling technique (***MT***) using boring machines (Figs 1a,b).
- “Hand Mining” (***HM***) techniques using a tunnel excavator or road header (Figs 2a,b).

Figure 1a: TBM launch at Dublin Port Tunnel - Dublin, Ireland 2002
Figure 1b: Raise Boring Machine for inclined shaft at a copper mine - Bolivia 1986


Figure 2a: Tunnel excavator at Heathrow Trial Tunnel - London, UK 1994
Figure 2b: Road header at Exchange Place Station - Jersey City, NJ 2002

For deep shafts, today's construction is dominated by the raise bore (Fig 1b) technique while shaft sinking with pre-cast liners and/or shotcrete support is used for rather shallow projects. In tunneling, TBM's for hard rock and Shield machines for soft ground both of which use pre-cast segmented liners as ground support, are considered the fully mechanized technique (***MT***).

"Hand mining" (***HM***) in soft ground for shafts and tunnels means using a tunnel excavator or road header (Figs 2a,b) with the excavation proceeding incrementally. Earth support of each increment follows immediately step-by-step using shotcrete, lattice girders and rebar spiling, etc. Hard rock excavation uses drill and blast techniques with automated "boomer" rigs drilling patterns of blasting holes with similar support elements as used for soft ground conditions (Fig 3).

Figure 3: "Boomer" Automated Drill Rig used on the Graz Bypass Tunnel – Graz, Austria 2001

While the ***MT*** usually blocks (clogs) the excavation face, ***HM*** techniques provides free access to the entire excavation area, thus accommodating changing ground conditions and also changes to the shape of the tunnel. Although the excavation rate of a ***MT*** device is usually much higher than that of ***HM***, the latter can be applied for **excavation in any kind of ground conditions**. Mechanized techniques basically are suited for uniform geometry (circles) and uniform geotechnical formations providing high production rates under these conditions (three to ten times that of ***HM***). This fact can however be compensated in many cases by multiple excavation headings using additional shafts or adits for ***HM*** (and thus guaranteeing the schedule) while maintaining the advantages of face observation and ability to modify initial support system if necessary.

II …..AND BEYOND

Did you know

1. **Underground Construction** is a hidden art/science. In contrast to roads, buildings, bridges, dams, etc. where public visual access is easy and colleagues, competitor and/or other interested people can see, comment or audit it, "underground work" has very limited access. Therefore transparency between Designer, Contractor and Client is essential if they are to achieve their mutual goal. "Geology has a wide back" and is frequently used to cover up "unanticipated" events.

2. **Tunnels In Lieu of Bridges.** A popular misconception is that tunnels are more costly to construct than bridges! Today costs are comparable, often less expensive and less impacting for construction of tunnels especially for river crossings. In addition: *Bridges have a lifespan of 50 years compared to at least the 150 year lifespan of state-of-the-art waterproofed tunnels, which require a minimum maintenance program!* Mined solutions also offer a competitive alternative to the antiquated cut and cover approach with the added advantage of time and money savings. When factoring the additional cost attributed to environmental impact, utility relocation, extended construction time and volume of material, muck, concrete and steel; mining is the preferred method.

3. **Construction Methodology** depends on selected skill. One cannot let a consultant decide on something influencing his own fee without paying severe consequences.

4. **Prequalification** can reduce / eliminate competition and innovation. A level playing field must be maintained to assure fair evaluations of <u>all competent</u> firms.

5. **Teaming** cannot be left to the sole interest of the dominant leader (JV). To assure the best design team worthy of the owner's total confidence, the RFP should provide flexibility to allow the client to suggest changes utilizing qualified firms of his choice notwithstanding which proponent the firm was originally associated with.

6. **Dual Design** creates competition; it enhances identification with ones own work among Contractors. Hand mined techniques (***HM***) versus mechanical mining methods (***MT***) compare to house medicine versus the pharmaceutical industry; both should get a fair chance and not be killed by lobbying.

7. **Contract Flexibility.** Unit prices and appropriate specs can minimize/avoid disputes and gridlocks on site. It usually leads to the most cost effective quality end product.

8. **Schedule Can be Guaranteed** only by providing a flexible contract and an adaptable construction technique (***HM***) which minimizes environmental impact.

9. **"Tunneling is** a **dynamic** exercise where geotechnical properties, excavation steps and immediate support and excavation rate interact with each other while creating the final product (underground structure) from which the factor of safety is between 1 and over." This statement by Prof. L. Müller of Salzburg has been well reinstated by Dr. Liebsch in his paper which

compares the alternating movements of a bicycle rider to the state of equilibrium of a tunnel under construction.

10. Underground **Construction** such as Tunnels **is Not Replicable.** Construction methodology influences geotechnical properties. Products like tunnels cannot be dissembled into their original components such as mechanical or structural works. Ground movement is directly related to the mining technique and a wrong design concept does not become right just because it succeeded due to a more tolerant ground condition!

11. **Toolbox is the Key.** It allows mining in *all* ground conditions (Fig 5) and through all obstructions, including buried foundations without compromising geometrical requirements. This is also true for excavation of large caverns with minimal cover. No impact at the surface is a major factor and eliminates many problems arising when using ***C/C*** methods.

12. **Collapses / Downfalls** (Figs 7a,b,c) happen mainly on night shifts and/or on weekends. In most cases, they are a management problem. If specified and priced in the bid documents their occurrence reduces substantially!

13. **Seismicity.** NATM / SEM tunnels have survived severe shock and shear waves of seismic activities without damage. *To date, there are no reported cases of any NATM tunnels collapsing due to an earthquake.*

14. **Site Supervision** quality which meets the highest possible international standards must be emphasized for the construction. To assure that this goal is achieved, the responsible designer must participate in supervision of his specified techniques. Destructive competition between third party field supervision and the designer should be eliminated; it only feeds lawyers and ruins the quality of the end product.

15. **Monitoring** (in-situ control) is documentation! It should be awarded to an independent special contractor and paid directly by the client.

16. **Competence and Risk are Inverse Proportional.** How to identify competence? Track record? There is a direct relationship between the competence of the Designer, Execution Group and the effort exhausted by the Client in identifying and putting his trust in his group of choice (Venturato)……and the Risk? Risk can be controlled by asking the right questions and accepting the true answers. The insurance industry has suffered huge losses by ignoring these simple facts.

III SOFT GROUND TUNNELING

Sprayed Concrete Support - A Brief History

Sprayed concrete (shotcrete) was invented in the US at the turn of the 20th century and has since been used as a protection layer for corrosion, fire and also for slope protection and support. It was first used as a structural support to stabilize squeezing ground in 1954 in an 8m diameter diversion tunnel for an Austrian power plant. Its name “New Austrian Tunneling Method” was reinstated by Prof. Rabcewicz (1964) after having been used for a modification of the “Austrian Tunnel Method” in the turn of the 19th century. After a number of successful applications in water, rail and road tunnels, this method was adopted for the first time in an urban area in 1968 for a section of the Frankfurt Underground Scheme in Frankfurt Clay. Its flexibility, economy and excellent safety record led in the 70's to using NATM for more than two thirds of Germany’s urban mass transit tunneling in more than 10 major cities where the geology was mostly clay, silty clay, silt, soft marl and other similar soft ground conditions.

In the intervening years many large cities around the world have taken advantage of this method, e.g. Athens, Brasilia, Calgary, Dallas, Edmonton, Frankfurt/Main, Folkstone, Göteborg, Hong Kong, Istanbul, Johannesburg, Kyoto, Lisbon, London, Madrid, Nürnberg, Oslo, Paris, Rome, Sao Paolo, Santiago, Seoul, Tokyo, Ulm, Vancouver, Vienna, Washington D.C., York, Zürich amongst many others.

Design Principles

Soft ground, when excavated can be compared to a highly viscose liquid with a limited stand up time. This fact leads to the most important requirements/rules of NATM:

- The excavated cross section should always be an *ovoid* shape.
- Installation of immediate and continuous *smooth support* around its perimeter (and, if required, smooth support at the face) is a significant factor in minimizing initial movement in the surrounding ground.
- It is also essential to structurally *close the supporting ring* (shotcrete) as quickly as possible within one tunnel diameter of the advancing excavation face.

The 3-dimensional *stress redistribution* around the tunnel depends on geometry and time. This must be carefully considered particularly where multiple openings are planned. It will govern the progress of tunneling with respect to stress redistribution interaction and the hardening of the shotcrete support.

