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Master's Thesis

Gegenüberstellung von offener Tunnelbauweise zu Neuer Österreichischer Tunnelbauweise (NÖT) für innerstädtische Tunnel mit geringer Überlagerung

Comparison of Cut-and-Cover Tunneling Method vs.
New Austrian Tunneling Method (NATM)
for Urban Tunnels with Shallow Overburden

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....
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Abstract

In urban tunneling both the New Austrian Tunneling Method (NATM) and the Cut-and-Cover Tunneling Method are possible options, if shallow overburden and favorable geology for either method exist. Typical applications are subway or metro running and station tunnels. While running tunnels are often built using a TBM (Tunnel Boring Machine), NATM and Cut-and-Cover techniques are common worldwide today for station construction.

The Cut-and-Cover Method entails many disadvantages in urban areas, resulting especially from surface interruptions. Both methods differ in terms of surface settlement, restrictions with the alignment, direct and indirect construction cost, construction risk and other. A risk comparison example in this thesis shows, that Cut-and-Cover Tunneling is not necessarily less risky – as might be expected – but may involve much higher risks than NATM.

Historically, NATM was always been considered to be costlier than Cut-and-Cover Tunneling, if the tunnel is situated at a depth of not more than one and a half times the tunnel height. Studies have shown, that NATM can be competitive even above this depth. By counting all the costs like utility relocation and reinstatement of the surface, NATM is usually the cheaper solution.

As an example, a subway station was designed in Open-Cut, Top-Down and using NATM. The quantities of the main materials were compared, construction schedules were developed and cost estimates prepared. The results show, that the Cut-and-Cover options have a higher demand of reinforcement, excavation and backfilling material. The construction duration is shorter with the NATM, not only because of shift-work, but also because less time is needed for relocation of utilities and backfilling works. Concerning the construction cost, NATM is the more favorable method in this example.

This thesis does not only explain the different advantages and disadvantages of the two construction methods. By citing international studies and real world examples and by developing a simple calculation example it also illustrates that the NATM represents an economic and advantageous alternative even for tunnels in urban areas and with shallow overburden.

Kurzfassung

In dichtbebautem Gebiet sind für den Tunnelbau sowohl die offene Bauweise, als auch die Neue Österreichische Tunnelbauweise (NÖT) mögliche Optionen, sofern geringe Überlagerungshöhe und für beide Bauweisen günstige geologische Verhältnisse vorliegen. Diese Bedingungen treffen vor allem für U-Bahn-Strecken- und Stationstunnel zu. Während Streckentunnel häufig mittels TBM (Tunnelbohrmaschine) hergestellt werden, sind für Stationstunnel heutzutage sowohl die Neue Österreichische Tunnelbauweise als auch offene Bauweisen weltweit gebräuchlich.

Die offene Bauweise bringt viele Nachteile mit sich, die vor allem aus den Belästigungen an der Oberfläche resultieren. Beide Baumethoden variieren bezüglich Oberflächensetzungen, Einschränkungen in der Linienführung, direkter und indirekter Baukosten, Konstruktionsrisiko usw. Ein Risikovergleich anhand eines Beispieles in dieser Diplomarbeit zeigt, dass die offene Bauweise nicht unbedingt weniger Risiko involviert – was oft vermutet wird – sondern ganz im Gegenteil ein viel höheres Risiko beinhalten kann als die NÖT.

In der Vergangenheit galt die NÖT von vornherein teurer als die offene Bauweise, sofern der Tunnel nicht tiefer als die 1 ½ -fache Tunnelhöhe liegt. Studien haben gezeigt, dass die NÖT auch oberhalb dieses Bereiches preislich konkurrenzfähig ist, besonders wenn man auch Kosten wie die Verlegung der Versorgungsleitungen oder die Wiederherstellung der Oberfläche mit einrechnet.

Es wurde als Beispiel eine U-Bahn-Station in Offener Bauweise, Deckelbauweise und in NÖT geplant. Die Mengen der wichtigsten Baumaterialien wurden verglichen, Bauzeitpläne erstellt und Kostenschätzungen erarbeitet. Das Ergebnis zeigt, dass die offenen Bauweisen einen viel größeren Bedarf an Bewehrung, Aushub- und Verfüllmaterial haben. Die Bauzeit bei der NÖT ist geringer, nicht nur durch die Annahme durchgehender Schichtarbeit, sondern auch dadurch, dass weniger Zeit für die Verlegung von Versorgungsleitungen und für das Rückfüllen der Baugrube erforderlich ist. Auch bezüglich der Baukosten ist die NATM in diesem Beispiel die günstigere Variante.

Neben der detaillierten Beschreibung der einzelnen Vor- und Nachteile der verschiedenen Bauweisen wird in dieser Diplomarbeit anhand von internationalen Studien, Beispielen aus der Praxis und einem einfachen Rechenbeispiel erläutert, dass die NÖT auch bei oberflächennahen Tunneln im Stadtbereich eine preiswerte und vorteilhafte Alternative darstellt.

Preface

This thesis was written in close cooperation with tunneling design engineers. Many different people added their knowledge and experience and made it possible to create a paper with reference to practice and reality.

Therefore I would like to thank everybody who added somehow to the outcome, especially:

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All terms and dates of the paper are in American English, all units are metric. If not otherwise specified, costs are expressed in US-dollar.

Numbers in brackets relate to the reference list at the end of the paper.

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1. Introduction

The underground construction business is a very unique business. Decision making processes are not only influenced by objective arguments, like construction costs, construction durations, environmental influences etc, but to a very high degree also by entrenched opinions, political issues and personal preferences. It even seems that finding the option which can provide the most jobs and be carried out by local companies is sometimes preferable to finding the most cost affective alternative.

People, who are engaged in the decision making process about which construction method to use are not always familiar with the available technologies and may be influenced easily by advocates of certain methods. Therefore it is difficult to establish a new method in a market that has high confidence in a frequently used and well known technology.

In tunneling, one of the first crucial decisions to be made in planning is the choice of the construction method, i.e. Cut-and-Cover or mined tunneling. In some cases the local conditions allow just one solution, for example, if high overburden exists due to topography, mined tunneling is the only feasible option. Often, however, the answer is not that easy. Especially in urban tunneling both methods are possible most of the time. Today the majority of urban tunneling is Metro or light rail construction. For running tunnels the Cut-and-Cover method is used only rarely anymore, because mined tunneling or tunneling with TBM are more favorable options.

For Metro stations, however, the situation is not that clear and very often a decision between Cut-and-Cover and mined tunneling has to be made. Many statements have been made by different people involved, but only a few are based on an objective background. Of course, it is hard to compare two methods, which have totally different effects, some of which are not even quantifiable in monetary units.

This thesis is an attempt to making a realistic comparison. It summarizes the pros and cons of both methods and shows a cost comparison based on a basic example.

2. NATM (New Austrian Tunneling Method)

2.1 History
[14, 15]

The "New Austrian Tunnelling Method", also known as "Sequential Excavation Method" and "Sprayed Concrete Lining", was pioneered by Austrian engineers in the later half of the twentieth century.

It is often linked to a patent by Professor Ladislaus von Rabcewicz, who invented the dual-lining support for tunnels (initial and final support). This concept, however, had little to do with the application of shotcrete: it merely expresses the concept of letting the rock deform before the final lining is applied so that the loads are reduced. The idea behind this concept of the necessity for deformation was based on a theoretical investigation by Engesser in 1881 and was applied by Schmid in 1926. Rabcewicz's achievement, however, was the introduction of systematic anchoring and, together with Müller, in-situ measurements.

In 1954 Brunner assumed full responsibility for stabilizing squeezing ground in a diversion tunnel for the Runserau power plant with the use of shotcrete, having been required to do so, in writing, for all claims against his own company and the consulting engineers. This was the first major incursion into the domain of the soft ground shield tunnelers.

The "Shotcrete Method", as the New Austrian Tunneling Method was called at that time, gained worldwide recognition when it was applied under the consulting guidance of Professor L. Müller and Professor L. von Rabcewicz in the Schwaikheim Tunnel in 1964. As both academics and practitioners they began to explain the method on a more theoretical basis in terms of the newly developed concepts of rock mechanics. The term "New Austrian Tunneling Method" (NATM) – in German "Neue Österreichische Tunnelbauweise" (NÖT) – was created during a lecture by Professor Rabcewicz at the thirteenth geomechanics colloquium in 1962 in Salzburg. International recognition of NATM sprang from Rabcewicz' articles in Water Power in 1964, but the technique is disputed by some experts worldwide.

The outstanding success of the method in soft ground tunneling in urban areas was due to the publication by Brunner, who had already proposed, unsuccessfully, the application of the NATM in urban areas. His letters to leading figures in Austrian and German cities received negative or no responses. It was Professor Müller who interested the company Beton- und Monierbau to introduce the method to the soft ground (Frankfurt Clay) of Frankfurt am Main in 1968 by building a test tunnel to prove its applicability. [15]

This test tunnel turned out to be a great success and therefore NATM was used for constructing the Frankfurt Metro and subsequently subways in Bochum, Munich and other European cities. Today NATM in soft ground is applied worldwide. [14]

2.2 Definition and Principles
[3, 16]

As defined by the Austrian Society of Engineers and Architects, the NATM "…constitutes a method where the surrounding rock or soil formations of a tunnel are integrated into an overall ring-like support structure. Thus the supporting formations will themselves be part of this supporting structure." In world-wide practice, however, when shotcrete is proposed for initial ground support of an open-face tunnel, it is often referred to as NATM, even though the methods do not always follow the general principles of NATM.

Key features of the NATM design philosophy are:

- The strength of the ground around a tunnel is deliberately mobilized to the maximum extent possible.
- Mobilization of ground strength is achieved by allowing controlled deformation of the ground.
- Initial primary support is installed having load-deformation characteristics appropriate to the ground conditions, and installation is timed with respect to ground deformations.
- Instrumentation is installed to monitor deformations in the initial support system, as well as to form the basis of varying the initial support design and the sequence of excavation.

Key features of NATM construction methods are:

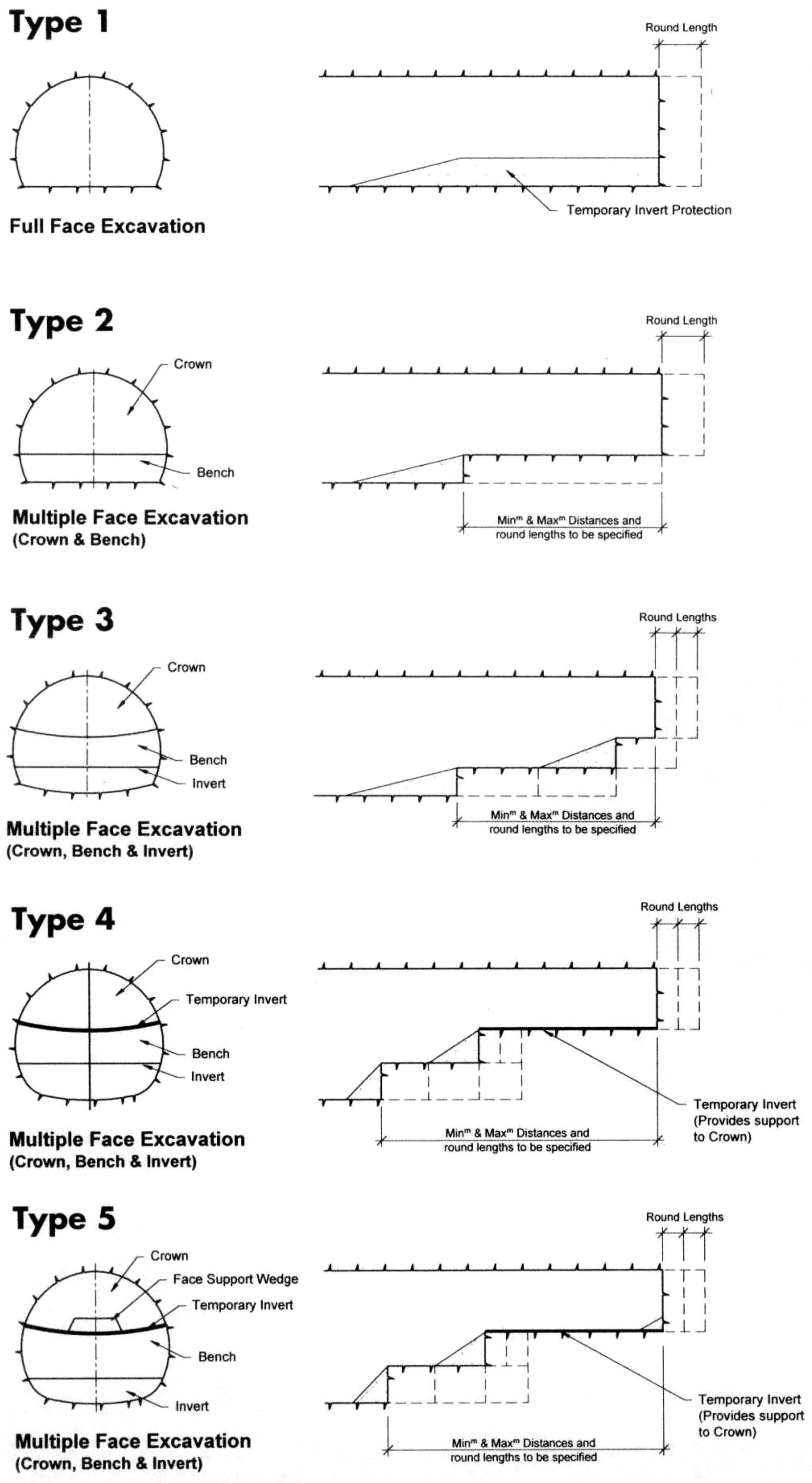
- The tunnel is sequentially excavated and supported, and the excavation sequences can be adjusted.
- The initial ground support is provided by shotcrete in combination with fiber or welded-wire fabric reinforcement, steel arches or lattice girders, and sometimes ground reinforcement (e.g., soil nails, spiling).
- Membrane based waterproofing system sandwiched between initial and final lining.
- The permanent support is usually (but not always) a cast-in-place concrete lining.

In current practice, for soft-ground tunnels which are referred to as NATM tunnels, initial ground support in the form of shotcrete (usually with lattice girders and some form of ground reinforcement) is installed as excavation proceeds, followed by installation of a waterproofing system and final lining at a later stage. [3]

The design of the excavation and support sequence for the construction of an underground space is a complex engineering project. The designer must consider many factors in order to choose the most appropriate system. These may include:

- Tunnel size and required geometry
- Nature and quantity of support elements to be used
- Anticipated ground conditions
- Anticipated ground behavior during tunneling
- Available space to carry out construction
- Surface settlement requirements
- Available labor force

The figures below show excavation and support types 1 to 8, which feature typical configurations of commonly used tunnel heading designs. These are for tunnels supported with some combination of reinforced sprayed concrete, steel arches, rock bolts, dowels and other elements (not shown in the figures). [16]


Type 1
Round Length
Temporary Invert Protection
Full Face Excavation
Type 2
Crown
Bench
Round Length
Min^m & Max^m Distances and round lengths to be specified
Multiple Face Excavation
(Crown & Bench)
Type 3
Crown
Bench
Invert
Round Lengths
Min^m & Max^m Distances and round lengths to be specified
Multiple Face Excavation
(Crown, Bench & Invert)
Type 4
Crown
Temporary Invert
Bench
Invert
Round Lengths
Temporary Invert (Provides support to Crown)
Min^m & Max^m Distances and round lengths to be specified
Multiple Face Excavation
(Crown, Bench & Invert)
Type 5
Crown
Face Support Wedge
Temporary Invert
Bench
Invert
Round Lengths
Temporary Invert (Provides support to Crown)
Min^m & Max^m Distances and round lengths to be specified
Multiple Face Excavation
(Crown, Bench & Invert)

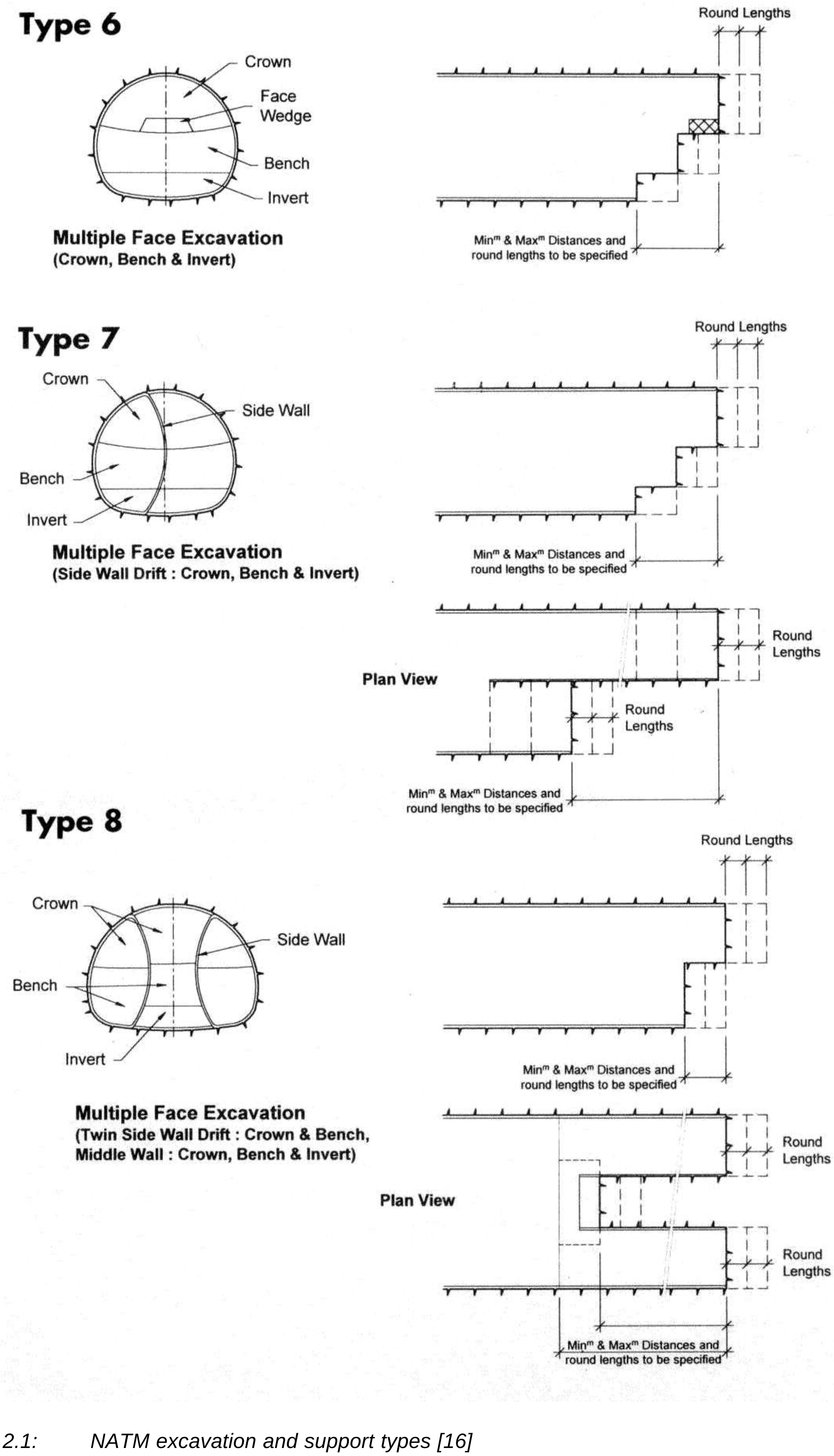


Figure 2.1: NATM excavation and support types [16]

Generally, the most critical factors are the anticipated ground condition and the variability of the ground. Therefore it is important, that an understanding of the nature of the ground as well as the likely behavior of the ground during tunneling is gained. The encountered ground conditions should be compared to those anticipated during the design stage. It is then possible to adjust the excavation and support system to improve the overall tunneling performance. Alterations should only be made on the basis of interpreted geotechnical monitoring data and with the full agreement of the designer. Such alterations during construction are common practice in modern tunneling, but only reluctantly used in some countries, e.g. US, Taiwan. Examples of such adjustments are:

- The reduction of time to invert closure by, e.g. changing from Type 5 to Type 6 (see figure 2.1), in order to minimize surface settlement
- The increase of production rate by e.g. eliminating headings if they are unnecessary, such as a change from Type 3 to 2 (see Figure 2,1). [16]

The flexibility of the method is not only guaranteed by variation of the excavation and support measures, but also by the other elements of the NATM "Toolbox", as shown in Figure 2.2.