After providing the basic design parameters as described above, the required thickness of support (shotcrete) for a given tunnel/shaft diameter and overburden is basically a reversed function of the internal angle of friction of the formation. Calculated bending moments in ovoid shaped tunnels have little to do with reality. Heavy reinforcement in the lining only weakens the shotcrete support capacity due to shadowing and, therefore, produces an inconsistent lining with a questionable shotcrete quality. Proper structural models applied with skill and experience result in minimum bending moments and therefore require less reinforcement.

Continuous (and, if applicable symmetric) excavation of (multiple) drifts avoids inhomogeneities in stiffness and smoothes the stress redistribution in both the lining and the surrounding ground.

NATM is an *observational method*, which means that monitoring (in-situ-measurements) of *deformation* in the ground and *stress* in the initial lining (shotcrete) is essential to the actual support means.

Any *remedial work* caused by violation of material specification, miss-alignment, or other construction errors and unforeseen conditions must be carefully designed and must follow the same step-by-step approach as adopted for the main design work.

The success of execution of the NATM is based on four premises:

- Thoughtful design by an experienced engineering team
- Execution by a skilled contractor
- Competent supervisor
- Interpretation of monitoring results

Dual Design

For short tunnels (<1.5 mile), shafts and tunnels with changing geometry, and/or substantially changing geotechnical behavior, hand mining is more cost effective. There is a gray area where hand and mechanical mining may be equally considered (Fig 4) and where a dual design is recommended.

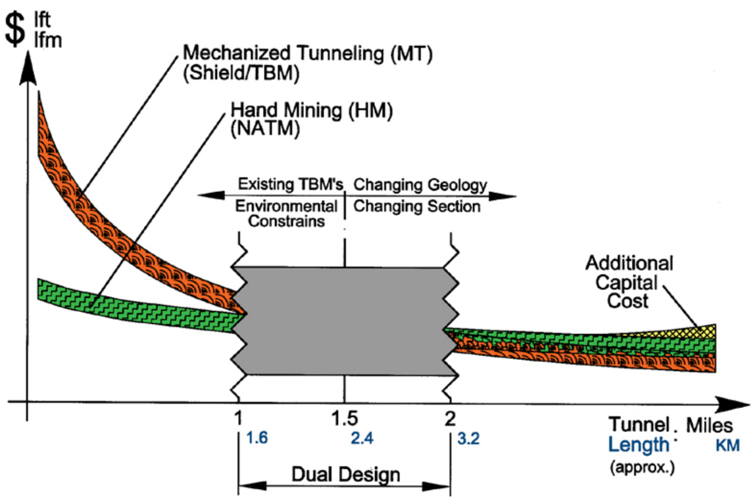
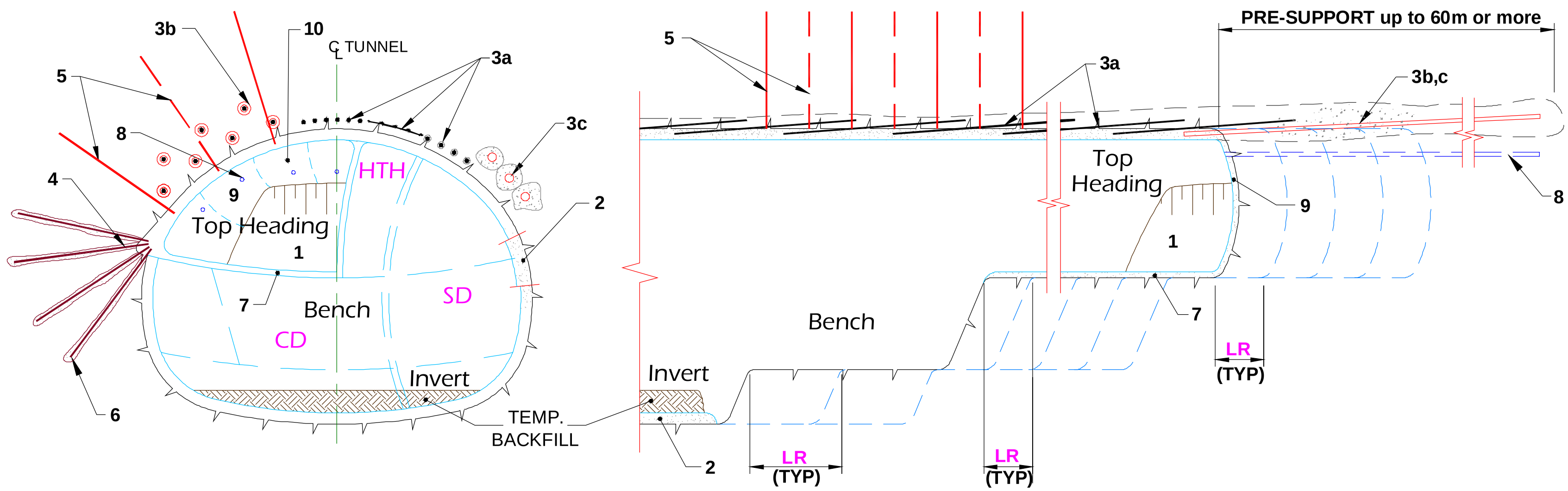


Figure 4: Tunnel cost of Mechanized Tunneling (**MT**) versus Hand Mining (**HM**) over tunnel length.

It has been proven advantageous to provide a *dual design* giving the bidders the choice to select their preferred construction method (e.g. TBM, Shield, or NATM). The minimal additional design expense is by far compensated by the increased competition and finally by the much stronger identification of the contractor with his chosen method.

Toolbox

I am often asked, "What is the limit of NATM / ***HM***?" "None!" is my answer. With today's available ***TOOLBOX*** (Fig 5) any kind of ground condition can be handled safely by following the incremental excavation/support and/or pre-support approach.



GEOMETRY & PROGRESS:

Multiple Drift Method (reducing excavated area) i.e.
Top Heading, Bench, Invert or Half Top Heading (**HTH**),
Bench Invert/Side Wall Excavation Method/
Multiple Drift Invert Support (Shotcrete),
Decrease Invert Closure Distance.
Decrease Length of Round (**LR**).
Subdivision of Cross Section
-Side Wall Drift (**SD**)
-Center Drift (**CD**)
-Multiple Drift
Continuous Excavation/
Support Rate 24 hours

PRE-SUPPORT:

Dewatering of the Excavation Area, (if necessary with Vacuum Lances (**8**)).
Spiling with Various Elements like Rebars, Cement Bonded Rebars (GSA), Grouted Pipe Spiling, Metal Sheeting, etc., (**3a**).
Barrel Vault Method (BVM), Length approx. 35 to 60m (**3b**).
Horizontal Jet Grouting Method, maximum Length approx. 20m each (**3c**).
Grouting of Face Area Ahead of the Excavation.

FACE SUPPORT:

Stabilization of the Face with Earth Wedge (**1**). Stabilization of the Face with 2" Flashcrete (**9**).
Pocket Excavation Method (**10**).

SIDE WALL IMPROVEMENT:

Increasing the Width of the Shotcrete Foundation (**4**) (If viable).
Improving the bearing capacity at springline with Grouting, Grouted Pipe Spiling or GSA (**6**).

ANNULAR SUPPORT:

Increasing the Thickness of Shotcrete (**2**). Increasing the Number of Rockbolts Increasing their Length (**5**). Installing a Temporary Shotcrete Invert in the Top Heading (**7**). Grouting of the Entire Surrounding Ground.

OTHER SPECIAL METHODS:

Excavation under Compressed Air. Excavation in Frozen Ground (Ground Freezing Method).
Doorframe Slab Method (DSM). Barrel Vault Method (BVM) (**3b**). Micro Tunneling Methods, etc.

EMERGENCY INTERVENTIONS:

1. High pressure PU steel bottles with 3m lances.
2. Timber or Steel beams (various sizes for bracing).
3. Crushed gravel (20 cy face support backfill, coarse grained, 3" to 8" diameter).
4. Pre-mixed dry shotcrete bags for immediate support.

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Figure 5: NATM Toolbox

These are the elements of its success:

- ***Geometry and Progress*** may vary from full face to subdivision of the excavation face in top heading, bench, side wall drift, or multiple drifts, etc. The reduction of the length of round or, if necessary, continuing excavation and support flow around the clock in extremely (viscose) soft ground, influences the progress. Geometry and progress can be adapted as necessary.
- ***Pre-support*** may start with dewatering of the excavation area and/or spiling with various elements. The barrel vault method is probably today's most effective pre-support over longer stretches. Horizontal jet grouting also improves the ground ahead of the excavation line as does conventional grouting of the surrounding ground.
- ***Face support*** may consist of only the existing ground (earth wedge) or additional shotcrete, or even face bolting. Pocket excavation or multiple drifts are another safe and effective face support technique.
- ***Side wall improvement*** and full annular support.
- ***Special methods*** (i.e. Ground freezing, Compressed air, Barrel Vault Method or Doorframe Slab Method etc.) provide a variety and enormous number of possible combinations to tackle any kind of ground.

Today, NATM is used for any type of tunnels, but typically for mined stations, shafts, adits, widenings, caverns (US), mined branches (UK), step plate junctions, escalator drifts and all other underground and mined facilities.

IV CONTRACTUAL ISSUES

Type of Contract

A few words about the crucial contract philosophy: The climate around a construction site is controlled by a fair bid price, the construction contract, and the *competence* of all involved parties! It is the basis for the project's success both technically and financially. The contract should follow a fine line between *performance specs and method specs* to balance the client's and contractor's interest and risk (Fig 6a). Given this and a competent construction management, with experienced and skilled supervising personnel on one side and an experienced and skilled contractor on the other side, a successful project is guaranteed.

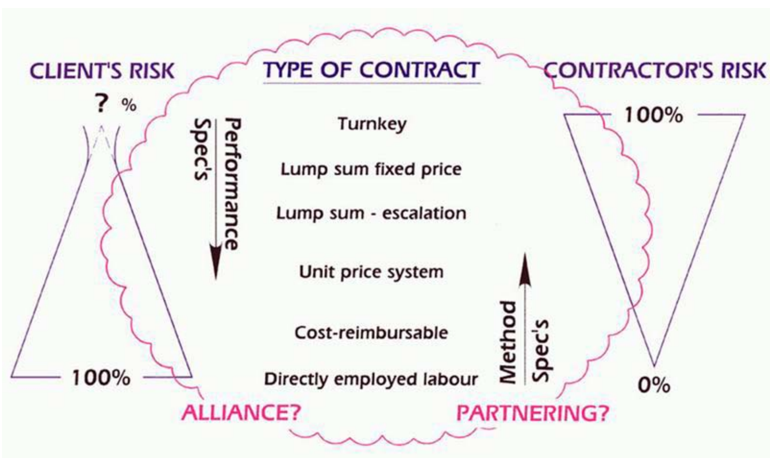


Figure 6a: Type of Contract, Spec's and Sharing of Risk Diagram (CIRIA 1978, modified)

Size of Contracts

Mega contracts, according to the motto "the bigger the better" are tempting, in that by putting all eggs in one basket it appears to make the client's life easy and simple! The consequence however lies in control and flexibility. Many tunnel projects are part of an overall scheme which includes surface lines, buildings, bridges, etc. If subdivided into smaller segments (even one long tunnel can be attacked from different locations using multiple portals, shafts and adits by several contractors with flexible volumes competing with each other) the client can then control, amend or change parts of the work as necessary without jeopardizing the entire project.

Construction Methods

One can also reflect upon the trend of consultant's default usage of proven construction techniques in lieu of an innovative approach. By introducing latest technologic advancements the client stands to gain from possible cost reductions, time savings and less obtrusive effects on the local environment but sometimes they shy from the perceived risk of innovative methods.

Documentation

Monitoring, in-situ-measurement and document control performed independently (by a specialized contractor hired directly by the client) not only wages the viability and effectiveness of chosen excavation and support steps and elements but serves as an escrowed documentation for later attempts to divert from target.

Site Supervision / Professional Relationships

The three columns on which the success of the project rests are as mentioned: Bid Documents, Execution and Supervision (Fig 6b). The ongoing discussion whether the designer should be part of supervision should be answered with a clear "YES!" He created the philosophy behind and can be involved in the execution to control its implementation, effectiveness and create necessary alterations. As far as professional cooperation, each entity (Client, Contractor, and Engineer) must be represented by qualified professionals whose common goal is the success of the project. This encompasses Quality Control, Budget Control and Timely Completion.

Figure 6b: Three pillars for the Client's success.

Unit Price System

Getting paid for what has been done on site under actual conditions eases tension and risk for both sides. Reasonable allowances provided in the bid documents avoid cost overrun during construction. There are, of course, also a number of fixed items which may be bid on performance specs and are paid for by lump sum (i.e. mobilization, waterproofing, documentation, etc.).

Tunnel Collapses / Sinkholes

Downfalls and Collapses (Figs 7a,b,c) always have to be considered in the contract since "unforeseen changes in geological conditions" are ironically occurring in its vast majority on night shifts and weekends. Utilizing the unit price system also for those occurrences as "pay items" has proven in the past to be the most effective way of avoiding them!

Even seismic activities do not pose a serious risk to completed tunnels. The physical principle behind this is simple: The sequential excavation produces a stress relieved (relaxed) zone around the tunnel while immediate sprayed smooth shotcrete support forms a composite structure with the surrounding ground. This cushion effect and its shell structure provide flexible resistance against shock and shear waves (Friaul, Northern Italy, 1974).

In contrast, cut-and-cover structures are prone to adverse stress peaks impacts, which can lead to their total destruction (Kobe, Japan 1995).



Figure 7a: NATM tunnel collapse on U-Bahn Subway - Munich, Germany 1994
Figure 7b: Shield tunnel collapse on Hollywood Blvd. - Los Angeles, CA 1995
Figure 7c: Cut-&-Cover SMRT station collapse destroys Nicoll Highway - Singapore 2004

V SUPPORT TECHNIQUES

Sprayed concrete is today's dominant support in ***HM***. Shotcrete or gunite (a wet or dry, fresh concrete mixture) is blown onto the wall by means of compressed air with or without additives such as accelerators for faster hardening or dust reducers, retarders, etc.

Shotcrete has revolutionized the effectiveness of ground support and has vastly replaced older support elements such as timber, ribs and lagging, steel arches and others. Shotcrete which is usually reinforced with welded wire mesh and/or fiber is typically applied in conjunction with lattice girders or in the old days with rolled steel arches. Shotcrete is applied after each excavation step and provides *immediate and smooth* support, the "secret" of this new support technique (Figs 8a,b)! It does not allow differential movement of ground particles hence avoiding raveling and ground movement. This unacceptable condition resulted in the past by slow and insufficient ground support, ending with excessive ground load.

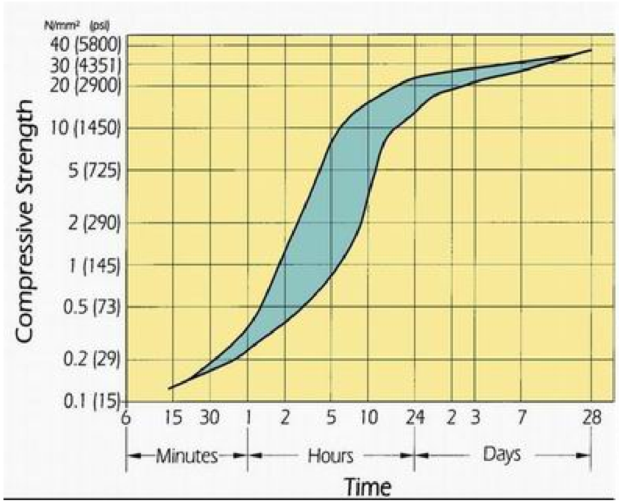


Figure 8a: Typical shotcrete hardening curve.
Figure 8b: Shotcrete application at top heading of Lehigh Tunnel #2 - Allentown, PA 1990

Pre-Support

In many areas, it became necessary to enhance (pre-support) the ground to provide adequate stand up time to accommodate hand mining. The stand up time can usually be improved simply by dewatering. The three dimensional stress redistribution, which produces a stress concentration in front of the face may lead to liquefaction of the ground, if too much water is encountered. By dewatering, this effect can be avoided or minimized. Another easily installed element is the physical roof support by means of spiling. These are steel bars with diameter of 1¼ – 1½ inch and length of up to twelve feet, driven above the excavation line ahead of the tunnel at one half to one foot centers (Fig 9a). One major advantage of spiling is the creation of *micro-arches* between the bars due to the compaction of the ground around the spile umbrella (Fig 9b).