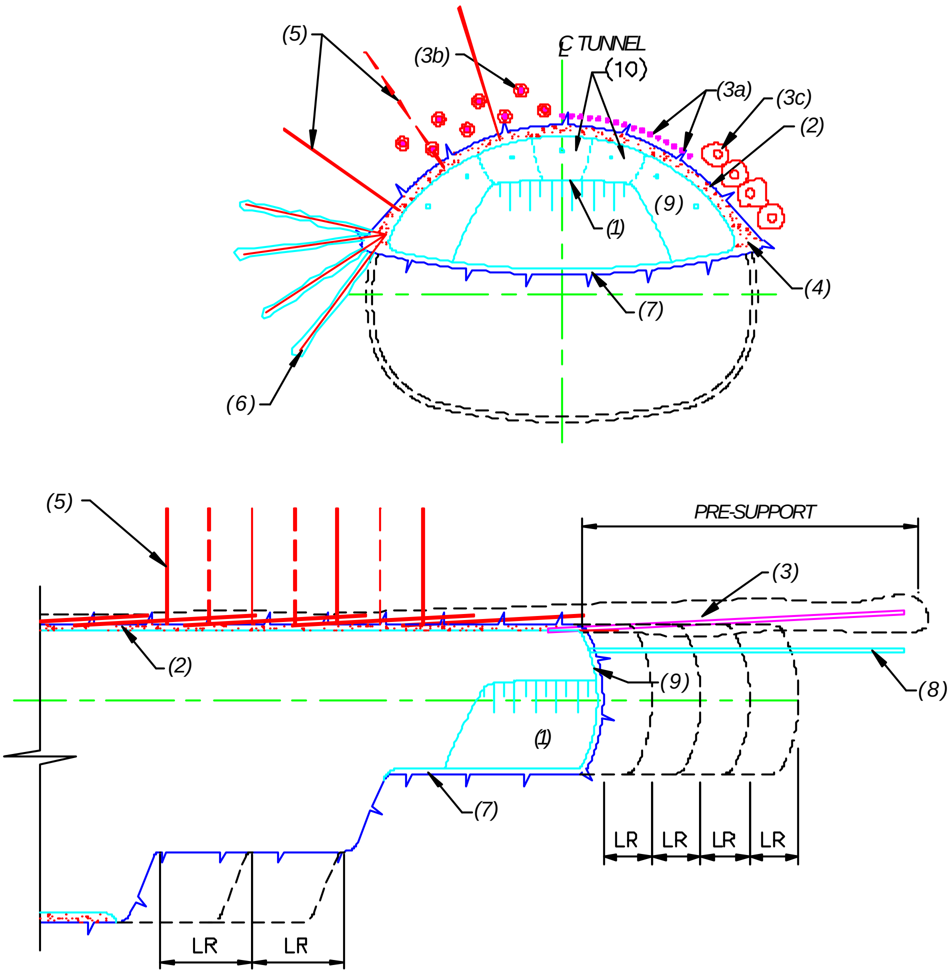


Figure 2.2: "NATM Toolbox" [16]

Pre-support:

- Dewatering of the excavation area, if necessary with vacuum lances (8).
- Spiling with various elements like rebars, cement bonded rebars (Grouted Spile Anchors – GSA).
- Grouted pipe spiling, metal sheeting, etc. (3)
- Barrel Vault Method, length approx. 35 to 60 m.
- Horizontal Jet Grouting Method, maximum length approx. 20 m each.
- Grouting of face area ahead of the excavation.

Face support:

- Stabilization of the face with earth wedge (1).
- Stabilization of the face with shotcrete (9).
- Pocket Excavation & Support Method (10).

Side wall improvement

- Increasing the width of the shotcrete foundation (4). (If viable with given ground conditions)
- Improving the bearing capacity at the spring line with grouting, grouted pipe spiling or GSA (6).

Annular support:

- Increasing the thickness of shotcrete (2).
- Increasing the number of rock bolts, 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

Waterproofing is installed between the initial and final lining and is achieved by utilizing a "closed" or "open" membrane system. The open system effectively forms an umbrella around the structure, and keeps the structure dry by permanently draining perched water or ground-water using a tunnel drainage system. The closed system is a fully closed waterproofing membrane sandwiched between the initial and final lining with the ability to resist the water pressure from a fully recharged water Table. This system is preferred in the USA, while the open system is more common in Europe.

The final lining or final interior invert and arch can be constructed either with cast-in-place concrete or shotcrete. While cast-in-place concrete is used for long tunnels with unchanged cross sections, shotcrete is advantageous for short tunnels or tunnels with changing geometries.

3. Cut-and-Cover Tunneling Methods

3.1 General

[1, 2]

Tunnel construction is characterized as "Cut-and-Cover" construction when the tunnel structure is constructed in a braced or tied-back, trench-type excavation ("cut") and is subsequently backfilled ("covered"). The tunnel is typically designed as a box-shaped frame, and due to the limited space available in urban areas, it is usually constructed within a braced or anchored excavation. Where the tunnel alignment is beneath a city street, Cut-and-Cover construction interferes with traffic and other activities. This disruption may be lessened through the use of temporary decking over the excavation. The deck is left in place with construction proceeding below it until the stage is reached for final backfilling and surface restoration. [1]

The Cut-and-Cover construction originated in the mid of the 19th century with the construction of the London underground train system. At the beginning of the 20th century it was further developed and applied in Berlin (Germany), and thereafter used all over the world. [2]

Figure 3.1 shows an overview of Cut-and-Cover construction methods depending on the availability of adjacent working space and the type of shoring wall.

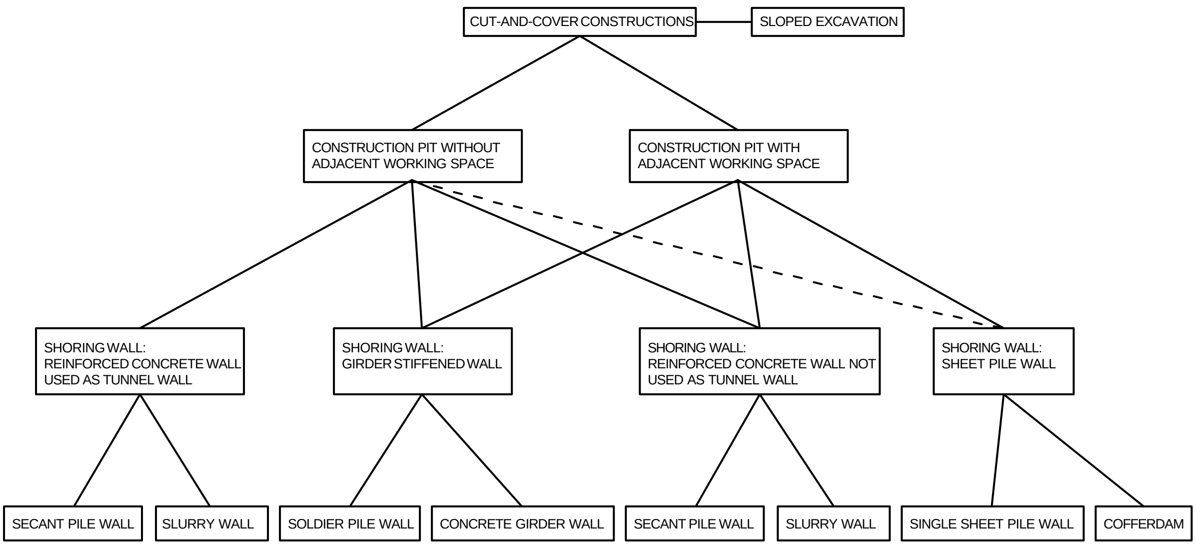


Figure 3.1: Overview of Cut-and-Cover construction methods (Source: [2])

Cut-and-Cover construction can be subdivided into two methods. For the first method, the shoring walls (support of excavation) are used only during the construction and the tunnel is built independently in the pit. The second method, which is also called "Open-Cut Method", employs the shoring walls as an integral part of the tunnel.

3.2 Sloped Excavation

[2]

Outside of urban areas with dense development tunnels can be constructed by building pits with sloped excavation. This offers more free working space, but requires considerable surface area, involves very high excavation volume and necessitates a high reach of the lifting gear positioned outside the pit. The advantage is that pit support is not necessary and therefore excavation can progress independently of the installation of shoring walls.

Due to a maximum slope inclination of 45º to 60º, depending on the angle of friction of the soft ground, and therefore the enormous amount of space required, this construction method is not an option for urban tunneling.

3.3 Construction Pit with Temporary Shoring Wall

[1, 2]

3.3.1 "Berlin Construction Method"

This construction method, also called "Soldier Pile Wall with Timber Lagging" is characterized by a vertical support of excavation with driven soldier pile walls and does not offer additional working space. It was developed for the ground conditions in Berlin (Germany), which consist of mainly sand and clay.

At high groundwater level an extensive ground-water lowering is necessary prior to the excavation. The wall of the "Berlin Construction Method" consists of vertically driven I-beams (I 140 to I 400 mm) with a spacing of 1.50 m to 2.50 m and a penetration depth of 2.00 to 3.00 m under the pit invert. Standard sections (I 340 to 400) and wide-flange sections (I PB 300 to 400) in length of 10 to 18 m are mainly used. Wooden planks (5 to 10 cm thick) are wedged between the girders simultaneously as the excavation progresses. Loosening or moving of the ground behind the wall should be avoided.

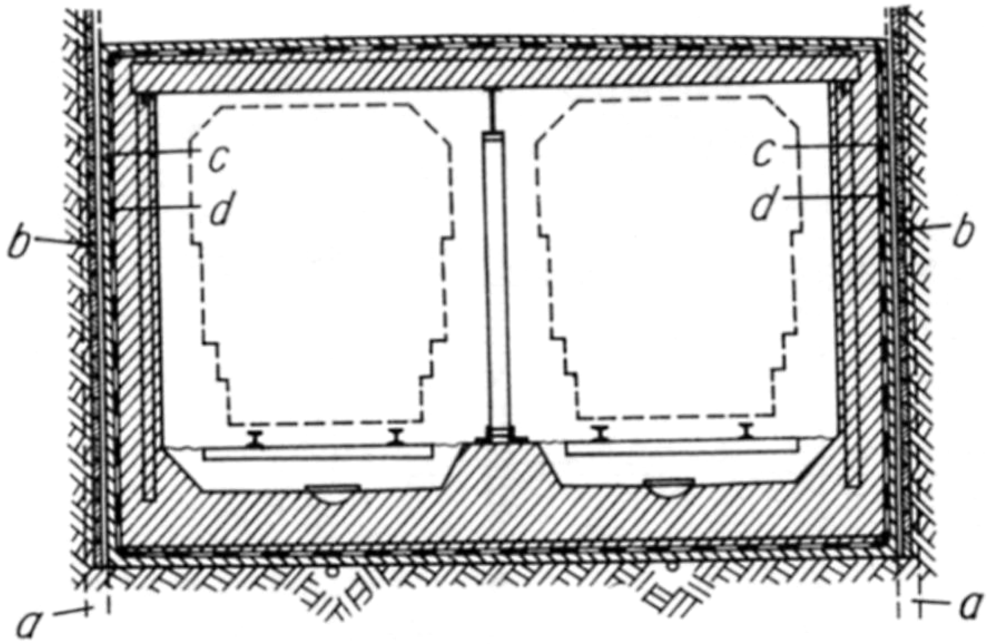
The tunnel walls are constructed directly adjacent to the shoring walls. When the I-beams are pulled out, laterally diverted beams may damage the waterproofing layer. Because of their high cost, steel sheet piles are only used for very difficult ground and hydrologic condition. They prevent "ground flowage" and settlement of structures with shallow foundations. In ground with low permeability, an open dewatering system may be feasible if the wall penetrates deep enough.

The disadvantages of the sheet pile walls are:

- High cost
- High ramming vibrations (can be mitigated by using vibrators instead of rams)
- Induced settlements
- Compression of the underground
- Furling and springing of the sheet piles at obstacles, e.g. boulders

Features of the "Berlin construction method" are:

- Application only at favorable ground conditions (rammable ground, no obstacles)
- Shoring wall and tunnel wall touch each other
- Additional concrete protective layer on the lateral waterproofing
- Wooden planks remain and can not be reused
- Difficult connection of invert waterproofing and wall waterproofing



a … Soldier Pile (I-beam) *c … Waterproofing*
b … Timber Lagging *d … Concrete Protective Layer*

Figure 3.2: "Berlin Construction Method" [2]

3.3.2 "Hamburg Construction Method"

To avoid the disadvantages of the "Berlin construction method", especially under unfavorable dense ground conditions, the "Hamburg construction method" was developed. It is characterized by the installation of free working space (width approximately 80 cm) between the tunnel exterior wall and the support of excavation on both sides. Instead of normal sections, peine sections in 2.50 m distance and 3 m penetration depth are rammed. Generally the pit wall includes the same elements as the "Berlin construction method".

The following features and advantages characterize the "Hamburg construction method":

- Even deviated driven pilot beams do not cause damage to the protective layer nor the waterproofing when being pulled
- The wooden planks can be reused
- After recovering of the plank wall the free working space is backfilled with sandy filling material and subsequently packed
- The earth pressure is sufficient to press-on the waterproofing layer
- The protective layer can be installed easily
- If artesian water exists, dewatering can be carried out from the free working space

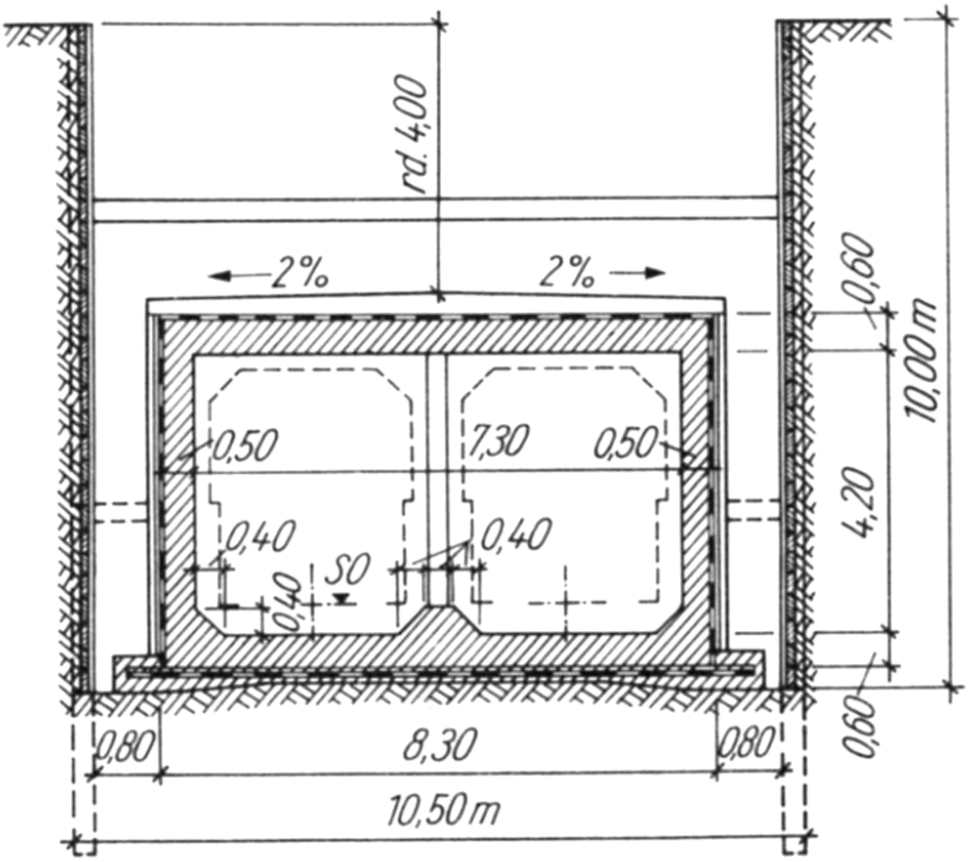


Figure 3.3: "Hamburg Construction Method" [2]

The average time-consumption of the different construction steps for the methods with temporary shoring walls are:

Excavating	12%
Concrete work	43%
Dewatering	45%

3.3.3 Excavation of the Pit

The excavation of the pit and the construction of the tunnel walls must be synchronized. For the bracing of the pit, mainly round timber, section girders, steel tubes, lattice girders or telescopic systems are used. The bracings have to be wedged tightly, so that ground movements behind the pit walls are avoided. In special circumstances the bracings have to be prepressured to anticipate shortenings.