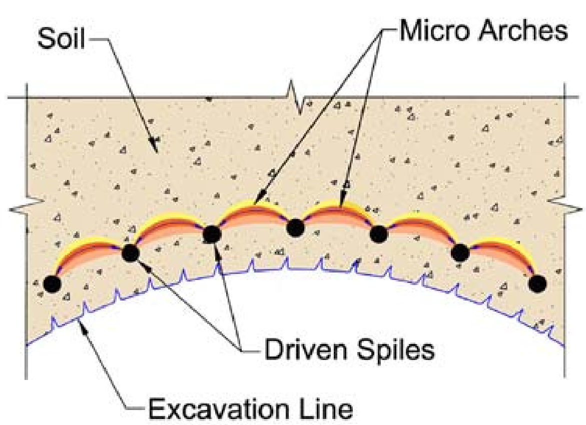


Figure 9a: *Micro-Arch* Detail (Soil Compaction from Spile Installation = Soil Support at Excavation)
Figure 9b: Rebar spiling installation at Rupertus Tunnel, OBB Austrian Rail Line – Austria 1990

Grouted pipe spiles (Fig 10a) are usually driven or pre-bored steel tubes in which grout is injected into the ground, thereby improving the physical ground conditions. Its diameter may very according to geology and excavation geometry (Fig 10b).

Figure 10a: Grouted pipe spiles MBTA – Boston, MA 2004
Figure 10b: Grouted pipe spiling installation at tunnel face Monastiraki Station - Athens, Greece 1995

Another development in the last twenty years is horizontal jet grouting (Fig 11). Most of us know vertical jet grouting, since it has been used for more than forty years. By turning the rig in the horizontal position, jet grout columns of about three to four feet diameter with a length (depth) of up to 40-50 ft. are installed in advance of the tunnel, forming a protective grouted umbrella around the excavation perimeter.

Figure 11: Jet grouting umbrella in Talus material for highway tunnel - Karinthia, Austria 1986

Grouting and/or freezing the ground above, around and ahead of excavation is used today with great success (Figs 12a,b) and will be introduced on a current innovative project in Boston later within this article under “Special Construction Methods”.

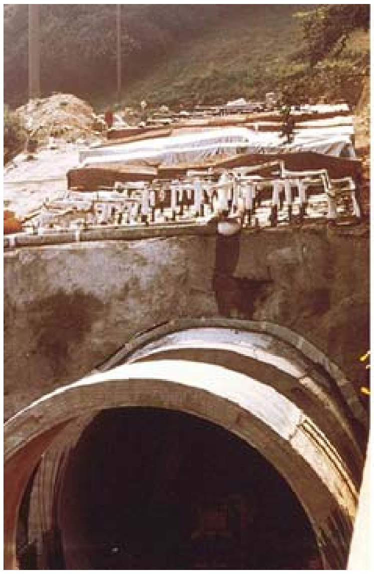



Figure 12a: Vertical freeze pipes above rail tunnel portal - Hannover, Germany 1985
Figure 12b: Horizontal freeze pipes at Stuttgart Metro - Stuttgart, Germany 1974

The most proven and cost effective method of pre-support is the so called Barrel Vault Method (***BVM***). This method consists of an array of horizontal boreholes 60 to 120 ft. or more in length (directional drilling, if necessary) from which grout is introduced into the ground under pressure up to the equivalent of the overburden pressure. This process develops a pre-stressed vault under which the excavation can commence without any noticeable surface deformation. The ***BVM*** has been used in the past on many different sites and can be installed in most ground conditions today (Figs 13a,b).

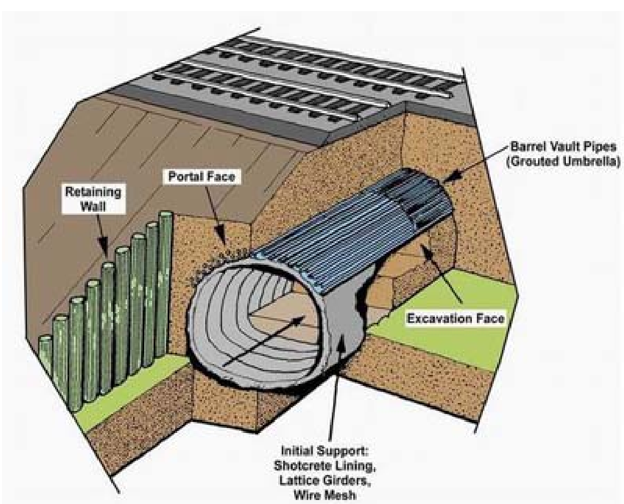


Figure 13a: Illustration of the ***BVM*** installed under rail embankment.
Figure 13b: Barrel Vault tubes installed beneath active rail line - Oberrieden, Germany 1990

Another innovative application for the ***BVM*** was recently introduced for a grade separation rail underpass located in Chicago (Fig 14a,b) where the proposal called for construction of a tunnel below an active three-track rail crossing located within a busy industrialized area. The design utilizes directional drilling to construct a grouted vault support arch to accommodate mining of a binocular tunnel without interrupting rail traffic. The rail crossing is not unlike many of the dangerous, traffic blocking, problem crossings that exist throughout the US. This new approach introduces a cost effective solution to remedy the hazards inherent in both rail and road crossings.

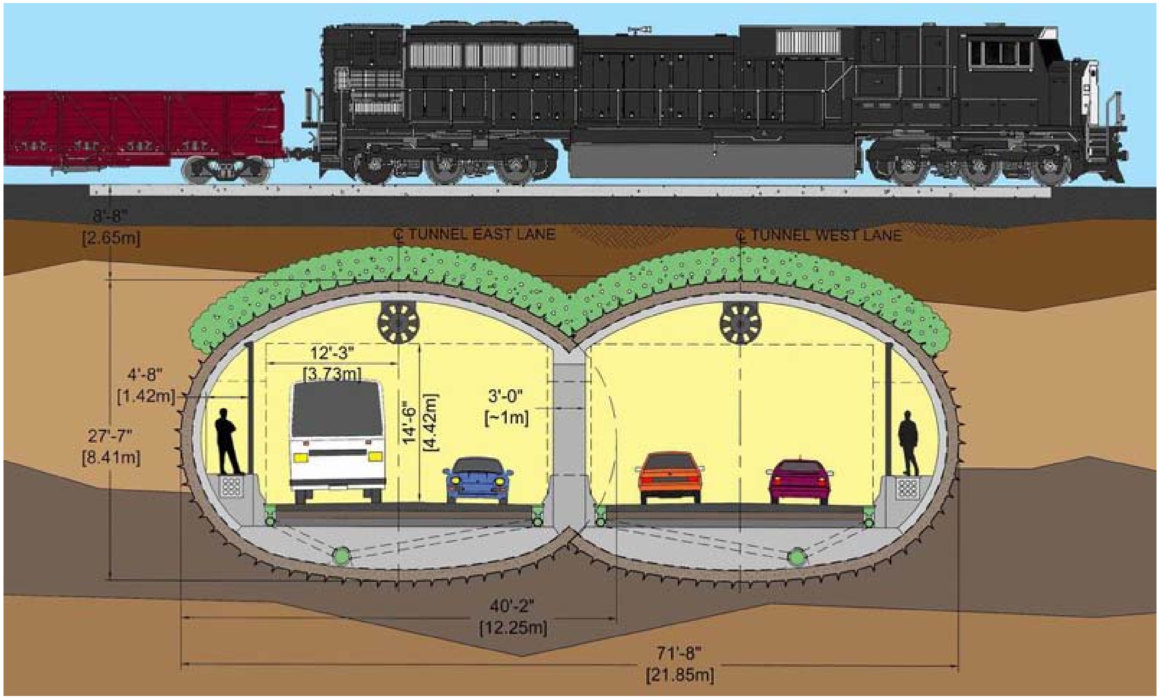


Figure 14a: Cross section for grade separation using the ***BVM*** – Chicago, Illinois 2003

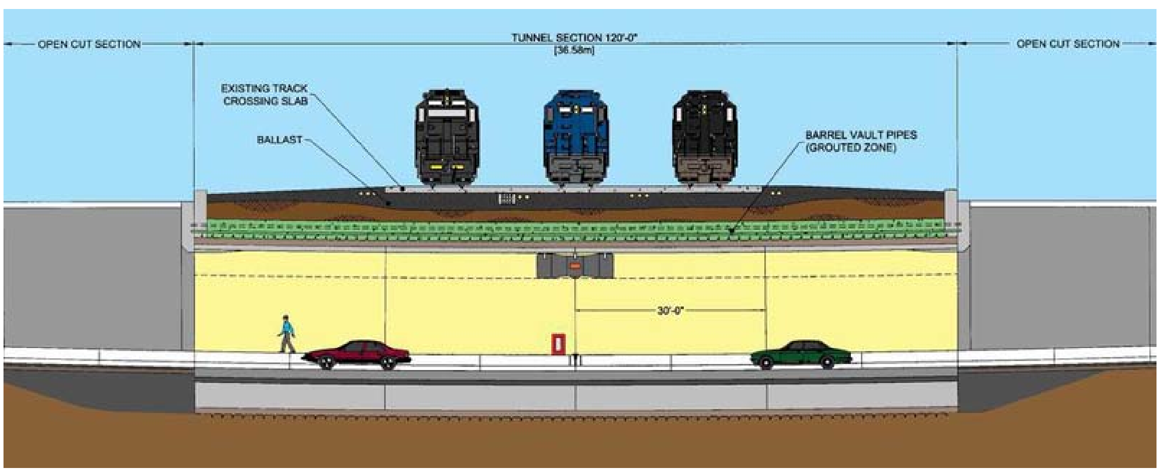


Figure 14b: Profile for grade separation using the ***BVM*** – Chicago, Illinois 2003

Face Support

One of the most common and simple support methods is leaving an earth wedge in front of the face to support it against raveling and moving inward (Fig 15a). Shotcrete face support is often used in combination with the earth wedge or other methods. Another type of face support used in the past, consists of face nailing. It is expensive compared to the other choices; however hinders the progress and does not always serve its purpose. Pocket excavation in very soft ground has been used many times as a last resort with success. It is excavating a series of small (one bucket) pockets with immediate shotcrete support as each pocket is exposed. This procedure is continued until the full round is completed (Fig 15b).

Figure 15a: Face support earth wedge at Paris Metro - Paris, France 1976
Figure 15b: Pocket excavation in soft ground CTRL Wayside Shaft - London, UK 2002

One of the most proven face stabilization techniques is simply the reduction of the excavation size by subdividing the face into multiple drifts. Geotechnical physics shows that the deformation of the surrounding ground is a function of the diameter of the excavation face to the power of 2.5 (Figs 16a,b)!

In Santiago, Chile, 150m² caverns are excavated 7-9m below the city streets for the metro. The cavern's face is divided into side-wall drifts and a central core section. Each section utilizes a top heading, bench and invert sequence. This approach eliminates the need for forepoling or spiling ahead at full span top heading rounds under shallow cove and allows optimum rotation of equipment and crews between several advancing faces.

Metro de Santiago commissioned a comprehensive study of the probable costs, logistics and feasibility of using TBM technology on the 8-9km of Line 4 running tunnels between Rhotonda Grecia and Tobalaba Stations. This was initiated particularly to address excavation options for a section of this route through deposit clay and through potentially water bearing ripio close to the San Carlos Canal.

Three TBM alternatives were studied: one large TBM, two smaller TBMs and four TBMs. It was confirmed that NATM was the most cost effective option. NATM was 20% cheaper than the lowest TBM alternative.

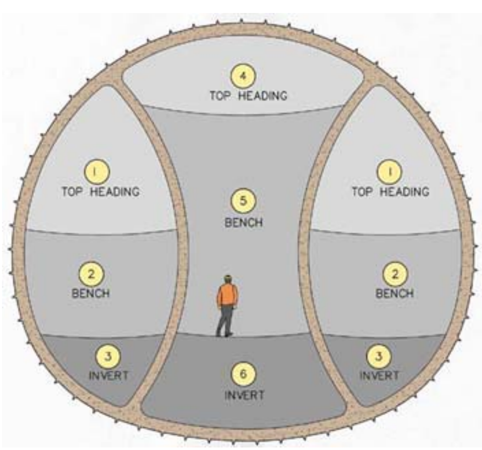
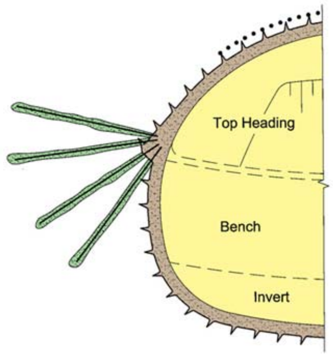


Figure 16a: Cross Section of Multiple Drift Method.
Figure 16b: Twin Sidewall Support Drifts at Metro de Santiago - Santiago, Chile 2002

Side Wall and Annular Ring Improvement

In the old days, the "elephant footing" was the only workable way to rest the (brick or steel) arch on the ground at the springline by means of enlarging its footings. Grouted spiles in this foundation area and also at side wall footings are much more effective (Figs 17a,b). The bearing capacity of the annular support can be enhanced with systematic bolting or anchoring and if necessary increasing the thickness of shotcrete (Fig 17c).



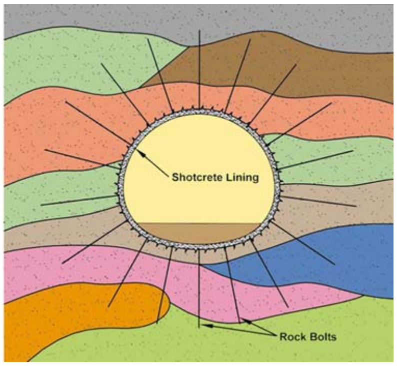


Figure 17a: Grouted spiles at sidewall footings.
Figure 17b: Installation of grouted spiles at sidewall of Wadeküppel Tunnel – Kassel, Germany 1984
Figure 17c: Systematic rock bolting to enhance the "Arching Effect"

Since ground deformation is time dependent, the increase of excavation rate is advantageous. Moreover, the continuous excavation and support cycle (no night breaks, no weekend breaks) has been proven very effective taking into consideration the shotcrete hardening process.

Special Construction Methods

Compressed Air – NATM

For more than a hundred years compressed air has been used to construct foundations using the caisson technique but also for hand mined tunnels in combination with air locks. More recently NATM has taken advantage of compressed air to keep groundwater in place during open face mining (Fig 18). Since the use of compressed air in underground conditions has been thoroughly studied and regulated, it has become a common and safe method of construction.

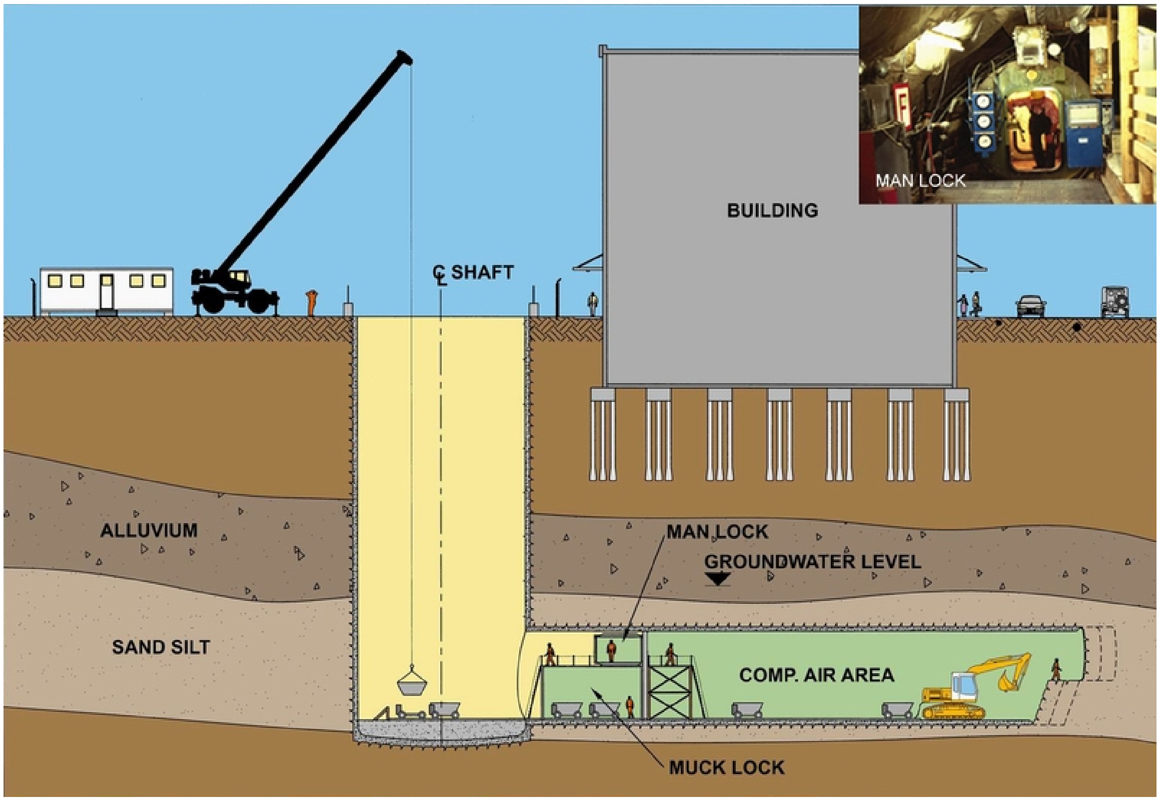


Figure 18: Typical compressed air tunnel layout.