While removing the bracing and constructing the tunnel, attention has to be paid to the arrangement of the cross stiffening for safety reasons. For average tunnel depth (1 ½ times tunnel diameter) the primary bracing is situated at tunnel height. In the course of the construction of the tunnel the forces of the primary bracing have to be redirected to either the tunnel invert or wall.

Bracings with pillars in the center of the pit hamper the process of excavation and placement of concrete remarkably, but they offer the opportunity to cover the pit fully or partially. The bracings of the tunnel pits are generally very time and material-consuming, require a high amount of labor, and hamper the excavation and the tunnel construction, especially at wide and deep pits.

Every bracing system is subject to a certain degree of elastic deformation, and a displacement of the pit can affect adjacent structures. To ensure the stability of foundations of neighboring constructions, exterior safety measures like underpinning, injections and slurry walls are required. These measures outside of the pit prevent damages like cracks on buildings.

Interior safety measures would be for example the construction of very stiff and almost unyielding bracing. This has to be considered especially during the removal of the bracing, because the tunneling technology is related to the stiffness of the bracing.

A pit free of bracing is desirable, wherever possible, in order to achieve a rational configuration of the different working steps, a construction time reduction and a reduction of the risk for adjacent structures. It can be achieved by tying the enclosure wall back with

- anchors or stay piles
- grouted-anchors or injection-anchors and bored piles
- horizontally driven piles

During the construction it is important to monitor the corrosion and the stresses of the anchors.

For long underground tunnel systems a rapid construction sequence is essential and can be achieved by repetitive operations. A rational use of machinery for the excavation and the material transport inside and outside of the pit are important.

Figure 3.4 shows the construction sequence for the "Berlin construction method" and the "Hamburg construction method".

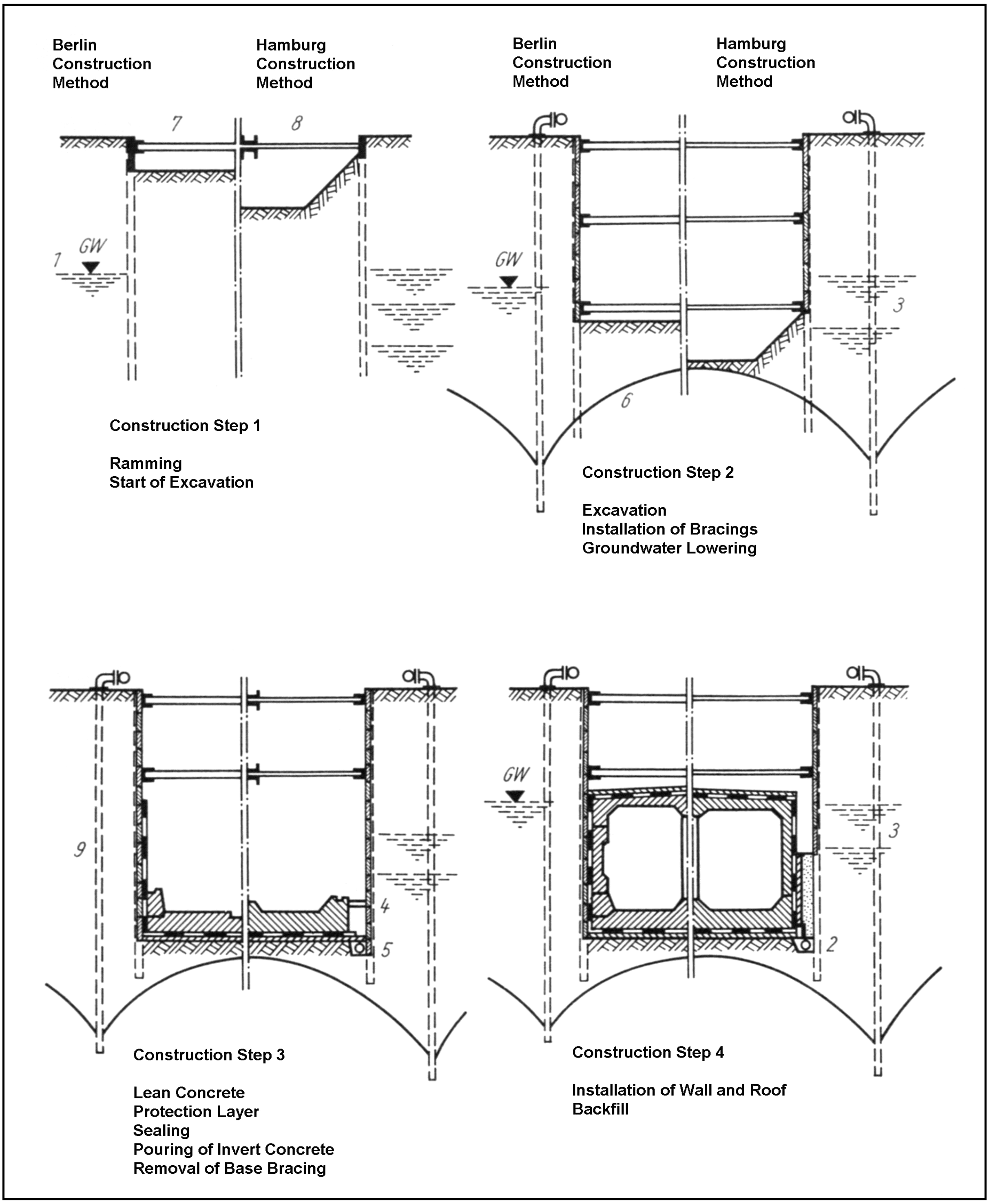


Figure 3.4: Construction sequence for "Berlin Construction Method" and "Hamburg Construction Method" [2]

3.3.4 Construction of the Tunnel

The rectangular tunnel section usually consists of a closed reinforced concrete frame with or without central pillar. It can be constructed either in cast-in-place or (partly) prefabricated.

An example of a tunnel construction with shallow overburden and high ground water level is shown in Figure 3.5, a design of a railway tunnel between Mannheim and Stuttgart (Germany).

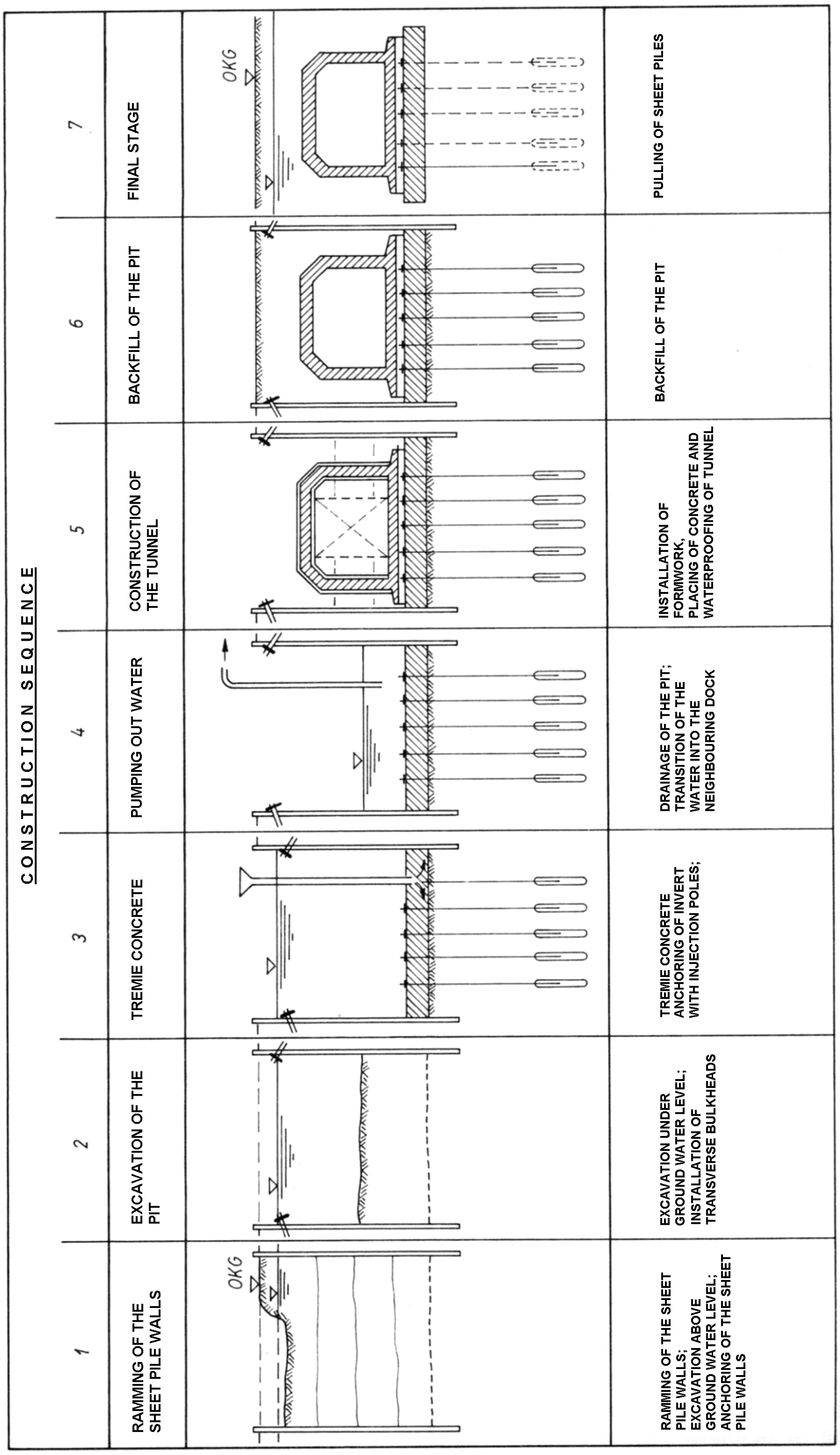


Figure 3.5: Construction sequence at high ground-water level [2]

3.4 Construction Pit with Permanent Shoring Wall (Open-Cut Method)
[1, 2, 17]

Construction methods, where the shoring walls also serve as tunnel walls are called "Open-Cut" constructions. In this case, the shoring walls are composed of "diaphragm walls", which consist of reinforced concrete, a combination of concrete and structural steel, or similar systems. [1]

The methods with permanent shoring walls tend to be more expensive than the methods with temporary shoring walls, if waterproofing of the tunnel is required.

The advantages of permanent shoring walls are:

- no additional tunnel wall necessary
- reduced width of excavation
- reduced quantity of excavation and backfill
- faster construction

The disadvantages on the other hand are:

- tighter construction tolerance required
- installation of exterior waterproofing systems precluded (unless there is a finish wall inside)
- seepage mitigation (grouting, seepage collection) required
- separate architectural cladding often desired [17]

3.4.1 Slurry Walls

The slurry walls used as remaining shoring walls are reinforced cast-in-place or prefabricated concrete walls with a width of 0.40 to 1.20 m. The continuous or incremental constructed trenches, excavated with a special clamshell-type bucket or hydro-fraise, are filled with a thixotropic supporting liquid. Guide walls, 0.50 m to 1.50 m deep and 0.20 m thick are installed prior to the excavation for the safeguarding of the slots and for the leading of the clamshells.

The thixotropic liquid subserves the maintenance of stability of the earth walls and consists of a clay (bentonite) slurry, which has to have a density of 1.03 to 1.10 g/cm^3. The suspension possesses a specific shear strength in dormant state, which decreases suddenly to a very low amount when vibrated (thixothrophy). During the excavation the liquid has to be refilled constantly.

If the excavation is made continuously, the slot is subdivided with tubes into several compartments, then a pre-assembled steel reinforcing "cage" is lowered into the slurry-filled panel. Subsequently concrete is placed by tremie techniques, displacing the slurry. After the concrete is hardened, the tubes are pulled out. If an immediate loadbearing capacity of the wall is required, a pre-fabricated slurry wall can be advantageous and may also become part of the structure.

3.4.2 Drilled Pile Wall

Drilled pile walls are similar to slurry walls and can be constructed as

- tangent pile walls
- overlapping pile walls
- intermittent pile walls

If the piles are placed in a single row, tangent, nearly tangent or slightly overlapping with each other, then they are called secant pile walls.

If a waterproof construction pit is required, overlapping pile walls are customary. The overlapping, reinforced piles are constructed after sufficient hardening of the non reinforced piles. Drilled pile walls can also be inclined, e.g. for underpinning.

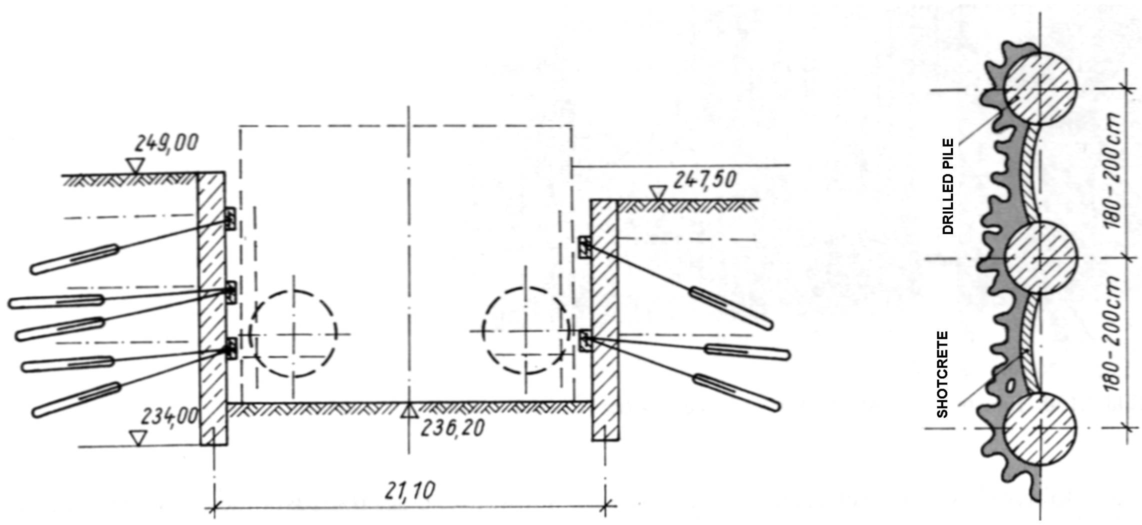


Figure 3.6: Soldier pile wall [2]

The time-consumption for the different construction steps for the methods with permanent pit enclosures are:

Excavating	24%
Concrete work	70%
Dewatering	6%

3.4.3 Soldier Pile and Tremie Concrete (SPTC) Wall

Soldier pile and tremie concrete (SPTC) walls are composed of soldier piles spaced at relatively close centers with a high-quality concrete placed between the soldier piles, thus forming a very stiff continuous wall. Soldier piles are typically 60-90 cm deep, rolled beams or deeper, built-up sections.

Soldier pile spacing for SPTC walls typically ranges from 1.2-1.8 m, with the upper limit being held to about twice the nominal wall thickness. Apart from the great strength that can be achieved using these walls, there is the added advantage that the soldier pile element of the wall can be extended deeper than the tremmie concrete element. Thus, the soldier piles can be extended below the tremie concrete into very strong soil or into bedrock when there is a structural reason to do so. [1]

SPTC walls are often used in the USA.

3.4.4 Top-Down Method

This construction method is also known as "half-open" or "Milan construction method", because its first application was in Milan (Italy).

The construction sequence starts with the installation of the shoring walls. Subsequently, the pit is excavated to the bottom of the tunnel ceiling and partly braced. Then the tunnel ceiling is cast in place on grade or installed as a prefabricated concrete element. Once the ceiling is finished, the pit is backfilled and the surface reconstructed.

The excavation of the tunnel takes place underneath and under protection of the tunnel ceiling. The excavation material has to be transported horizontally to the remaining openings of the pit, where it is lifted to the surface.

The advantages of this method are:

- The road traffic is only partially disturbed. Total interruption happens only during the time of the excavation of the upper level, the installation of the tunnel ceiling and the reconstruction of the road surface. Then, the construction is only noticeable at the remaining openings.
- The shoring walls and the tunnel ceiling provide sufficient stiffening for the construction pit.
- No obstruction of the excavation due to bracings.
- The concrete walls are partly waterproof, although not permanently.
- No noticeable lateral deformations, no vibrations.
- Early investigation of the ground conditions.
- If the concrete walls are cast carefully, they can be considered as a part of the tunnel construction.

The disadvantages are:

- Under the groundwater level the pit enclosure walls and the tunnel walls have to be designed for the entire water pressure, which involves a substantial over-design.
- Waterproofing on the inside and between walls to hold the water pressure back is not as reliable as and more expensive than waterproofing on the back of the wall.
- The installation of utility lines and the construction of support for temporary roads are more difficult and more expensive.
- Lifting gear like cranes only at the openings, horizontal transportation is necessary underneath the roof slab.

The construction sequence of the Top-Down method is shown in Figure 3.7.