Ground Freezing

It has been said, *"when all other methods failing, ground freezing still works"* (Howard Haywood, MBTA, Boston 1995). It was introduced into shaft sinking and tunneling some 50 to 60 years ago and is used with success in conjunction with NATM as recently demonstrated in Boston (Figs 19a,b).

Figure 19a: Freeze pipes in basement of Russia Wharf Building above tunnel MBTA – Boston, MA 2002
Figure 19b: Tunneling around an obstruction and timber piles in frozen ground MBTA - Boston, MA 2002

Tunneling under Russia Wharf, a historic building complex located in Boston (Fig 20) is the first U.S. application of NATM in combination with ground freezing. The 325 ft. long binocular tunnel passes through a forest of 100-year-old timber building foundation piles. The piles are cut and incorporated in the tunnel liner, thus transforming the pile foundation to a large strip foundation. Excavation sequencing comprises 2 rounds of top heading followed by bench and invert excavation. Advance rates range from 3–4 ft./day, depending on the number of piles incorporated in the tunnel liner (Figs 21a,b).

Figure 20: Historic Russia Wharf building complex - Boston, MA 2003

Advantages of NATM include preservation of the historic value and undisturbed operation of the occupied building during construction.

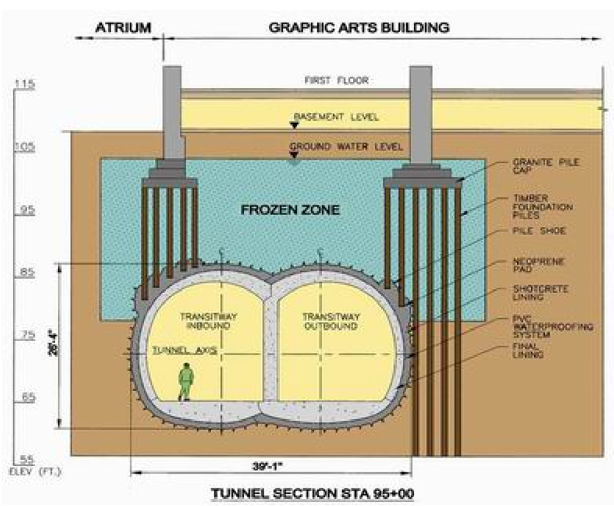


Figure 21a: Typical cross section beneath building at Russia Wharf MBTA - Boston, MA 2002
Figure 21b: Exposed frozen ground and timber pile caps in tunnel crown MBTA - Boston, MA 2002

Doorframe Slab Method (DFM)

The Door Frame Slab Method (***DFM***), a semi-cut-and-cover method, provides a pre-installed concrete roof slab with brackets for rather shallow tunnels. This allows for safe mining beneath this protective slab (Figs 22,23).

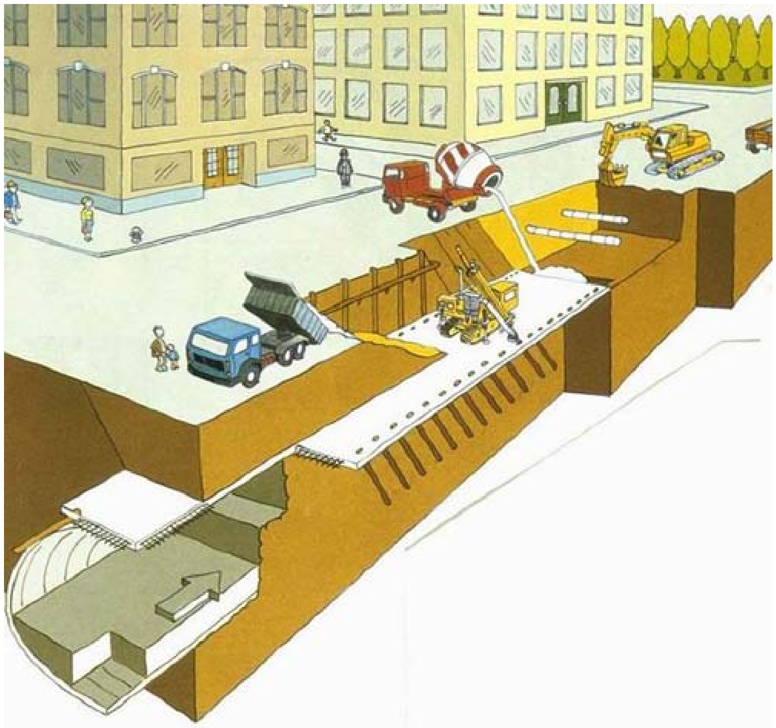


Figure 22: Schematic diagrams of ***DFM*** installation sequence.

Figure 23: ***DFM*** installation at Taquatinga Metro Tunnel - Brazília, Brazil 1995

It also can be applied in water saturated sand formations. The major problem of constructing a shallow tunnel in these conditions is keeping the water out, keeping the face and invert stable while the structure is advanced within the slurry walls. An alternative to today's methods of jet grouting the bottom, chemical grouting between the slurry walls etc. is using a localized dewatering concept within watertight slurry walls. By means of immediately placing a watertight sprayed concrete invert step by step and as close as possible to the excavation face, water inflow is restricted to a minimum. A system has been developed as shown in the series of drawings below (Fig 24a,b).

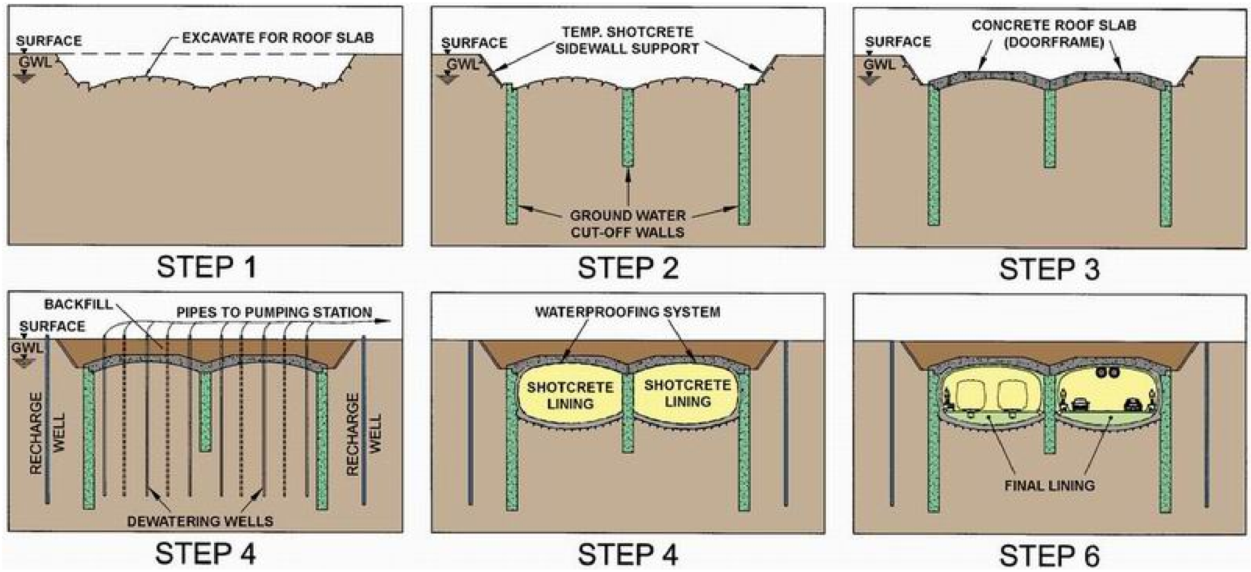


Figure 24a: Proposed installation sequences sections for JFK Airport Access Tunnel - New York, NY 1998

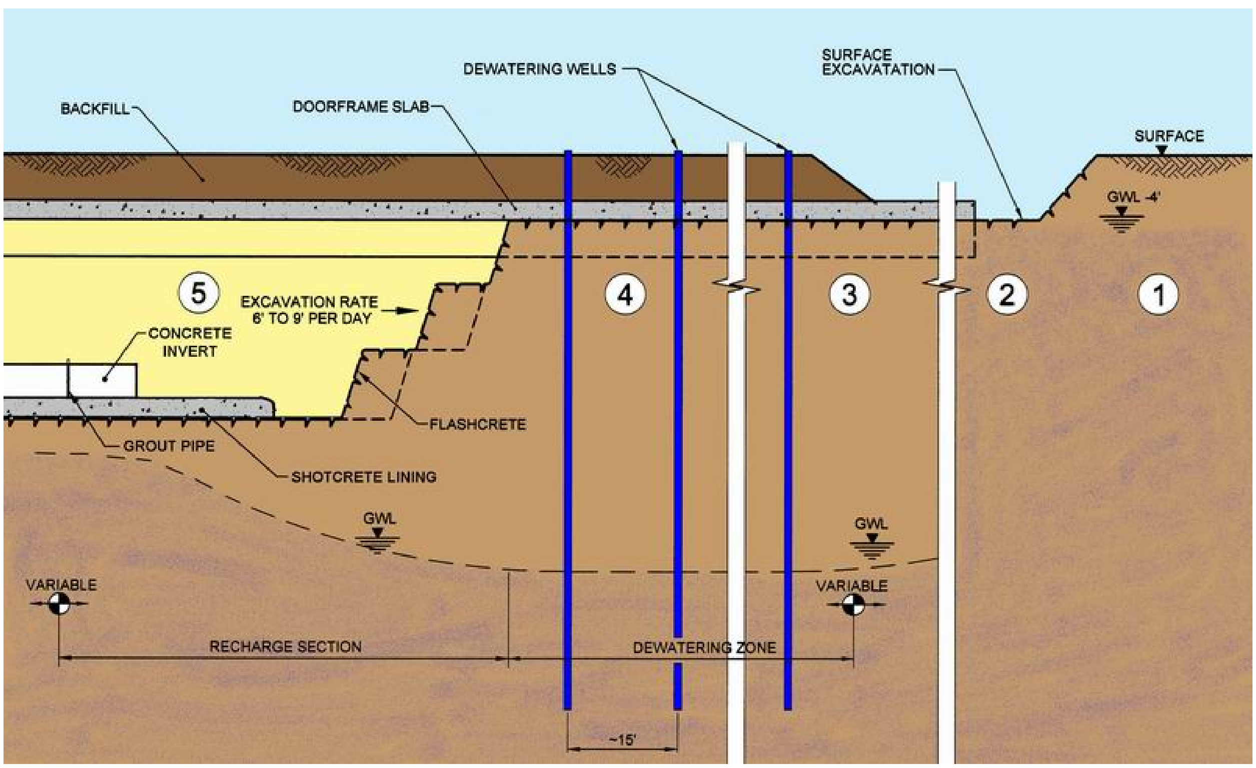


Figure 24b: Proposed excavation sequence with dewatering scheme for JFK Airport Access Tunnel - New York, NY 1999

Caisson Method

To design a river crossing south of London, the concept of an underwater DFS Method was developed by DSC and Howard Humphry. The method consists of first dredging a trench in the river bed to provide formwork for the tunnel roof. Reinforcement cages are then placed within the trench. Underwater concrete is poured with a thickness of approximately two feet (varies depending on the size of the tunnel). The area beneath the concrete roof slab is then jet-grouted to improve ground conditions. Subsequently, the trench is backfilled followed by mining the tunnel beneath the concrete roof slab.

An improvement of this method recently developed is the so called "Caisson Method". The concept is based on the creation of a "caisson" by installing watertight lateral walls and a watertight roof slab on top. The roof slab may consist of either cast-in-place (Fig 25) or pre-cast concrete elements (Fig 26). The tunnel is subsequently excavated, protected by the roof slab and the lateral cut and cover walls. Compressed air can be applied as required to control water inflow. Excavation of the ground is carried out by using an excavator or road header, etc. with NATM support elements (Fig 5). Usually a top heading / bench / invert excavation is proposed with side wall drifts or dual side wall drifts as required (Figs 16a,b).

Benefits

- Tunnel construction costs are comparable when factoring bridge alternatives.
- In addition the usable life span of a tunnel is four times longer than that of bridges.
- Maintenance and operational costs are far below those of bridges.
- Open waterway: no limit to navigable watercraft size nor draw-bridges to tie up traffic.
- Urban revitalization for the public such as parks or river walk developments.
- Removal of the typical "under bridge" desecrated areas.

Underwater jet grout columns are state-of-the-art as is sheet piling and freezing in tunneling operations. The tunnel lining is constructed using an initial shotcrete lining installed immediately after excavation, followed by a watertight membrane waterproofing system and a final concrete or shotcrete lining. Special emphasis is given to the waterproofing system. The proposed closed membrane system is enhanced with a compartmentalization and remedial grouting option to assure a watertight structure.

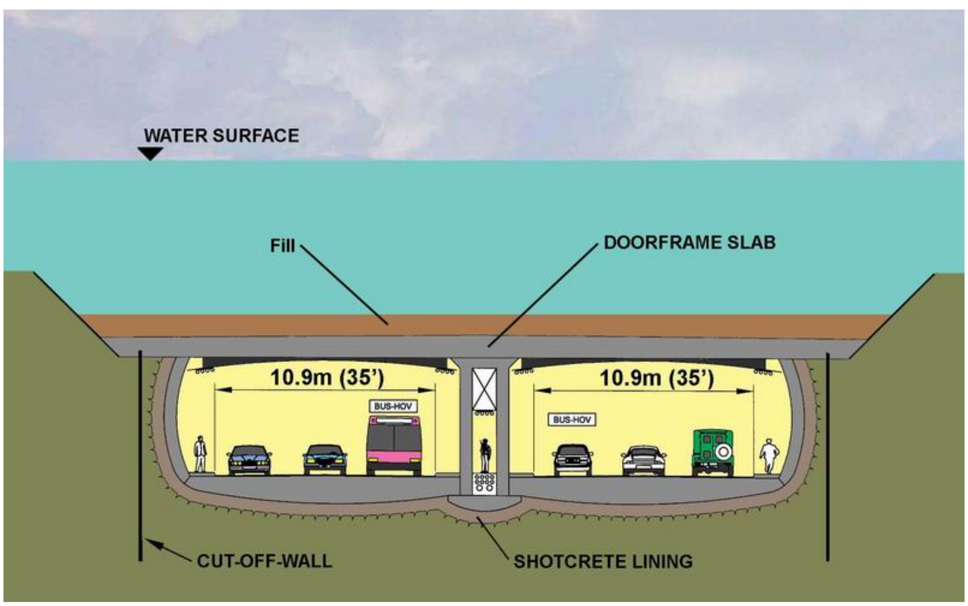


Figure 25: Underwater DFS section proposed for the 3rd Harbor Tunnel at Hampton, Virginia 2001