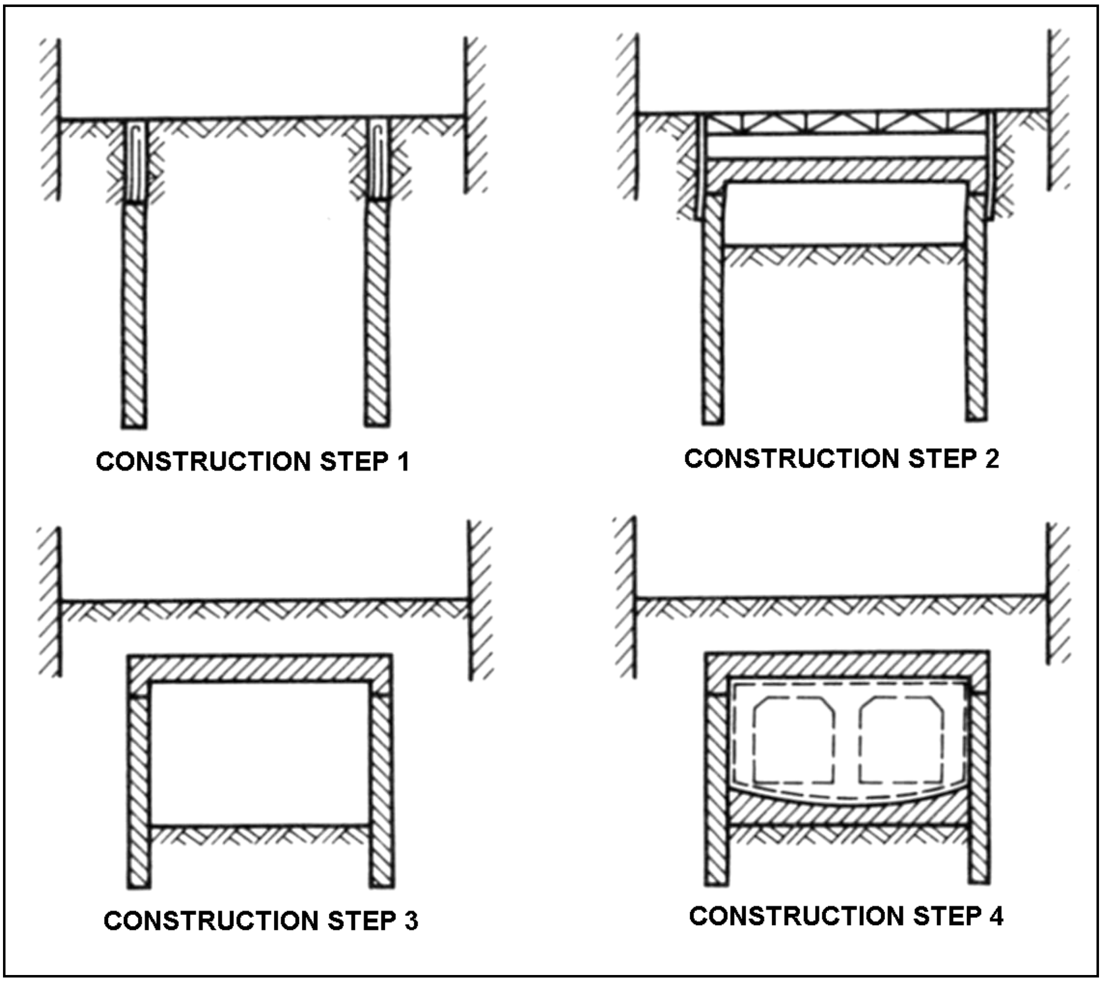


Figure 3.7: Construction sequence of the Top-Down Method [2]

3.5 Special Construction Methods
[1, 2]

In Cut-and-Cover construction special difficulties are encountered when stretches of water, other traffic routes or urban developments have to be under-passed. Depending on the nature of the construction and the possibilities of implementation, the expenses can become unproportionally high, so alternative construction methods have to be considered.

Special construction methods for difficult ground or environment conditions include:

- Injections, Jet Grouting
- Ground freezing
- Deep foundation
- Tube umbrella method

Due to the special character of these methods no further explanation is provided and reference is made to special literature.

3.6 Doorframe Slab Method

[16]

The Doorframe Slab Method is a semi Cut-and-Cover construction method for shallow tunnels, which also involves the application of NATM. In the first step a trench is opened along the tunnel alignment, then the roof slab concrete is poured and a side wall spile support is installed. After the backfilling of the trench and reinstating the surface there are no further interruptions on the surface. The majority of the work is carried out as a subsequent mining operation using the elements of the NATM.

During the installation of the slab, utilities can be temporarily supported and do not have to be relocated. After backfill and road surface restoration mining can commence beneath the roof slab. The Doorframe Slab Method can be considered as a compromise between Cut-and-Cover and NATM tunneling. It is used, where the ground conditions and the low overburden do not allow the application of the conventional NATM. It has, however, fewer disadvantages than the Cut-and-Cover method, concerning surface interruptions.

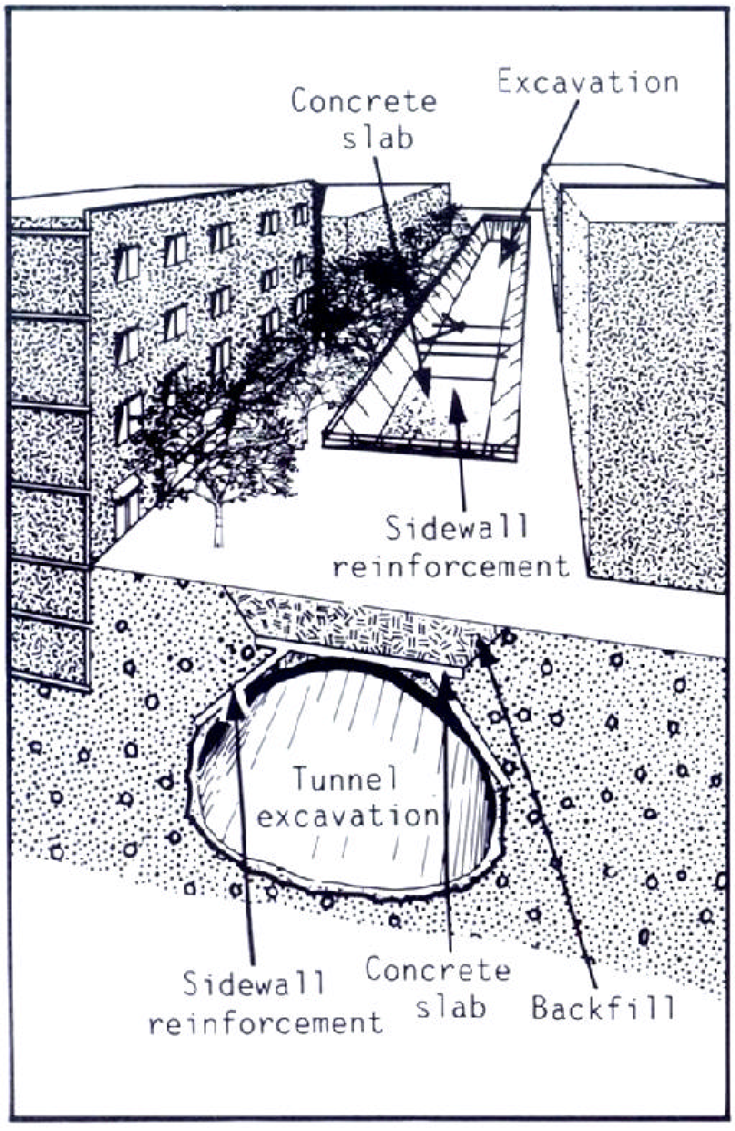


Figure 3.8: Doorframe Slab Method [16]

4. Comparison of Cut-and-Cover Tunneling vs. NATM

4.1 General Comparison

[1, 2, 3]

4.1.1 Attributes of NATM

Mining of an underground structure is compared to any Open-Cut construction less disruptive at the surface. In addition, NATM provides a great amount of flexibility for the alignment. The position of the tunnel is mainly specified by operational and easement requirements. The only factors which may alter the optimal position are:

- The minimum required overburden, depending on the ground condition, ground improvement and support of excavation
- The ground conditions (intermittent layers of unfavorable ground)
- Legal restrictions (land owner)
- Existing structures

Tunneling can be carried out despite some of these factors, but leads to higher construction cost.

The cross section can be designed following the space requirements when utilizing NATM. All round or oval shapes are possible, but edges have to be avoided, according to the principles of the NATM. Therefore a rectangular shape would be very unfavorable, because of the concentration of stresses in the ground around the edges. A longitudinal variation of the cross section can be carried out easily and all sorts of transitions, connections, turn-outs or crossings of NATM tunnels have already been designed and constructed. The minimum volume of excavation material can be achieved, which has to be hauled off and deposited and thereby minimizes the amount of heavy traffic within urban areas.

For NATM tunneling, access to the drifts is accomplished via shafts, which can be located as desired and are preferably situated off-site. The access shafts are the only penetration to the surface during the construction and the only place, where the construction is noticeable and may cause annoyances. Multiple shafts result in a multiple heading excavation and therefore accelerated advance.

NATM tunnels may be constructed in any ground condition. Ground improvement may be required in soft ground. The "NATM Toolbox" is available to handle the different situations as shown in chapter 2.2. Detrimental ground conditions influence the advance rate and the construction cost.

If tunneling takes place close to building foundations or other underground structures, counteraction to prevent settlements may be required. This may involve grouting or compensation grouting.

Due to the possibility of variation, modification and adjustment of the excavation and support system to the encountered ground conditions, the construction cost and the construction schedule can be controlled and even influenced positively if the ground is better than expected.

The design and construction of NATM tunnels requires a certain degree of engineering experience and know-how. Experienced labor is also required on-site to guarantee a quick and correct reaction to the encountered conditions.

4.1.2 Attributes of Cut-and-Cover

The alignment of Cut-and-Cover tunnels is very restricted. The horizontal position is limited to open areas, preferably on public property, which can be temporarily utilized. Most time the only places that meet these requirements are roads and public parks. However, that implicates the relocation of all the utility lines, which usually run underneath the road surface, like sewers, water pipes, fiber optic cables, gas, power and telephone lines. What usually is even more distempering is the redirection and staging of the traffic. With full or partial traffic decking this problem can be limited in its duration or location, but the covering increases the cost considerably. Also, the technical difficulty of installing temporary decking should not be underestimated, as the covering has to withstand the entire traffic load and has to be designed to have the same capacity as a permanent bridge.

The Top-Down method has limited surface impact. After excavation to the level of the tunnel roof and installation of the slab, excavation continues beneath and under protection of the roof slab from openings at various locations. The interruptions are reduced to the duration of the utility relocation, installation of the sidewalls and roof slab and the backfilling. The Door-frame Slab Method has even less impacts, as the utilities do not have to be relocated, when temporarily supported. But the opening of a trench is still necessary to pour the slab, which can be accomplished in sections.

The relocation of the utility lines takes up a considerable percentage of the Cut-and-Cover construction cost and time. It involves the risk of interrupting utilities and it also happens that lines can not be properly identified.

Historically, the complaints of people affected in their everyday life by the construction of Open-Cut tunnels had sometimes not been taken all too seriously by the responsible authorities. Recently, however, environmental impacts are starting to be of vital importance in the decision-making process of finding the appropriate construction method.

Similar to the horizontal alignment, the vertical alignment is very restricted too. A deep position of the tunnel increases the cost dramatically, because the excavation volume grows exponentially with increasing depth and the area above the tunnel has to be backfilled. The room above the tunnel can only be used in special cases, e.g. as storage space or for air-raid shelters. The higher amount of excavation material increases not only the cost, but also the construction duration evoked transportation activities.

If the running tunnels between the stations are constructed as mined tunnels, a shallow position of the station has some disadvantages: The running tunnels have to enter the geology closer to the surface, which is in most cases unfavorable for mining.

For architectural reasons, shallow station tunnels are desired, because the access facilities (like escalators and elevators) are less expensive and the access time for passengers is shorter, which makes the system more attractive. This wish however, can rarely be satisfied due to the design of modern stations, providing central platforms and a concourse level. Crossings with tracks of other subway lines and limited gradients of the alignment may lead to deeper stations, which makes Cut-and-Cover stations less competitive.

Restrictions apply for the tunnel cross section shape. Tunnels, which are constructed with remaining shoring walls, feature a more or less rectangular cross section. This generates a larger profile than usually necessary and therefore "lost" space. Tunnels, which are built within temporary shoring walls, can have a more optimized cross section shape, but it should stay continuous along the tunnel length, so that the concrete work can be done using one formwork only.

Cut-and-Cover construction causes noticeable noise and dust. It is moreover subject to weather and climate conditions, which may influence the construction duration.

The ground conditions are not as vital as for mined tunneling. Construction is possible for almost all types of grounds; however they surely do influence the method, duration and cost of the construction. Hard rock, for example, requires hydromills to install the support of excavation and larger volume of excavated material has to be loosened. Slurry walls in dense ground necessitate the use of heavy and special machinery.

If the shoring walls penetrate the ground water level, the groundwater flow gets cut off or diverted. The installation of a sag pipe is often required and dewatering measures during construction can be expensive.

Buoyancy may be a problem for Cut-and-Cover construction and has to be counteracted with higher volume of concrete, anchors and the like. Adjacent structures need to be underpinned, because there is no other possibility to control settlements during construction.

4.1.3 Comparison

Two related factors in tunneling that influence particularly costs are depth and construction method. Technical feasibility limits the vertical position of both methods.

Regarding the Cut-and-Cover method, the ability for ramming the ground and horizontal stiffening of open pits tend to be uneconomical and technically infeasible for invert elevations of 18 to 20 m under ground (3 times tunnel height). The capital investment for the bare station increases sharply for constructions deeper than 1 ½ times the tunnel height. The cost increase per meter additional depth was estimated as 5% to 15%, depending on the tunnel elevation. [11]

NATM, on the other hand is nearly unrestricted with its vertical position. However, a minimum overburden is required for practical reasons, especially concerning surface settlements and disintegration risk at compressed-air-assisted excavation.

Both methods are possible in depth between 1 to 3 times tunnel height, and the decision in every particular case of what method to use is influenced by various parameters such as:

- Subsoil and ground water conditions:
  Stableness, homogeneity and properties of subsoil, feasibility of ramming, boring and slashing, existence of obstacles, possibilities of dewatering (capacity of outfall drain, interference of ground water flow etc.)

- Tunnel depth and surface development:
  Structural sensitivity of buildings above, type of development, underpass construction severity and safety

- Technical conditions and type of tunnel:
  Station tunnel, running tunnel or tunnel for turning and parking, required waterproofing, quality and maintenance of tunnel

- Impacts:
  Impact on surface traffic (blockage times, detours, complications...), annoyance of residents (limitation of room, dirt, noisiness, restrictions in public life, aesthetics...), destruction of environment or historic development

- Financial resources:
  Costs for construction and maintenance, capital investment, durability

- Construction duration [2]

A major difference of the two investigated construction methods is the impact on surface activities. The Cut-and-Cover construction requires a substantial amount of surface space, traffic has to be redirected, roads have to be excavated and rebuilt and so on. With NATM on the other hand, the construction activity is noticeable only at the access shafts, which can be located where most suitable and can potentially be used later as access (elevator shafts).

Utility relocation is required for most Cut-and-Cover methods, but only to a limited extent for NATM construction (at shaft locations).

Another difference between the methods is the freedom of the alignment. As mentioned before, NATM provides more options for the alignment and a variety of cross section shapes. It produces a minimum excavation volume, which is desirable especially in urban areas with high volume of traffic and limited landfill space. The traffic due to backfilling activity is required to a much higher degree for Cut-and-Cover tunneling than for NATM.

Common construction machinery is required for NATM in soft ground. For hard rock a roadheader or blasting equipment is necessary. Depending on the nature of the shoring wall a trench cutter or other heavy equipment is required for Cut-and-Cover constructions.

NATM is very dependent upon the ground conditions. Today mined tunnels can be built in any ground; however prior improvement is necessary for soil, which is not stable for the time it takes to install the support ring. The supporting methods like jet grouting, ground freezing, dewatering, grouted pipe spiling or the use of compressed air increase the construction cost considerably.

Surface settlements occur in both, NATM and Cut-and-Cover method. However, with the Cut-and-Cover method, once the construction is started, only few ways exist to influence surface settlements. In mined tunneling, using the NATM "Toolbox", surface settlements can be counteracted during the excavation.

The design of NATM tunnels requires qualified and experienced engineers, which increases the design cost. Cut-and-Cover constructions on the other hand have been carried out in most parts of the world and are therefore often the preferred method, as local engineers are familiar with it.

A direct cost comparison between Cut-and-Cover methods and NATM may be possible, but can only be of limited validity. Many factors influence the construction cost and every particular case is different. Moreover, the construction method can not be chosen only by considering costs. For example, in some cases NATM has a clear advantage due to the alignment (building underpasses) or determinate longitudinal gradients (deep elevations) or for reasons of limited disturbance on the surface.

On the other hand a Cut-and-Cover method can be the preferred application if the ground condition and ground water situation are so unfavorable, that a mined excavation poses too high cost for ground improvement and groundwater control.

Cost and schedule comparison are discussed in chapter 4.2 and 4.3 and a rough comparison between the methods using a general base case is explained in chapter 6. The characteristics of the two different construction methods can be summarized as shown in Table 4.1.

	Traditional Cut-and-Cover	Mined Option
Alignment	Horizontal tunnel **alignment** is restricted by developments on the surface and land owner (preferably public owned). Vertical tunnel **alignment** is restricted by construction cost; shallow tunnels are preferred.	Horizontal and vertical **alignment** is less restricted and may only depend on existing foundations; ground conditions and deep utilities.
Surface Activities	Huge impact of **surface activities**, which causes annoyances (noise, dust, disruption) for residents, businesses (fewer customers) and traffic (diversions).	Construction activities are only perceptible at flexibly located shaft areas, where excavation material can be hauled off and construction material delivered.
Utilities	Necessity of **utility relocation**, which can be time consuming and costly and an additional annoyance.	**Utility lines** are not affected unless deep or sensitive.
Over-excavation	**Over-excavation** of usually unnecessary space, especially at deep alignments leading to high volume of excavation material which has to be hauled off and a high backfill material supply and increases surface settlement problems.	**Optimized space** requirements and geometric flexibility of tunnel shapes.
Ground Conditions	Construction in all **ground conditions**.	Minimum face stability necessary. Poor ground conditions require pre-treatment (e.g. ground freezing, jet grouting)
Groundwater	Lowering of the **groundwater** level outside the pit (dependent on support of excavation) and diversion of the groundwater stream.	Lowering of **groundwater** level can be necessary.
Settlement	Difficult to control with pre-treatment methods.	Can be controlled by limiting the partial drift sections, compensation grouting, etc.
Underpinning	May be necessary.	May be necessary.
Weather	Dependence, e.g. working conditions, concrete curing.	Not influenced by **weather** and climate conditions.
Concrete Volume	High **concrete** and reinforcement volume.	Low **concrete** and reinforcement volume.
Buoyancy	**Buoyancy** has to be counteracted.	Usually no **buoyancy** problems.
Noise/ Vibrations	More critical	Less critical.

Table 4.1: Comparison of Cut-and-Cover and NATM Mined Tunnels

4.2 Schedule Comparison

The construction duration depends on various factors, which are different for every particular project. One major factor for the duration of NATM constructions is the number of access shafts and therewith simultaneous drifts. Depending on ground conditions and the cross section size, the excavation method (single or double side wall drift, top heading-bench-invert excavation etc.) is chosen, which is decisive for daily advance rates. And of course, special support measures, like pre-spiling, ground freezing, barrel vault installation etc. reduce the advance.