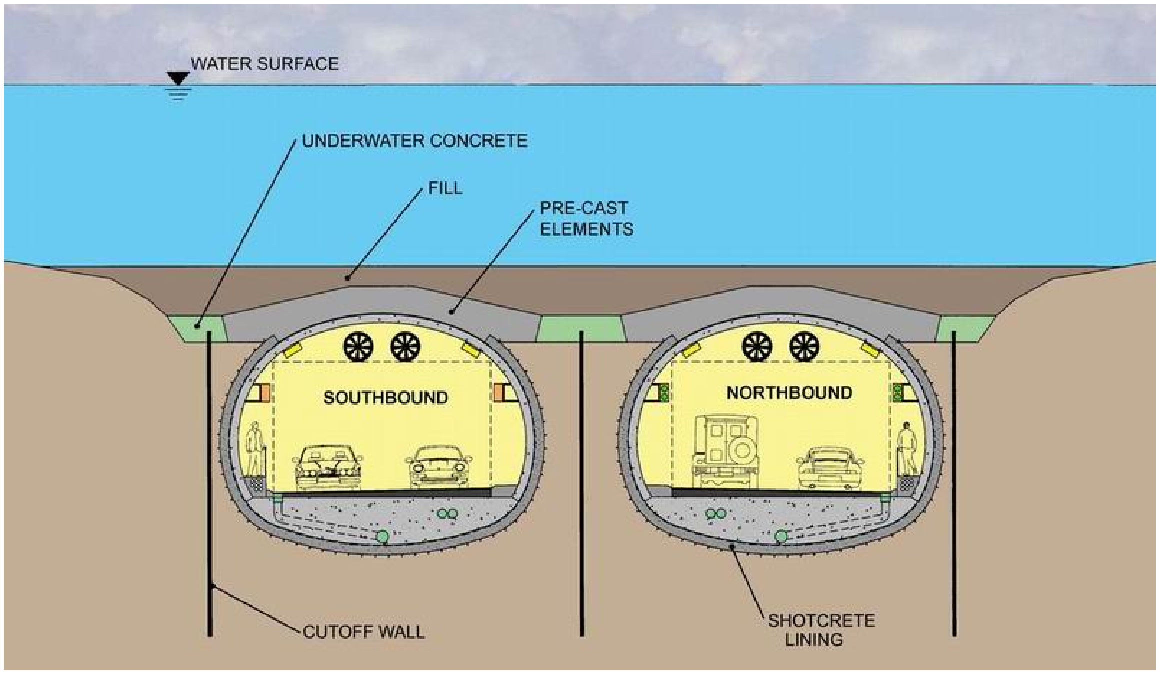


Figure 26: Caisson Method using pre-cast elements for river crossing Miami, Florida 2003.

VI WHAT ELSE?

Portal Canopy

To construct a tunnel it has been proven prudent and cost effective to begin with canopy structure. This consists of a reinforced shotcrete arch to protect the construction activities in the portal area and to provide a final portal structure which can be waterproofed continually throughout the tunnel (Fig 27).

Figure 27: Shotcrete canopy portal structure at B27 Bypass Tunnel - Schürzeberg, Germany 1991

Waterproofing

All underground openings produce moisture, dripping or flowing water! Ventilated tunnels may appear to be dry along most sections but only because the natural dampness evaporates on the shotcrete surface! As soon as an impervious vapor barrier is applied dampness on the ground side will build up / collect immediately!

In addition, underground structures as well as surface structures are undergoing permanent motion. The causes of this strain and stress redistribution are temperature, moisture changes, tectonic activities, and other sources of strain. The consequences of this permanent movement in concrete are cracks which open and close periodically hence the only effective waterproofing is: ***wrap the final structure in an impermeable flexible membrane!***

Fortunately more and more clients understand today (burned in the past by older leaking tunnels) that waterproofing in underground structures not only protects electrical and mechanical equipment but also provides a clean and safe environment. It further protects the final structural lining against corrosion and adverse effects of ground water, corrosive minerals, and aggressive chemicals.

Four principles in waterproofing have to be observed:

- *Where is the water coming from?*
- *Where can the water be drained?*
- *How to maintain the drainage system?*
- *How to avoid clogging and freezing of the system?*

The waterproofing system introduced in the US in 1983 on a section at WMATA with a flexible impermeable plastic membrane has been proven successful and has been applied since then on many NATM and Shield Tunnels but also on cut and cover structures (Figs 28a,b).

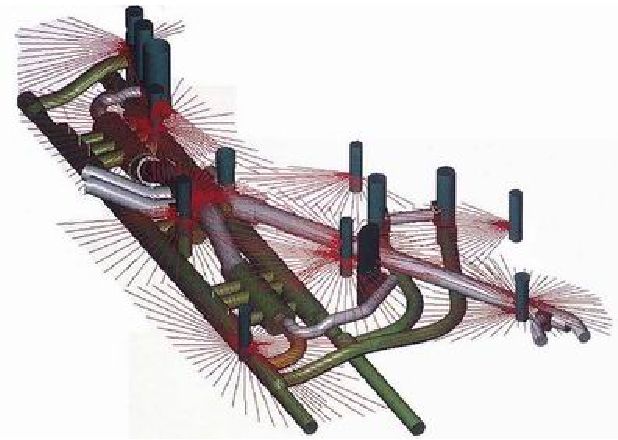
In the meantime, this system has been recommended by the Federal Transit Administration in their *Lessons Learned Program* as the waterproofing system of choice for underground structures.

Occasionally, we still hear the story that a colleague overheard while visiting our project at the Washington Dulles Airport Pedestrian Tunnel: An E&M worker holding a concrete drill with an overly long bit attached saying, “What’s all this white stuff coming out of these drilled holes?”, apparently not realizing the blunder made by drilling through the invert waterproofing membrane!

Figure 28a: Membrane waterproofing used on Section F6b WMATA - Washington, DC 1995
Figure 28b: Waterproofing on a Cut-and-Cover box at the World Trade Center Station - Boston, MA 1998

Compensation Grouting

In urban areas surface deformation (settlements) causes more and more environmental problems. It cannot be avoided but can be minimized and/or compensated by grout injection adjacent to the underground structure. This compensation grouting has successfully been applied in a number of cities world wide, one of the more recent applications has been in London during the construction of the Jubilee Line Extension, 1992-1998 (Figs 29a,b).



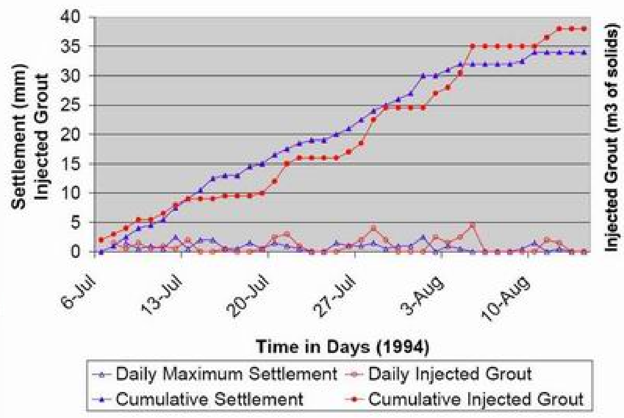


Figure 29a: Compensation grouting 3D model for Jubilee Line - London, UK 1994 (Dimmock, Lackner)
Figure 29b: Compensation grouting at Red Cross Way, volume record with settlement, London, UK 1994

Rehabilitation

Most old tunnels are leaking because of sediment or grouting related clogging of their originally designed drainage system. This is the major aspect of rehabilitation; however there are a few brick or stone lined tunnels which need relining or widening. A major issue of rehabilitation is therefore the revitalization or the establishment of a positive waterproofing system. Not always an easy task in existing tunnels (Figs 30a,b and 31a,b)!

Figure 30a: Brunel Tunnel constructed beneath the Thames River in 1830's LUL - London, UK 1995
Figure 30b: Brunel Tunnel after rehabilitation with intricate cast-in-place lining LUL – London, UK 1997


Figure 31a: Berry Street Tunnel prior to rehabilitation - Pittsburgh, PA 1983
Figure 31b: Berry Street Tunnel after rehabilitation – Pittsburgh, PA 1996

Final Shotcrete Lining

The construction of a steel form or shutter is, in many cases, not economically feasible hence final shotcrete lining is a cost effective alternative. One of the first final shotcrete linings applied to a waterproofing membrane was on WMATA's Redline for the Hildarose Double Crossover (Fig 32a) in 1986 located near Wheaton, Maryland (north of Washington, DC). Since that successful application there have been many other projects to follow, such as DART's CityPlace Station (Dallas, TX), the Washington Dulles International Airport's Pedestrian Tunnel (Dulles, VA Fig 32b) and MBTA's Russia Wharf project (Boston, MA) in which shotcrete was applied successfully over waterproofing membrane.


Figure 32a: Shotcrete final lining at Hildarose double crossover WMATA - Wheaton, MD 1985
Figure 32b: Shotcrete final lining at Dulles International Airport pedestrian tunnel - Dulles, VA 2001

Air Conditioning

Innovative design utilizes construction elements such as foundation piles, underground station walls and tunnel walls (where required) to introduce a heat exchange system, and thereby deleting the requirement for complex chiller plants and associated ductwork. Economics are derived from deletion of equipment rooms and minimizing maintenance requirements.

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