With Cut-and-Cover construction excavation can be carried out faster, but the excavation volume is higher. Moreover, the relocation of utilities is very time consuming. If possible, all the utility relocation should be carried out in advance, in order not to hinder the process of excavation and construction of the tunnel. The restoration of the surface is another time-consuming process.

If no extensive utility relocation is required, usually the durations for both methods do not differ significantly. A schedule comparison for an example project is presented in chapter 6.

4.3 Cost Comparison

[2, 8, 18]

4.3.1 General

A general statement about the cost effectiveness of the two different methods is difficult; too many factors are of influence: location, position of the tunnel, geology, surface development, know-how of local engineers, market price volatility (machinery) etc. However, certain investigations have been carried out in the past which allow a general overview of the competitive capacity of both methods.

A rough estimate of construction costs for both NATM and Cut-and-Cover construction method is listed in [2]. Costs for NATM are shown for different grades of support and different tunnel diameters.

NATM			
Tunnel diameter	Shotcrete	Shotcrete, Wire mesh, Lattice girder	Shotcrete, Wire mesh, Lattice girder, steel anchors
3.0 m	4,320	4,630	4,940
4.5 m	6,170	6,790	7,100
6.0 m	7,710	8,950	9,260
7.5 m	9,870	10,800	11,410

Table 4.2: Standard values of tunnel construction costs for NATM in US-Dollar * *per meter according to [2].*

The same source provides standard values for Cut-and-Cover constructions, depending on pit depth and ground water conditions. It is distinguished between absence of ground water and necessary ground water lowering, with and without additional fee for the discharge of

*) converted from German Mark into US-Dollar with an exchange rate of:
1 DEM (German Mark) = 0.617 US-$ (by 01/01/1993)

water. The cross section size is 8.50 m x 5.10 m and the construction method is the "Berlin method" with tunnel walls made of cast-in-place concrete.

Cut-and-Cover			
Pit depth	No ground water	With lowering of groundwater table	With lowering of groundwater table and additional fee
10.0 m	15,430	17,280	18,510
12.5 m	18,510	19,740	23,450
15.0 m	21,600	23,450	27,770
20.0 m	29,620	33,940	43,190

Table 4.3: Standard values of tunnel construction costs for Cut-and-Cover in US-Dollar per meter according to [2].*

Comparing the two tables above, NATM is the cheaper solution in any case. It has to be remembered however, that these are standardized values and should only give an indication of approximate values.

4.3.2 Study 1: City Railway Construction in Bochum

An extensive cost analysis has been carried out for the city railway construction in Bochum (Germany) [18].

As the city council of Bochum started its city railway construction in 1970 it was common knowledge that Cut-and-Cover tunneling is at least 50% cheaper than mined tunneling. A value engineering design alternative, which was carried out in 1973 for a certain section disproved this opinion clearly. The NATM alternative was more than 20% cheaper than the second cheapest offer, which featured the Cut-and-Cover method. After scrutinizing the proposal from the technical, structural, constructive and geologic points of view, the offer was finally accepted. Beside the cost advantage, the prospects of fewer interruptions and annoyances on the surface influenced the decision. Moreover it was proposed that settlements would be negligible and that very little surface space would be required.

G. Laue [18] has collected quantity and cost data of several unit items of different sections in Bochum and subsequently compared them with each other. For the quantity comparison a uniform overburden of 5 m above the tunnel top heading was taken into account. This led to the conclusion that for the construction of a mined tunnel only 28% of the excavation mass occurs compared to the Cut-and-Cover option.

Three tunnel sections with different numbers of parallel tracks have been compared for both, NATM and Cut-and-Cover version. The main points of comparison were:

- Excavation quantities
- Area of primary lining (NATM) vs. area of shoring walls (Cut-and-Cover)
- Area of final lining (NATM) vs. area of concrete walls of the tunnel itself (Cut-and-Cover) for calculation of the concrete consumption.

*) converted from German Mark into US-Dollar with an exchange rate of:
1 DEM (German Mark) = 0.617 US-$ (by 01/01/1993)

Single-track tunnels

The area of the primary lining of an NATM tunnel amounts to only 75% of that of the shoring wall area of a comparable Cut-and-Cover construction. A comparison of the inner lining area with the area of the tunnel walls of a Cut-and-Cover construction shows similar savings for NATM. Due to the structurally optimized section shape it amounts only to about 65% excavated volume compared to a tunnel placed into an open pit. NATM is usually more cost effective for single-track tunnels in good geologic conditions (e.g. greensand, medium to hard marl).

Table 4.4 shows that a single-track NATM tunnel costs on average 50% of a Cut-and-Cover tunnel. The cost difference is even higher if a traffic decking is necessary for the Cut-and-Cover construction. For 75% temporary decking the cost of an NATM tunnel results in 40.8% of the cost of a Cut-and-Cover construction.

Twin-track tunnels

It was found, that twin-track tunnels with a cross section size of 50 m^2 (NATM) respectively 75 m^2 (Cut-and-Cover) are the most cost effective sections. However in soft ground and silty clay a big NATM section can not always be driven without ground improvements and therefore a division into two smaller drifts can be favorable.

The excavation volume of an NATM tunnel is 28% of that of the Cut-and-Cover tunnel (same as for single-track). The other main positions however differ from the single track tunnel. The area of the primary lining is similar to the area of the shoring wall, but the areas of the inner lining, respectively the walls of the tunnel in Cut-and-Cover differ widely. The structurally ideal inner lining of the NATM tunnel requires only 39% of the area of tunnel wall for Cut-and-Cover construction. The savings of concrete volume affect the cost considerably.

The cost of the excavation is much higher for mined tunneling (about 2.5 times), but this is equalized by lower quantities (28%). Totally, the NATM tunnel is 36% less expensive for twin-track tunnels if no temporary traffic decking is required and 55% less if traffic decking is taken into account.

Triple-track tunnels

Triple-track tunnels are necessary when an additional track for parking or turning of a train is required. The cross section size is about 100 m^2 for NATM and 85 m^2 for Cut-and-Cover tunnels. The NATM excavation volume amounts to 41% of that of Cut-and-Cover. The inner lining area is 62% of the concrete wall area of the Cut-and-Cover alternative. The entire NATM section size exceeds that of the Cut-and-Cover construction and therefore the primary lining area is bigger than the area of shoring walls.

In the case of a triple-track tunnel the costs for both methods are similar, if temporary decking is not required. Otherwise the cost advantage of the mined tunnel option is up to 35%, depending on the amount of covering.

Stations

Extensive experience could be gathered with the construction of Open-Cut and mined stations in Bochum. The difference of the construction cost of stations depends again on the amount of traffic decking and is between 7% and 33% in favor of NATM. Despite the fact that hauling costs are double as high and the primary lining is 13% more expensive, the total costs are still lower for NATM. This is due to the lower concrete consumption, as the concrete area of the NATM tunnel is one third smaller than that of the Cut-and-Cover tunnel.

Table 4.4 shows a summary of the findings of the study.

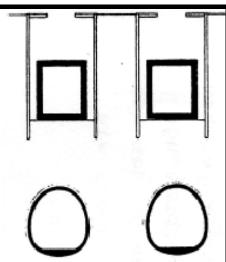
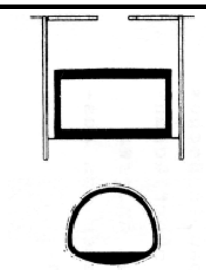
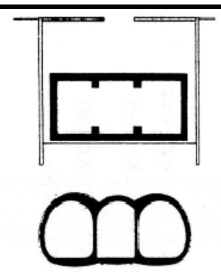
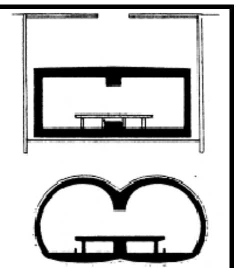
	 Two single-track tunnels - in Cut-and-Cover construction with separated pits - in NATM with separated drifts	 Twin-track tunnel in both Cut-and-Cover and NATM as twin-track section	 Triple-track tunnel in Cut-and-Cover and in NATM	 Station with central platform in Cut-and-Cover and NATM
Bid price for **CUT-AND-COVER** construction	100%	100%	100%	100%
Cost percentage for - Excavation - Support - Reinforced concrete - 75% traffic decking	 9.0% 36.0% 35.0% 20.0%	 10.1% 20.8% 39.2% 29.9%	 10.7% 20.0% 36.6% 32.7%	 9.5% 15.6% 46.6% 28.3%
Relative bid prices for **NATM** - regardless of traffic decking - considering a 75% traffic decking (at Cut-and-Cover)	50.0% 40.8%	63.5% 44.5%	97.2% 65.4%	93.0% 67.5%
Cost percentage for - Excavation - Primary lining - Final lining	 25.7% 29.2% 45.1%	 33.1% 33.3% 33.6%	 35.0% 31.2% 33.8%	 29.4% 26.3% 44.3%

Table 4.4: Bid price relationships of main positions of Cut-and-Cover and NATM tunnels for city railways in Bochum (Source: [8])

In Bochum some experience could be gained for the cost of utility relocation. For NATM structures the costs were about 20% lower than those of Cut-and-Cover constructions. For obvious reasons, the cost depends on the location of the tunnel. The highest value for the utility relocation of a Cut-and-Cover construction has been up to one third of the construction cost of the entire station. NATM is usually situated deeper and is more flexible in the alignment, so that a crossing of utility lines can be avoided in most cases.

The cost for traffic decking increases the total construction cost tremendously. As mentioned above, a decking of 75% of the open pit was considered. The cost for the traffic decking amounts to 20% to 33%, depending on the tunnel size. For triple-track tunnels the costs for the covering are almost as high as for the bare concrete construction.

The great cost advantage of NATM tunnels favors its application even if extensive additional measures, like ground improvements, have to be applied. The numbers shown were calculated for the conditions encountered in Bochum, but can also be applied to for other projects.

4.3.3 Study 2: Tunneling Costs and their most important Relationships

[11]

A cost comparison between the Cut-and-Cover tunnelling method and mined tunnelling method has been carried out by the German research organization for underground traffic structures STUVA (Studiengesellschaft für unterirdische Verkehrsanlagen e.V.) in the year 1978. [11]

It was based on the assumption that for a special subway contract section Cut-and-Cover as well as mined tunneling are possible. For neither of them any special or additional difficulties regarding the construction are expected, which would lead to higher costs. Under these conditions the different construction methods are economical within certain application limits.

The objective of this study involved two alternatives:

Alternative 1: Running tunnels and stations tunnels constructed in **Cut-and-Cover** method.
Alternative 2: Running tunnels excavated by **mined** method, but station tunnels constructed by **Cut-and-Cover** method.

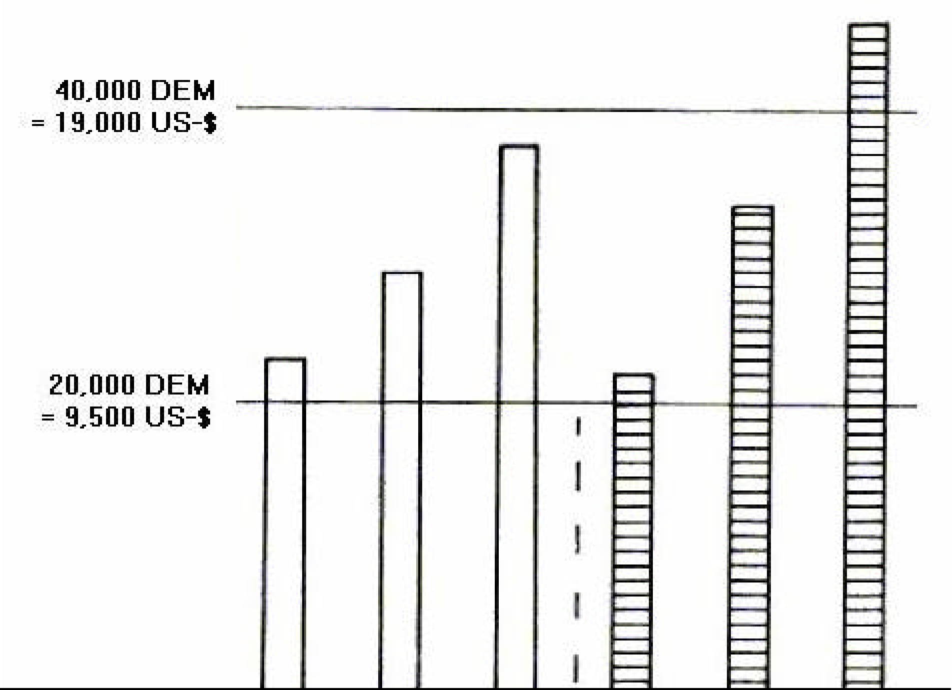
Today it is common to excavate also station tunnels by NATM, which usually leads to lower cost.

For a cost comparison on the same reference base it is necessary to have the same passanger transport capacity as a basis. Depending on the capacity (persons per hour and direction) the most reasonable section sizes have been developed for the various construction methods as shown in Table 4.5.

Capacity [pers. / (hr. x dir.)]	**up to 7,000**	**up to 13,000**	**up to 17,000**	**up to 33,000**	**up to 50,000**
Persons per m train length	2.2	2.2	5.5	5.5	8.4
Train intervall in minutes	2	2	2	2	2
Section dimension for Cut-and-Cover	4.0 m x 2.4 m	4.0 m x 2.4 m	6.0 m x 3.6 m	6.0 m x 3.6 m	8.0 m x 5.1 m
Tunnel diameter for mined version	2 ∅ 3 m or 1 ∅ 4.5 m	2 ∅ 3 m	2 ∅ 4.5 m or 1 ∅ 6 m	2 ∅ 4.5 m or 1 ∅ 6 m	2 ∅ 6 m
Number of staircases per station	1	2	1	2	2

Table 4.5: Relationship between passanger capacity and the most reasonable section size (Source: [11])

For both alternatives shallow overburden and a location above ground water level were assumed. The Cut-and-Cover construction features a soldier pile wall, the mined alternative is designed conventionally, with shotcrete, lattice girders and welded wire fabric. The tunnel length is 750 m for both alternatives and includes one station. The results of the study are summarized in Figure 4.6.



Max. Capacity in thousand (persons per hour and direction)	13	33	50	13	33	50
Section size [m]	4.0 x 2.4	6.0 x 3.6	8.0 x 5.1	2 ∅ 3	1 ∅ 6 or 2 ∅ 4.5	2 ∅ 6
Construction method	Cut-and-Cover			NATM		

Figure 4.6: Comparison of Cost per Meter of Running and Station Tunnels (stations with 200 m platform length and 2 staircases) in a cohesionless mixed soil between the cut-and-cover and mined method dependent upon the maximum transport capacity (Source: [11])*

For a capacity of 13,000 persons per hour and direction the cost for the subway line (running tunnels and stations) vary just slightly between the different methods. For increasing capacity and therewith larger tunnel sections the NATM becomes more expensive compared to the Cut-and-Cover method.

Due to a minimum required overburden for mined tunnels in alternative 2 the invert depth increases with growing section area. That, however, leads to the necessity that also the depth of the (Cut-and-Cover) station increases. Deeper Cut-and-Cover stations increase the cost of the whole system. That explains to a certain degree, why the NATM-constructed subway system is relatively more expensive for higher capacities.

Within the same study, also construction costs of station tunnels were analyzed and mined tunneling was compared to the Cut-and-Cover method. The stations were designed with two

*) exchange rate of 01/01/1978: 1 DEM (German Mark) = 0.475 US-$

staircases and a platform length of 100 m. The results of the calculations showed, that the cost per m³ excavation were:

- 340 DEM (= 162 US-$)* per m³ for stations in Cut-and-Cover construction
- 450 DEM (= 214 US-$)* per m³ for stations in NATM

However, the excavation mass of NATM stations is 10% to 70% less than that of Cut-and-Cover stations, depending on size and number of the adjacent running tunnels, which results in lower total costs of stations.

Table 4.7 summarizes the investigated station alternatives and the results of the cost calculation are shown in Table 4.8.

Number	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**	**3**	**4**	**5**	**6**
Method	Cut-and-Cover						NATM					
Type	Side Platform			Central Platform			Side Platform			Central Platform		
Tunnel Diameter	1∅4.5	1∅6	1∅7,5	2∅3	2∅4,5	2∅6	1∅4.5	1∅6	1∅7,5	2∅3	2∅4,5	2∅6
Length total	152	130	132	140	160	164	152	130	132	134	134	134
Invert Depth	13.0	15.5	17.0	10.5	13.0	15.5	13.0	15.5	17.0	10.5	13.0	15.5
Construct. Duration	7 month	7 month	9 month	8 month	10 month	11 month	17 month	19 month	26 month	10 month	13 month	15 month

Table 4.7: Investigated Station Alternatives (Source: [11])

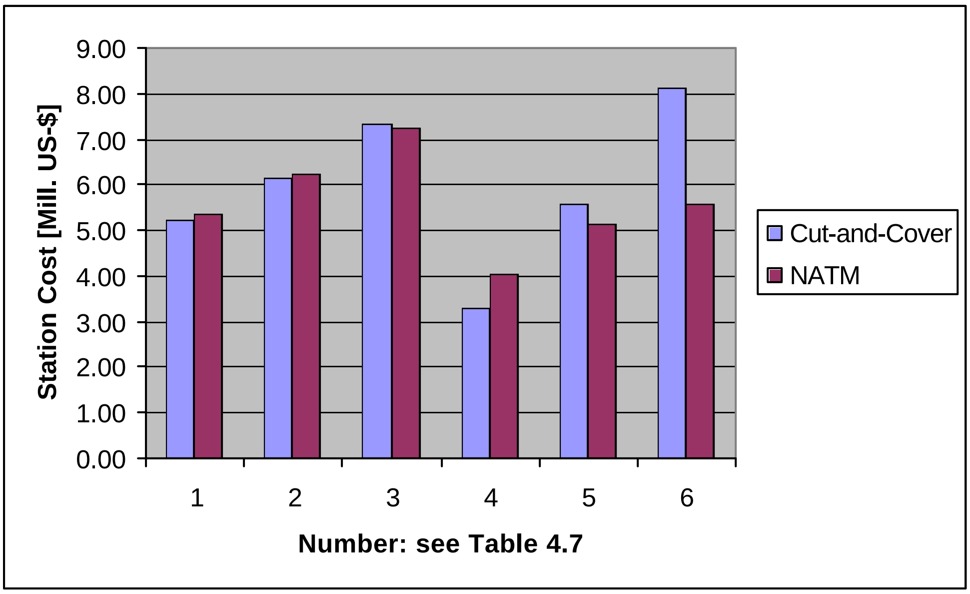


Figure 4.8: Comparison of Construction Cost of Cut-and-Cover vs. NATM Stations (2 staircases and 100 meter platform length)*

The study shows, that even in 1978, in the beginning of the application of NATM for urban tunneling, it was already a competitive alternative, considering the bare construction cost.

*) exchange rate of 01/01/1978: 1 DEM (German Mark) = 0.475 US-$

4.3.4 Study 3: Construction Cost of Road Tunnels

[5, 6]

In 1998 the German Federal Ministry for Transport, Building and Housing (Bundesministerium für Verkehr, Bauen und Wohnen - BMVBW) commissioned a research project with the goal of simplifying the choice of suitable tunnel cross-sections for roads. The German research organization for underground traffic structures STUVA (Studiengesellschaft fuer unterirdische Verkehrsanlagen e.V.) was in charge with the task of determining tunneling costs.

The approximate construction costs had to be determined for various road cross-sections and tunnel lengths as well as for different construction methods and subsoil conditions. Numerous alternatives had to be worked out in order to come up with comparative statements pertaining to the construction costs for various future road tunnel projects in Germany, whose marginal conditions differed in a number of points. Altogether, 176 alternatives were investigated, which arose through combining the mentioned parameters systematically.

Determining costs was confined to the approximate construction costs, as these influence the overall cost differences for neighboring cross-section types. The cost differences, which the various construction methods provoked for the installation of the operating equipment and for the operation itself, were estimated.

Two-way cross-sections with two lanes in each direction with and without emergency lane had to be examined comparatively for various construction methods, lengths and categories of difficulty. For the cross-section types 26 T and 26 t (see Figure 4.9), taken as the basis, minimum clearance of 12 m and 9.50 m per directional tube emerged. For the cross-section types 33 T and 33 t the clearances were 15.50 m and 13.00 m respectively.

The investigated cross-section types are shown in Figure 4.9.

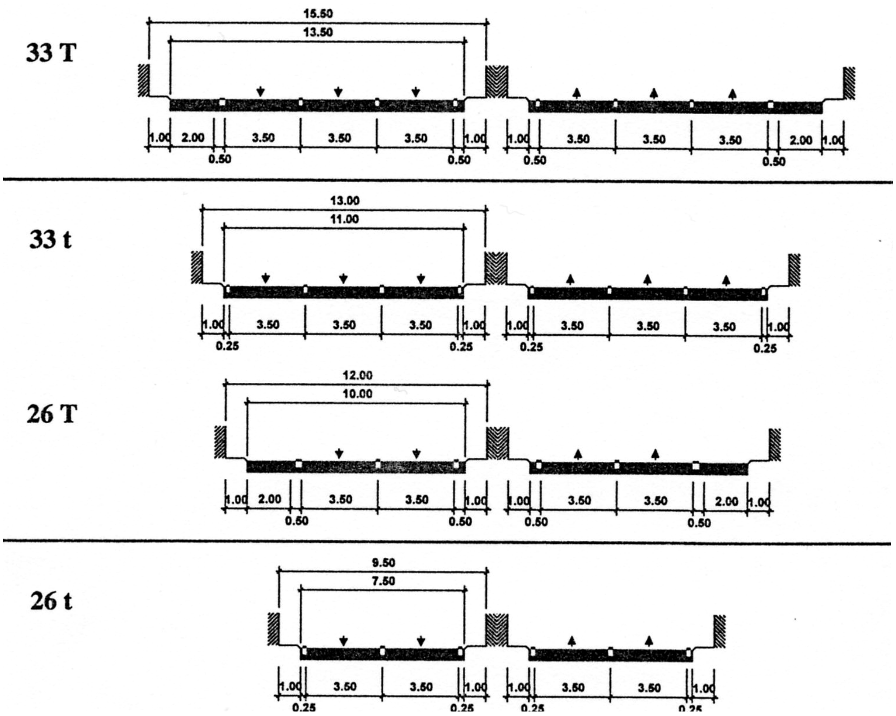


Figure 4.9: Investigated cross section types (Source: [5])

The construction performances, for which the costs had to be worked out, were described with the help of a bill of quantities developed in accordance with titles and positions. The year 1996 was taken as reference. Tunnel lengths in three stages of 500 m, 1,000 m and 2,000 m were investigated. In the case of a tunnel length of 500 m, a natural ventilation (with CO alarm) suffices for directional traffic. For tunnel lengths of 1,000 and 2,000 m, longitudinal ventilation with jet fans (without suction duct or shaft) is foreseen. In the case of Cut-and-Cover, the fans are installed in pairs in ceiling recesses at gaps of = 50 m in a longitudinal direction. In the case of the NATM (vaulted cross-section), the jet fans can be set up above the carriageway in the tunnel crown without enlarging the cross-section.

Standard prices and percentages were taken as the basis for determining costs with the active support of the construction industry and building authorities, in other words, prices largely geared to competitive level supported by findings obtained from actual projects. Hochtief AG, Philipp Holzmann AG and the Herrenknecht AG supplied significant contributions towards the technical execution and calculations. Several construction authorities also played a major role, particularly the Foundation Engineering Office of the regional capital of Stuttgart (Landeshauptstadt Stuttgart - Tiefbauamt), the Supreme Construction Authority in the Bavarian State Ministry of the Interior (Oberste Baubehörde im Bayerischen Staatsministerium des Inneren), the Construction Authority of the Free and Hanseatic City of Hamburg – Foundation Engineering Office (Baubehörde der Freien und Hansestadt Hamburg – Tiefbauamt) and the Lower Saxony Regional Office for Road-Building (Niedersächsisches Landesamt für Straßenbau).

The more comprehensively and the more detailed the conditions for the a construction are defined, the more accurately the standard prices and surcharges and in turn, the overall project can be calculated. For the sake of the investigation, it was, however, necessary to express the requirements in individual points more generally than would be appropriate in actual tenders. Local circumstances had largely to be neglected; "average" conditions were accepted – to the greatest extent. Otherwise, the number of possible variations would soar given the numerous combinations of parameters present, so that they can no longer be used in a standardized method.

The determined values enable an acceptable comparative estimation of the overall rough work costs for two-tube road cross-sections created by different tunneling methods. In this way, it is possible to carry out an initial estimation of the magnitude of the costs for concrete projects at an early stage in planning. The cost calculations undertaken within the framework of these investigations cannot, however, replace determining the cost in the sense of a thoroughly worked out, detailed estimation based on the circumstances of the individual case for a concrete project.

Furthermore, experience shows that in practice calculating prices produces results, which considerably vary from average costs or from cost estimates as well. In this context, the following factors have a particular influence:

- Local features (e.g. site conditions, dump costs, protection of existing buildings, maintaining traffic services, utilities etc.)
- Varying subsoil/groundwater conditions, overburden
- Fluctuation in the construction sector
- Competitive structure, regional differences
- Variation of essential material costs (e.g. price of steel)
- Special characteristics of the structure (e.g. portal design, intersections with other traffic arteries, enlargements)
- Automation, technical advances, improvements in building operations.

Subsoil risks also affect the price structure in some cases, in conjunction with Cut-and-Cover but more so when mining methods are applied.

<u>Cut-and-Cover</u>

Main cases of application for tunnels located at a shallow depth were examined. The tunnel overburden is 1 m, related to the tunnel apex, in other words, the carriageway gradient is to be found some 7 to 8 m below the surface. In cases typical for the Cut-and-Cover construction method, the tunnel axis and carriageway gradient are designed with a slight longitudinal incline and/or with a trough. The subsoil consists of largely non-cohesive mixed ground (sands and alluvial marl).

Depending on the groundwater conditions, the following layouts were selected:

a) The groundwater level is located beneath the tunnel base: a three-leg plate frame forms the supporting structure with continuous central wall on a foundation which is open at its underside. As a protective measure against seepage water (without it banking up) only, the ceiling is designed as watertight concrete construction

b) The groundwater can rise to a level, located 1 m below the tunnel's upper edge. The structure comprises a closed frame with continuous central wall, with complete supporting base. As a protective measure against pressure water, the entire frame is executed as watertight concrete construction (WUB-KO).

Figures 4.10 and 4,11 show the investigated cross sections.

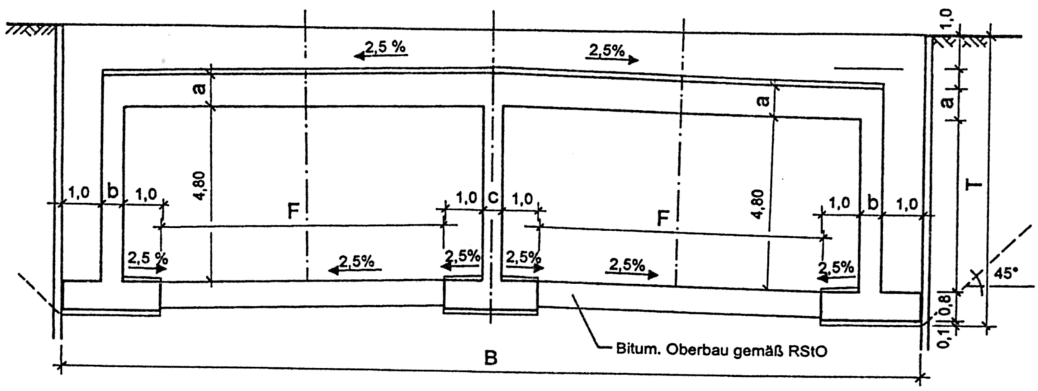


Figure 4.10: Investigated Cut-and-Cover method for ground water level below structure: Three-leg plate frame with continuous central wall on a foundation which is open at its underside. As a protective measure against seepage water the ceiling is designed as watertight concrete construction. (Source: [5])

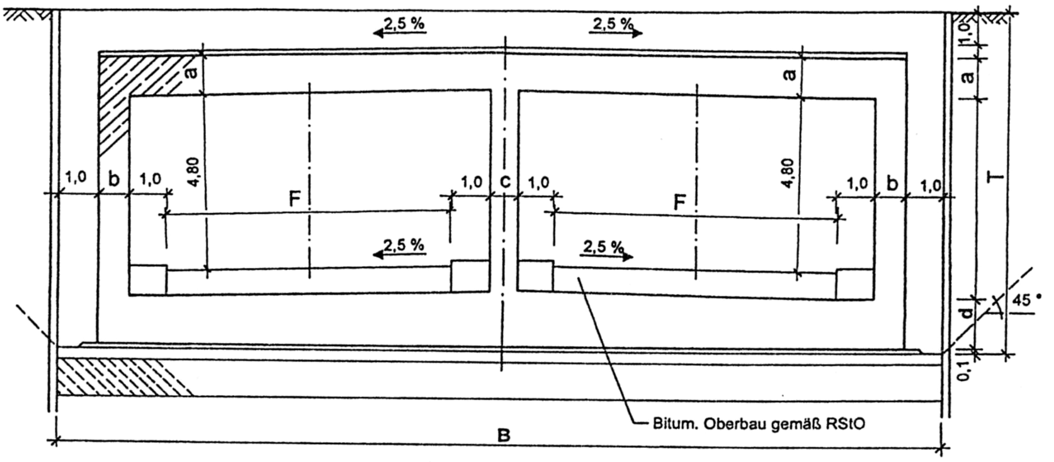


Figure 4.11: Investigated Cut-and-Cover method for ground water level which can rise to 1 m below the tunnels upper edge: Structure that comprises a closed frame with continuous central wall, with complete supporting base. As a protective measure against pressure water, the entire frame is executed as watertight concrete construction. (Source: [5])

As far as shoring walls are concerned, first and foremost, construction methods that conserve the groundwater and save space are suitable given the marginal conditions encountered. As a standard structure, steel sheet piling walls were chosen in conjunction with case a) and steel piling walls with anchored not reinforced underwater concrete base for case b). In order to have the possibility of a direct comparison with the results of a reference survey dating from 1980/81, two variants were also taken into account for enclosing the excavation (excavation with embankment as well as with soldier pile wall), which can only be applied in case of exception given the present marginal conditions.

Table 4.12 summarizes the investigated Cut-and-Cover alternatives.

	Bottom open frame	Closed frame
Pit with embankment	O1a	O1b
Soldier pile wall	O2a	O2b
Steel sheet piling walls (standard structure)	O3a	O3b

Table 4.12: Investigated design forms for Cut-and-Cover construction (Source: [5])

The location of the tunnel in the groundwater or above the groundwater level is one of the most important factors of influence for the total cost. If the excavation is enclosed by underwater concrete base and piling wall, it can be assumed that the construction costs would be considerably higher than at a location where the ground water is below of the tunnel. The additional cost in this case amounts to roughly 66%.

As the tunnel length increases, the relative costs per meter of tunnel length generally tend to decrease. For the investigated length of 500 m, 1,000 m and 2,000 m, however, the differences are relatively small compared to other factors of influence in the case of Cut-and-Cover. For tunnels in excess of 2,000 m in length, the costs per meter tunnel decrease by approx. 3 % to 5% compared to a 500 m long tunnel.

NATM

Nine different excavation classes or degrees of difficulty were taken into account during the survey: four alternatives in soft ground and five alternatives in solid rock.

Solid rock		
GFS1	*26T / 26t*	*Two stage advance, length of round > 1.5 m, no serious negative impact due to ground water, anchors, shotcrete (7 to 15 cm depending on excavation area size), welded wire fabric, low time effort for support work, top heading 10 m and more in advance, no invert vault and no invert support necessary.*
	33T / 33t	*Advance in 5 / 3 steps, single / double sidewall drift, round length > 1.5 m, no serious negative impact due to ground water, anchor, 20 / 15 cm shotcrete, welded wire fabric, low time effort for support work, sidewall drift 10 m or more in advance, no invert vault necessary.*
GFS2	*26T / 26t*	*Two stage advance, length of round = 1.5 m, negative influence on the ground due to ground water possible, immediate shotcrete sealing (including tunnel face) necessary, shotcrete thickness at least 20 cm, welded wire fabric, anchors, lattice girders, considerable time exposure for support measures, no invert vault nor invert support necessary.*
	33T / 33t	*7 / 5 stage advance, double / single sidewall drift (hurrying ahead), length of round = 1.5 m, negative influence on the ground due to ground water possible, immediate shotcrete sealing (including tunnel face) necessary, 30 / 25 cm shotcrete thickness, welded wire fabric, anchors, lattice girders, considerable time exposure for support measures, no invert vault nor invert support necessary.*
GFS3	*26T / 26t*	*Advance in more than 2 steps, length of round > 1.5 m, negative influence on the ground due to ground water possible, immediate shotcrete sealing necessary, shotcrete thickness at least 15 cm, welded wire fabric, anchors, medium time exposure for support measures.*
	33T / 33t	*Advance in 5 / 3 steps, length of round > 1.5 m, negative influence on the ground due to ground water possible, immediate shotcrete sealing necessary, shotcrete thickness 25 / 20 cm, welded wire fabric, anchors, medium time exposure for support measures, no invert vault necessary.*
GFS4	*26T / 26t*	*Advance in more than 2 steps, length of round = 1.5 m, negative influence on the ground due to ground water possible, immediate shotcrete sealing necessary, shotcrete thickness at least 20 cm, welded wire fabric, system anchoring, lattice girders, relevant time exposure for support measures.*
	33T / 33t	*Advance in 7 / 4 steps, length of round = 1.5 m, negative influence on the ground due to ground water possible, immediate shotcrete sealing necessary, shotcrete thickness 25 / 20 cm, welded wire fabric, system anchoring, relevant time exposure for support measures, no invert vault necessary.*
GFS4w		*Like GFS4 but invert vault due to high water pressure necessary.*
	26T / 26t	*For closed portal areas class GLS1 is used.*

Table 4.13: Investigated NATM excavation classes in solid rock (Source: [5])

Soft ground		
GLS1	*briefly stable, cohesive soft ground*	
	26T / 26t	*Partial excavation in three steps (top heading, bench, invert), length of round not more than 1 m, immediate support necessary, considerable time effort for support work, initial support via lattice girders and reinforced, at least 20 cm thick shotcrete.*
	33T / 33t	*Partial excavation in 7 / 4 steps, single / double sidewall drift (hurrying ahead), round length not more than 1 m, immediate support necessary, considerable time effort for support work, initial support via lattice girders and reinforced, at least 35 / 30 cm thick shotcrete, no invert vault necessary.*
GLS2	*not stable soft ground of regularly stratified sands and gravels*	
	26T / 26t	*Partial excavation in three steps (top heading, bench, invert), length of round 0.8 m, support via spiling, lattice girders and reinforced, at least 20 cm thick shotcrete, support of tunnel face via shotcrete and remaining soil wedges.*
	33T / 33t	*Partial excavation in 7 / 5 steps, single / double sidewall drift (hurrying ahead), round length 0.80 m, support via spiling, lattice girders and reinforced, at least 35 / 30 cm thick shotcrete, support of tunnel face via shotcrete and remaining soil wedges, no invert vault necessary.*
GLS3	*not stable soft ground of irregularly stratified sands and gravels and continuous debris (including erratic blocks)* *Construction method like GLS2, length of round: 0.80 m.*	
GLS3m	*Like difficulty class GLS3, but invert vault due to worse ground conditions necessary.*	

Table 4.14: Investigated NATM excavation classes in soft ground (Source: [5])

In the vicinity of the tunnel portals, an area of extremely soft ground with a length of 30 m was expected. As a consequence, 20 m of the portal zones were built via Cut-and-Cover method and the following 10 m where mined, albeit having a poorer excavation class than designated for the rest of the route.

The tunnels are not located in groundwater. However, the possibility of encountering seeping surface water or not particularly active stratum water must be considered. Furthermore, one difficulty class (GF4w) with extremely high water pressure (> 3 bar) was examined.

The clear distance between the two tubes amounts to roughly 15 m for cross-section types 26 T and 26 t, and approx. 19 m for types 33 T and 33 t, i.e. the axial distance is taken to be roughly twice the value of the maximum width of the individual tube concerned.

Apart from the temporary shotcrete support, an inner shell consisting of in situ concrete is foreseen. Between the inner and outer shell, a loosely laid, single layer plastic waterproofing membrane is installed to keep out seeping water. Special measures (e.g. a two-layer all-round seal) are necessary for the excavation class GF4w due to the extremely high water pressure.

Figure 4.15 shows the investigated NATM cross section.

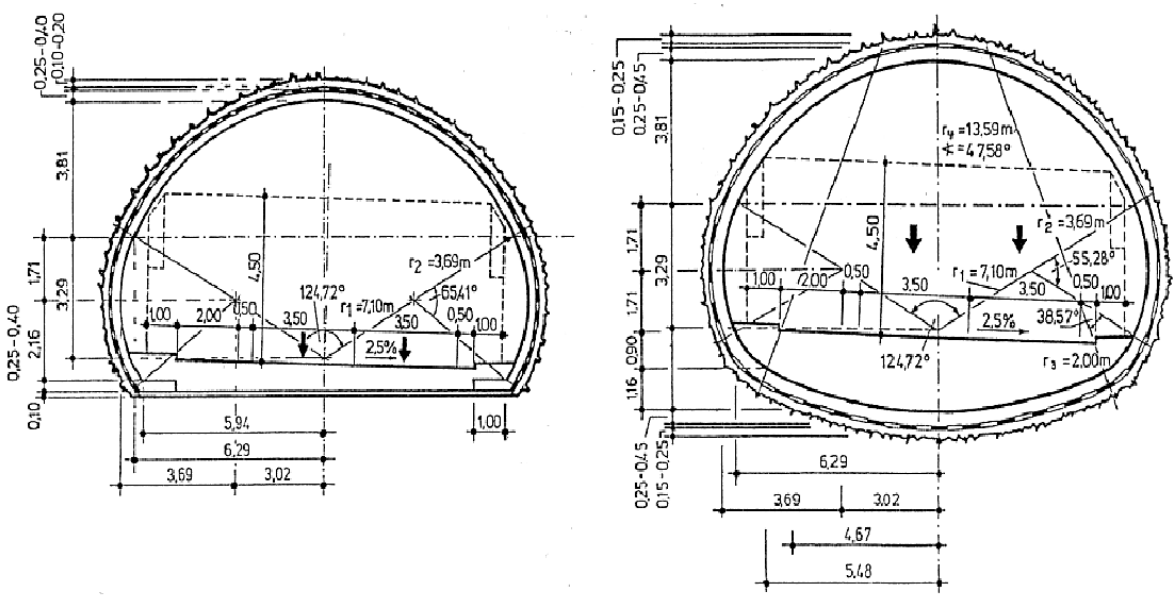


Figure 4.15: Investigated NATM cross section without and with invert vault. (Source: [5])

Because of the risks, especially the subsoil risks, which are always present in the case of mining methods of construction in spite of careful investigation, considerable deviations between the cost estimate and the final cost must always be expected. Proper predictions concerning costs of future projects are made more difficult through the fact that the execution of tunneling constructions takes several years and the reference to the relevant offer/award prices for current projects is limited.

The results confirm that it is inevitable that the difficulty classes are further split up to ensure realistic appraisals. The cost for the simplest difficulty class in solid rock taken into account here amounts to only about one third of the cost for the highest class in soft ground for cross-section types 26 T and 26 t. The dominating influence of the different excavation classes remains undiminished in the case of the very large excavation cross-sections 33 T and 33 t as well.

Results

The investigated construction costs are summarized in Table 4.16.

Length [m]	Cross section type	N A T M Difficulty class									C U T A N D C O V E R Design class					
		GFS1	GFS2	GFS3	GFS4	GFS4w	GLS1	GLS2	GLS3	GLS3m	O1a	O1b	O2a	O2b	O3a	O3b
250	26t	32.82	39.76	35.41	42.93	54.07	50.78	67.14	74.92	79.73	25.81	36.54	31.50	44.40	35.90	60.68
	26T	40.32	51.58	44.10	56.16	71.64	65.16	84.42	96.19	105.41	30.84	45.61	37.43	53.81	41.94	71.72
	33t	51.54	66.97	56.71	73.13	91.58	84.45	106.62	120.42	131.09					45.77	69.86
	33T	67.72	87.58	73.90	95.49	118.61	109.08	135.01	152.69	166.09					55.85	84.52
500	26t	27.17	35.80	30.72	39.54	49.81	47.16	64.68	72.72	77.39	24.43	35.56	29.85	42.26	34.04	57.77
	26T	33.44	46.72	38.30	52.05	66.41	61.00	81.94	94.03	103.04	29.21	43.43	35.51	51.22	39.80	68.31
	33t	42.80	60.72	49.03	67.39	84.41	78.93	103.02	117.27	127.66					43.44	66.52
	33T	56.27	79.44	63.93	88.02	109.35	101.96	130.45	148.70	161.75					52.96	80.55
1000	26t	25.70	34.20	29.06	38.09	47.38	44.36	61.71	69.81	74.98	23.87	34.73	29.17	41.28	33.14	56.20
	26T	31.65	44.61	36.13	49.70	62.63	57.53	78.13	89.96	99.01	28.53	42.44	34.69	50.05	38.76	66.48
	33t	40.79	58.30	46.46	64.63	80.17	74.96	98.65	112.81	123.20					42.32	64.84
	33T	53.75	76.35	60.66	84.54	104.22	97.08	125.03	143.16	156.28					51.61	78.52
2000	26t	24.51	32.96	27.75	36.75	45.36	42.49	58.96	67.52	72.54	23.82	34.71	29.10	41.24	32.96	55.90
	26T	29.82	42.38	34.03	47.29	59.15	54.36	74.39	85.79	94.24	28.20	41.94	34.28	49.46	38.24	65.55
	33t	39.27	56.51	46.59	62.68	77.26	72.20	95.44	109.11	119.29					42.22	64.67
	33T	51.09	72.99	57.48	80.88	99.21	92.32	119.47	136.73	149.46					50.94	77.51

Table 4.16: Approximate Construction Cost in 1000 US-Dollar per Meter (Source: [5])*

Results can be seen by comparison of the standard structure Cut-and-Cover tunneling method O3a and the various difficulty classes for NATM. NATM is competitive for all difficulty classes in solid rock (GFS1 through GFS4) and the difficulty class GLS1 in soft ground. For more difficult conditions (GFS4w, GLS2, GLS3 and GLS3m) the Cut-and-Cover method has a cost advantage according to this study. The numbers show, that NATM is more cost effective the smaller the cross section size and the longer the tunnel is.

The primary purpose of this study was to compare different cross section sizes and not different construction methods. Therefore, the results have to be considered with some precaution. For example, in order to achieve a fair comparison, the (high) cost for the temporary traffic decking has to be added to the Cut-and-Cover construction cost.

4.3.5 Example: Pedestrian Tunnel

A detailed cost comparison between Cut-and-Cover and NATM construction methods has been carried out for a pedestrian tunnel at Dulles International Airport in Virginia (USA). This tunnel, which serves as an underground corridor for pedestrians between two of the airport terminals, is about 235 m long. The NATM option has a cross sectional area of 85 m^2 which is comparable to a typical subway station cross section. The crown of the tunnel is located 4.7 m and the bottom of the invert 13.1 m below the ground surface.

*) converted from German Mark into US-Dollar with an exchange rate of:
1 DEM (German Mark) = 0.68 US-$ (by 07/31/1996)

The geologic conditions encountered may generally be described as those of a fissured, highly weathered to jointed rock overlain by decomposed rock and fill and a 38 cm thick concrete slab. A significant portion of the tunnel's crown is located in a mixed face (i.e. soil and rock interface). Also, several existing utility lines traverse the alignment of the tunnel, like fuel lines, storm sewer and fiber optic lines. The stand up time of the ground in certain sections was very short. The ground water situation was not detrimental for the construction, even though some sections of the tunnel had to be dewatered.

Due to limited site layout space on both ends of the tunnel and in order to reduce the construction schedule by concurrently mining multiple headings, the NATM alternative was designed to start the excavation from an access tunnel which would perpendicularly intersect the pedestrian tunnel near its midpoint. An access ramp had to be excavated first, followed by the top heading of the access tunnel. The next step was the excavation of the top heading of the pedestrian tunnel in north and south directions. The excavation of bench and invert of the pedestrian and the access tunnel completed the drift. The construction time was estimated to be about 50 weeks.

The Cut-and-Cover version was envisioned as a construction with typical temporary shoring walls consisting of shotcrete with tie-backs, soldier pile and lagging etc. The cross section was 10.8 m wide and 5.9 m high with a minimal overburden.

The cost estimate for the Cut-and-Cover option has been prepared by I.C.F. Kaiser, Engineers, and the NATM cost estimate has been provided by the Dr. G. Sauer Corporation of Herndon, VA in 1999. The results are summarized in Table 4.17.

		CUT AND COVER				NATM				DIFFER-ENCE
	ACTIVITIES	QUANTITY	UNIT	UNIT COST	TOTAL	QUANTITY	UNIT	UNIT COST	TOTAL	
1	**DEMOLITION/TEMPORARY CONSTR.**				$ 660,510				$ 660,510	$ 0
2	**SITEWORK**									
	Remove & Dispose Existing Ramp/Taxiway	6,400	sf	$ 25.00	$ 160,000	0			$ -	$ 160,000
	Replace Existing Ramp/Taxiway	6,400	sf	$ 130.00	$ 832,000	0			$ -	$ 832,000
	Excavation - Rock (Rippable)	72,600	cy	$ 25.00	$ 1,815,000	35,750	cy	$ 84.00	$ 3,003,000	$ -1,188,000
	Excavation - Rock (Blasting)	12,800	cy	$ 75.00	$ 960,000	0			$ -	$ 960,000
	Backfill & Compact	37,200	cy	$ 6.00	$ 223,200	12,225	cy	$ 6.00	$ 73,350	$ 149,850
	Load & Haul Spoils (Off-Site)	60,400	cy	$ 13.00	$ 785,200	25,900	cy	$ 13.00	$ 336,700	$ 448,500
	Utilities Relocation	1	allow.	$ 300,000.00	$ 300,000	1	allow.	$ 300,000.00	$ 300,000	$ 0
	Support of Existing Utilities	1	allow.	$ 75,000.00	$ 75,000	0			$ -	$ 75,000
	Support of Excavation	75,000	sf	$ 25.00	$ 1,875,000					$ 1,875,000
	Reinforced Shotcrete	0			$ -	3,690	cy	$ 290.00	$ 1,070,100	$ -1,070,100
	Rebar Spiling	0			$ -	112,000	lf	$ 2.25	$ 252,000	$ -252,000
	Lattice Girder	0			$ -	390	ea	$ 750.00	$ 292,500	$ -292,500
	Dewatering	1	allow.	$ 50,000.00	$ 50,000	1	allow.	$ 50,000.00	$ 50,000	$ 0
	Connect to Existing HTHW/CHW Lines	1	allow.	$ 300,000.00	$ 300,000	1	allow.	$ 300,000.00	$ 300,000	$ 0
	Connect to Existing Power	1	allow.	$ 200,000.00	$ 200,000	1	allow.	$ 200,000.00	$ 200,000	$ 0
	Modify Storm Drainage	1	allow.	$ 75,000.00	$ 75,000	0			$ -	$ 75,000
	SUBTOTAL				$ 7,650,400				$ 5,877,650	$ 1,772,750
	MOBILIZATION/DEMOBILIZATION				$ -	15	%		$ 881,648	$ -881,648
	TOTAL				$ 7,650,400				$ 6,759,298	$ 891,103
3	**STRUCTURE**									
	Form - SOG	6,700	sf	$ 7.00	$ 46,900				$ -	$ 46,900
	Form - Walls	96,200	sf	$ 15.00	$ 1,443,000				$ -	$ 1,443,000
	Form - Susp. Slab	49,300	sf	$ 6.00	$ 295,800				$ -	$ 295,800
	Rebar - SOG	460	tons	$ 800.00	$ 368,000				$ -	$ 368,000
	Rebar - Walls	290	tons	$ 1,200.00	$ 348,000				$ -	$ 348,000
	Rebar - Susp. Slab	700	tons	$ 800.00	$ 560,000				$ -	$ 560,000
	Conc. - SOG	6,000	cy	$ 160.00	$ 960,000				$ -	$ 960,000
	Conc. - Walls	2,300	cy	$ 200.00	$ 460,000				$ -	$ 460,000
	Conc. - Susp. Slab	4,000	cy	$ 180.00	$ 720,000				$ -	$ 720,000
	Mudmat	4,000	cy	$ 75.00	$ 300,000	380	cy	$ 75.00	$ 28,500	$ 271,500
	Invert Form, Rebar and Concrete	0			$ -	4,400	cy	$ 125.00	$ 550,000	$ -550,000
	Wall Form, Rebar and Concrete	0			$ -	2,850	cy	$ 260.00	$ 741,000	$ -741,000
	Waterproofing	153,400	sf	$ 4.00	$ 613,600	135,000	sf	$ 6.00	$ 810,000	$ -196,400
	Structural Steel Colums/Beams	40	tons	$ 3,500.00	$ 140,000	40	tons	$ 3,500.00	$ 140,000	$ 0
	Composite Floor Deck	15,400	sf	$ 8.00	$ 123,200	15,400	sf	$ 8.00	$ 123,200	$ 0
	Roof Deck	15,400	sf	$ 3.00	$ 46,200	15,400	sf	$ 3.00	$ 46,200	$ 0
	Membrane Roofing System	15,400	sf	$ 6.00	$ 92,400	15,400	sf	$ 6.00	$ 92,400	$ 0
	CMU Walls	2,100	sf	$ 12.00	$ 25,200	2,100	sf	$ 12.00	$ 25,200	$ 0
	Exterior Wall System	6,270	sf	$ 65.00	$ 407,550	6,270	sf	$ 65.00	$ 407,550	$ 0
	Emergency Egress Station	1	each	$ 350,000.00	$ 350,000	1	each	$ 350,000.00	$ 350,000	$ 0
	Structural Moidifications To "B" Concourse	1	each	$ 75,000.00	$ 75,000	1	each	$ 75,000.00	$ 75,000	$ 0
	SUBTOTAL				$ 7,374,850				$ 3,389,050	$ 3,985,800
	MOBILIZATION/DEMOBILIZATION				$ -	15	%		$ 508,358	$ -508,358
	TOTAL				$ 7,374,850				$ 3,897,408	$ 3,477,443
4	**SUMMARY**									
	Demolition/Temporary construction				$ 660,510				$ 660,510	$ 0
	Sitework				$ 7,650,400				$ 6,759,298	$ 891,103
	Structure				$ 7,374,850				$ 3,897,408	$ 3,477,443
	SUBTOTAL				$15,685,760				$11,317,215	$ 4,368,545
	ADDITIONAL DESIGN FEE				$ -				$ 363,425	$ -363,425
	TOTAL				**$15,685,760**				**$11,680,640**	**$ 4,005,120**
	COST PER FOOT	**770**	**ft**		**$ 20,371**	**770**	**ft**		**$ 15,170**	**$ 5,201**
	COST PER METER	**235**	**m**		**$ 66,834**	**235**	**m**		**$ 49,769**	**$ 17,065**

Table 4.17: Cost comparison between Cut-and-Cover method and NATM for a pedestrian tunnel at Washington Dulles International Airport (Source: Dr. G Sauer Corp.)

Even under the difficult ground conditions encountered the NATM option was 25% cheaper than the Cut-and-Cover option. As shown in the table above, the NATM option was especially cheaper for the construction of the tunnel structure, because it required less material and was faster. But also the site work (see activity number 2 in Table 4.17) was more cost effective. However, for NATM additional positions had to be added for mobilization and demobilization, as well as for a design fee due to the more sophisticated design.

The comparable construction costs and construction time but the huge advantage of low surface impact by the NATM alternative led to an execution of the project as a mined tunnel.

4.3.6 Valuation of Secondary or Indirect Cost

Secondary or Indirect costs normally are not paid by the client and are therefore overseen all too often. Moreover, they are usually hard or even impossible to evaluate. In urban tunneling, secondary costs derive especially from

- Redirection, interruption or even stopping of road traffic
- Obstacles for pedestrians or closings of pavements
- Loss of attraction of areas with retailers and therefore fewer customers
- Loss of parking space
- Loss of recreational areas
- Environmental pollution by dust, noise, dirt etc.

In 1990 the German Ministry of Transportation published a newsletter [19] concerning the acceleration of construction works on German freeways (autobahn). A valuation system was set up, which allows to express every day with construction-related speed limit or closing of a traffic line in monetary terms.

Alternative bids for highway construction projects, which allow a faster finish of the construction can so be compared easily with traditional bids. A conventional bid has to be calculated first, followed by an alternative with faster construction duration. The additional costs which arise by the acceleration of the construction have to be listed separately. Consequently, the pre-determined values per saved day of construction duration are deducted. The resulting value is the one taken for comparison.

The following example should explain the procedure.

	Bit sum (main offer)	8,895,000 US-$*
	Additional cost with a 20 day reduction of construction duration	237,000 US-$*
	Bid sum (alternative offer)	9,132,000 US-$*
-	Justifiable additional cost: 20,900 DM per day = 20,900 x 20 =	- 418,000 US-$*
	Bid sum for comparison purpose	8,714,000 US-$*

The "justifiable additional cost" depends on the amount of traffic (average daily traffic), the setup of the traffic lines (number and direction) and the length of the influenced road area. The cost per km and day ranges from 240 US-$* to 12,500 US-$*.

A similar approach can be used for the valuation of the disturbance of the traffic due to Cut-and-Cover construction.

*) converted from German Mark into US-Dollar with an exchange rate of:
1 DEM (German Mark) = 0.593 US-$ (by 01/01/1990)

4.4 Risk Comparison

[3]

A common misconception is that mined tunneling involves greater risk during the construction stage than cut-and-cover. There have been a number of collapses or other stability failures of NATM projects around the world including Turkey and the US. Perhaps the most known is the Heathrow Airport collapse in October 1994, which triggered a thorough review of the NATM by the British Health and Safety Executive (HSE). In a 1996 report, the HSE examined 39 NATM failures, categorizing the location (in the tunnel) of the failure.
In most cases, the failure was a result of heading collapse. Broadly speaking the cause of these failures varied, from unanticipated geologic conditions, to design errors, to construction quality problems, to poor management. Nevertheless, NATM failures, or for that matter any tunnel failure, have one characteristic in common: most are caused by human error. It is not the fault of the method, but misapplication of the method.

Cut-and-Cover construction methods also involve high risks, if not applied correctly. Emergency evacuation of houses along badly constructed slurry walls have been reported throughout the industry.

NATM requires more specialized engineers than a Cut-and-Cover design to apply the method correctly and safely.

Extensive and independent scientific risk analyses for tunnel constructions have been carried out worldwide for a variety of projects, e.g.:

- Los Bronces conveyor tunnel (Chile)
- Channel tunnel (limited to construction operation accidents)
- Great Belt tunnel (complete analysis)
- Adler tunnel (Switzerland), effect of particular geological conditions and construction problems
- Ring Roads tunnels, Stockholm
- Alpine tunnels, Switzerland
- Central Artery tunnel, Boston (USA)

In all of those projects, except the Channel tunnel and the Ring Roads tunnel, Prof. H. H. Einstein of the Department of Civil and Environmental Engineering of the Massachusetts Institute of Technology in Cambridge (USA), was involved.

The owner of the Central Artery project in Boston (USA) decided to evaluate the risks for the construction of a section of the project. The section included a tunnel that runs beneath Atlantic Avenue and the MBTA Red Line South Station. Significant features of the contract included a three to five-lane highway tunnel for northbound traffic, two highway ramps, a two-lane MBTA transit way tunnel with a turnaround, reconstruction of a large portion of the MBTA South Station, and utility relocation.

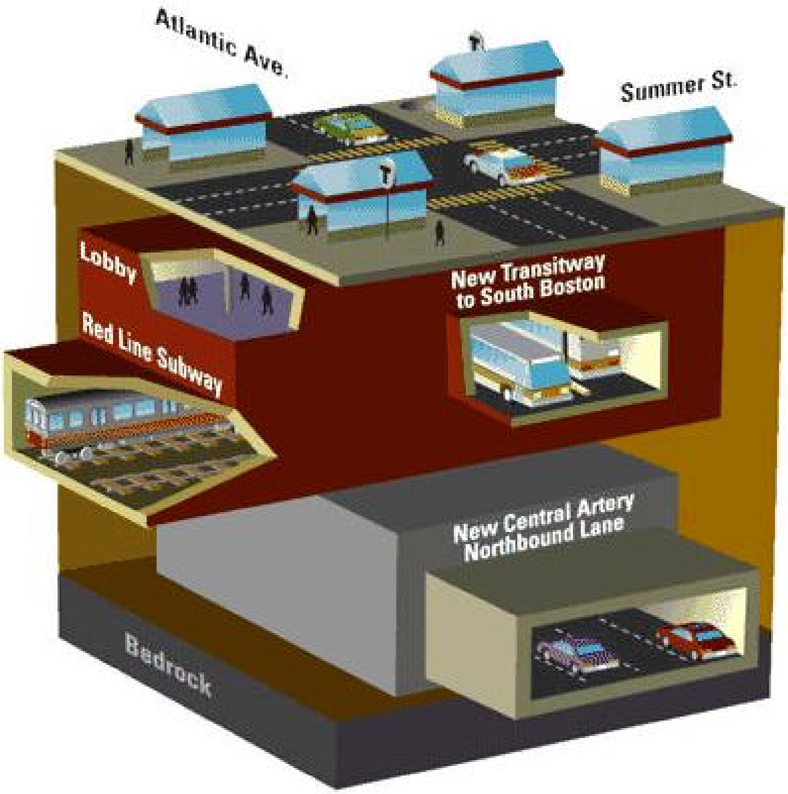


Figure 4.18: Central Artery project, Boston (USA) (Source: www.bigdig.com)

The project was originally designed as a Cut-and-Cover construction, but in October 1995 a Value Engineering Change Proposal (VECP) was carried out by the contractor Perini/Kiewit/Cashman (PKC), Boston, Massachusetts, featuring the New Austrian Tunneling Method (NATM).

With a risk analysis, the risks evoked by both alternatives should be evaluated and compared with each other. Prof. H. H. Einstein was engaged to carry out the analysis.

Risk analyses, if conducted correctly, require a careful assessment of the design and construction procedures and the contributions of highly knowledgeable people. That means that all contractors, designers, consultants and the owner have to be involved in the process.

Three different types of risk had been assessed: Constructability, Safety and Serviceability. Constructability risks reflect the uncertainties and difficulties which may lead to time and cost overruns. Safety risks involve the endangerment of people, both the public and workers, as well as structural failures both of adjacent, existing structures and the structure being built. Finally, serviceability, which in the given case refers mostly to deformations, settlements or related aspects (vibration, cracks) affecting usage, and interference with services such as utilities and public access.

The risk was defined as:

Risk = Probability of problem x Conditional Probability x Consequences of problem

Consequences are often defined in terms of cost. They often materialize only to a limited extent, even if the problem occurs, e.g. a slurry trench may fail but an adjacent structure is not affected or affected to a limited extent only. This is expressed by the so called conditional probability.

The probabilities and consequences of problems were estimated in a systematic manner together with the entire team of consultants as well as the contractor's representatives. This process involved the determination of probabilities in a formal procedure and, particularly important, the performance of so called consistency checks. The latter ensure that the relation between different probabilities express rationally founded differences or similarities.

In a scenario assessment the construction process and the performance of the final structure have been reviewed in detail. It was identified what can go wrong, how one finds out that something may go wrong and what can be done to correct the situation. In the risk analysis for the designer project (Cut-and-Cover) and the VECP (NATM) two different sections were analyzed, whereas Section 2 was the underpinning of the existing Metro line.

Table 4.19 shows a summary of the risk analysis. The risk is expressed in numbers, based on a certain calculation method. Zero means, that there is no risk at all, a higher number means higher risk.

	CONSTRUCTIBILITY		SAFETY		SERVICEABILITY	
	Cut-and-Cover	NATM	Cut-and-Cover	NATM	Cut-and-Cover	NATM
DURING CONSTRUCTION						
Sections 1	20.11	14.21	10.21	8.20	13.87	12.8 to 13.82
Section 2	24.97	13.58 to 13.78	32.53	9.29	47.18	11.09 to 11.81
AFTER CONSTRUCTION			0.18	0.09	2.79	1.83

Table 4.19: Summary of risk analysis for Boston Central Artery by Prof. H. H. Einstein, MIT

The results indicate that all risks for all sections are higher for the Cut-and-Cover project. By looking at the total risks one can see that the Cut-and-Cover and NATM risks for Section 1 during construction and for the entire project after construction are not too different (albeit greater for the Cut-and-Cover project). For Section 2 (underpinning), the Cut-and-Cover project has safety and serviceability risks between three to four times greater than those for the NATM. Clearly, there are risks which only occur for the Cut-and-Cover method such as those related to jacking, etc.

In this particular project the NATM was not only shown to be less risky. It was also estimated that it would be less expensive (approx. US$20 million savings), and that it could be carried out in shorter duration, in addition to the lower impact on surface settlement and surface activities. Nonetheless, for political reasons the project was carried out as a Cut-and-Cover construction.

4.5 Settlement Comparison

As mentioned before, settlements and displacements occur in either tunneling method. An advantage of NATM is that settlements can be controlled during the excavation, by reducing the drift section size or the length of round, increasing the amount of reinforcement, adjusting the shotcrete thickness, or by grouting measures. Cut-and-Cover methods are less flexible.

For the Central Artery project as described in the risk comparison (Chapter 4.4), a settlement comparison for two critical points of the alignment was carried out as well. Finite element analysis was used to predict the deformations. Using the same methods, parameters and assumptions, predicted movements for the NATM were about ½ to 2/3 those of Cut-and-Cover. Figures 4.20 and 4.21 show the calculated horizontal displacement and vertical settlement for both methods.

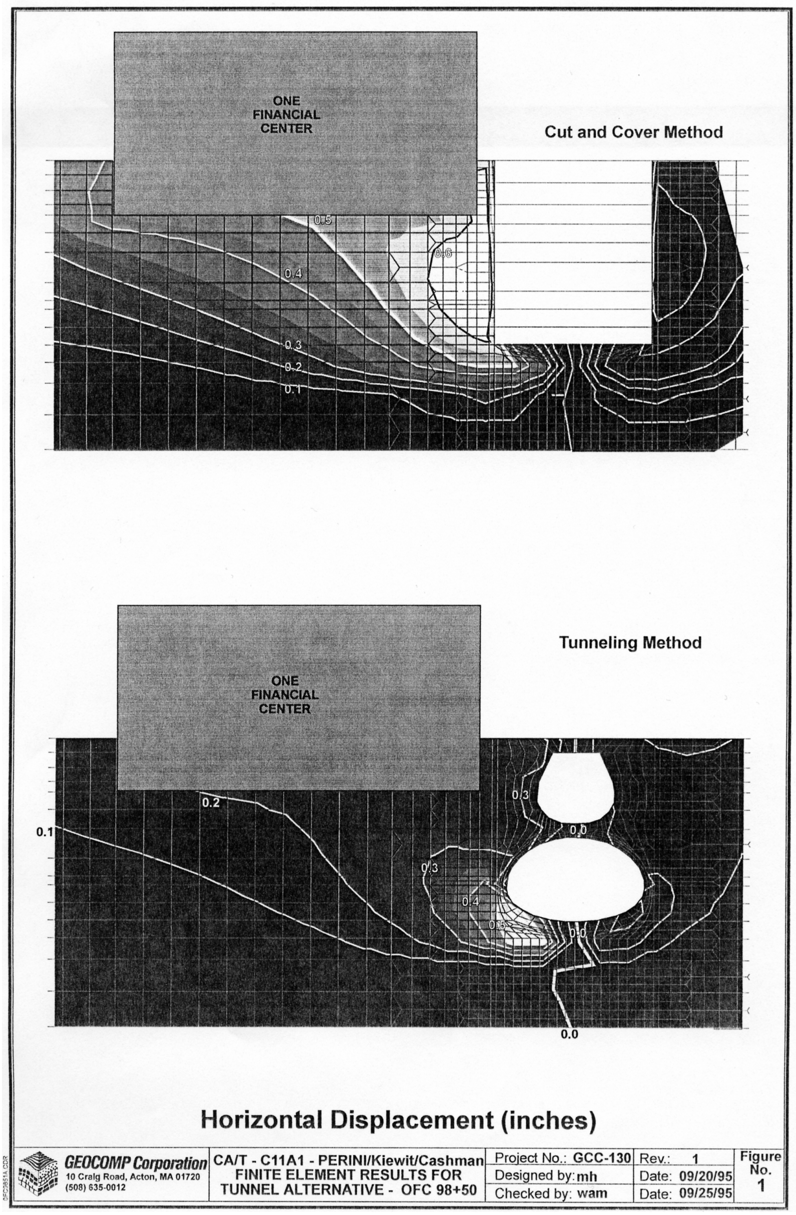


Figure 4.20: Calculated Horizontal Displacement, Boston Central Artery project (Source: Dr. G. Sauer Corporation)

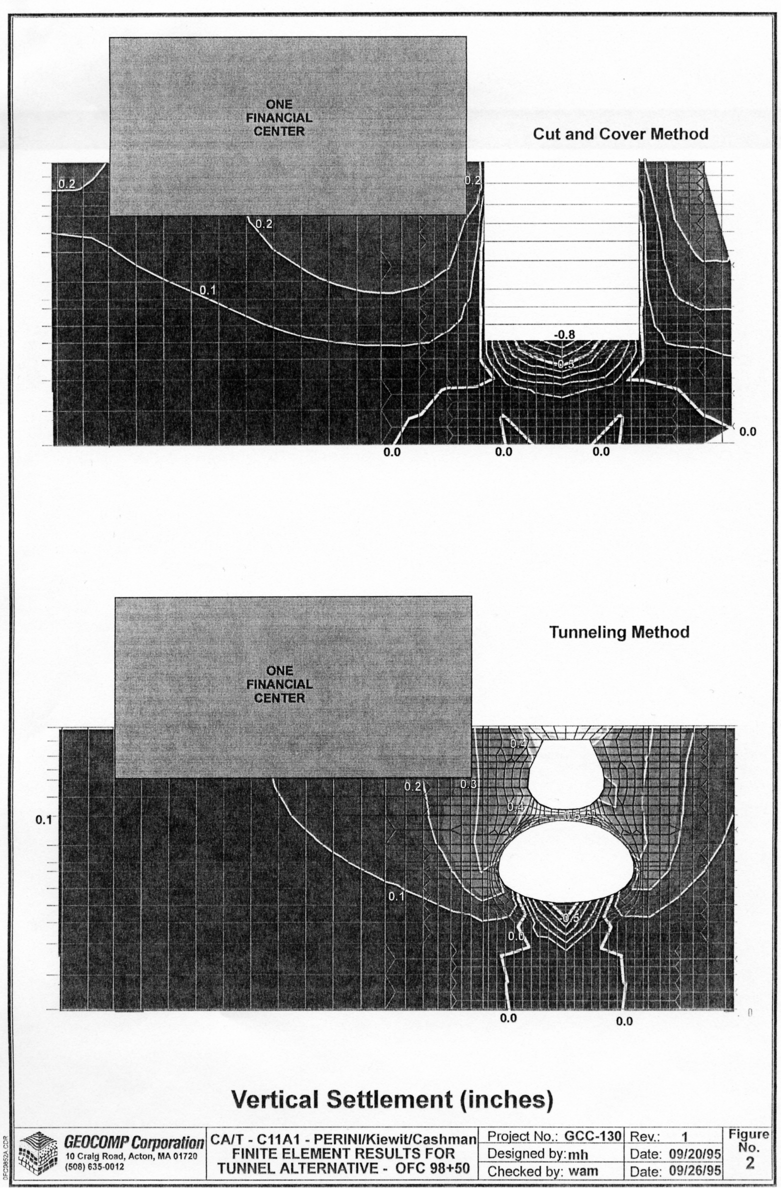


Figure 4.21: Calculated Vertical Settlement, Boston Central Artery project (Source: Dr. G. Sauer Corporation)

5. Development In Different Countries

5.1 Germany

[5, 8, 11, 12, 13]

Before 1970 tunneling underneath buildings sensitive to settlements could only be carried out with TBMs and pre-fabricated concrete elements or other complex construction methods. Later, mined tunneling using NATM was applied for the first time at the subway construction in Frankfurt. Subsequently NATM was developed step by step in an ingenious way and is now at a level, which outclasses the conventional methods in construction cost and allows structures, which could not be built with other tunneling methods before. NATM has proven to be very adjustable to different conditions. The development of NATM for complicated merging and adjoining tubes and for large structures in soft ground became not only possible but also state-of-the-art from then on. [13]

The progress made in the late 1970s allowed the construction companies to offer NATM design alternatives cheaper than conventional construction methods. The tendencies may be well described based on the examples of the subway construction in Munich and Bochum (both in Germany).

The general development of the bid price of traditional tunnel construction methods and NATM during its introduction and development for the subway construction in Munich is shown on Figure 1. The near equality of the bid prices by beginning of 1976 and the above mentioned advantages of the NATM induced the responsible authorities in Munich (U-Bahn-Referat München) to advertise for bids by NATM especially in urban areas. Relatively short contract sections (ca. 400 m to 750 m), usually with stations and often with changing sections pandered the NATM, so that this method was increasingly preferred.

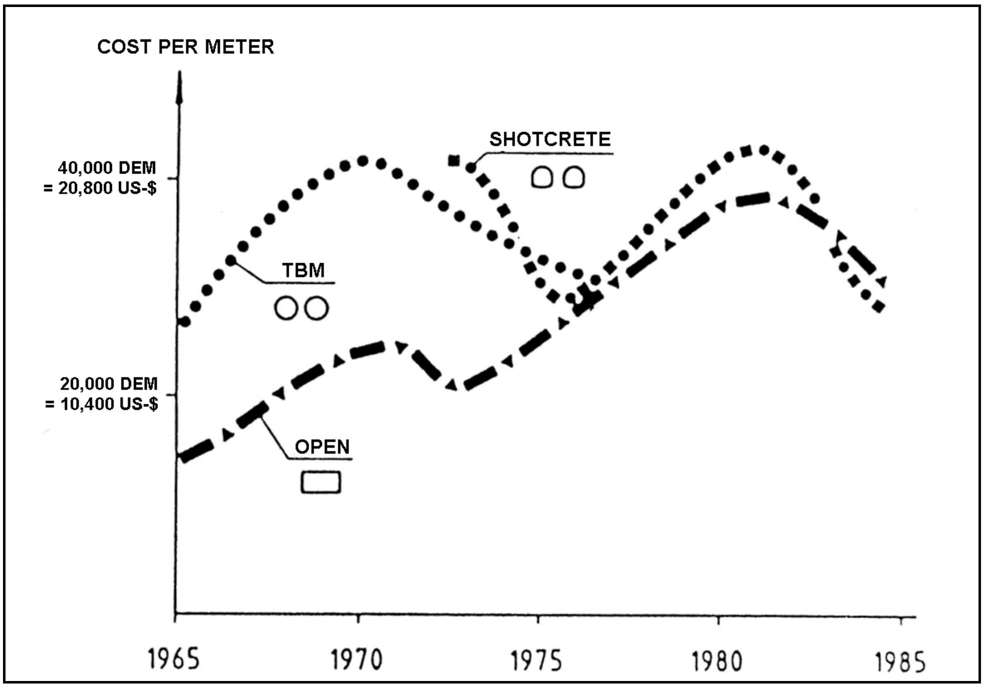


*Figure 5.1: Cost development of Cut-and-Cover, TBM and NATM running tunnels (bare cost) for the subway construction in Munich (Source: [12])**.

∗) 1 DEM (German Mark) = 0.520 US-$ (by 01/01/1987)

A similar development took place at the construction of the city railway in Bochum. A cost comparison study of main positions for cross sections with an average overburden of 5 m in Open-Cut respectively in NATM showed an explicit cost advantage for the NATM (see Chapter 4.3.2).

Its competitiveness, together with its other well-known advantages made the NATM the preferred construction method in Germany since the 1970th [8, 14].

5.2 Chile

[9, 10]

Construction of the Metro de Santiago started like most systems in the world with open cut stations and running tunnels. Today, construction is completely underground in NATM tunnels and caverns. One of the most remarkable aspects of the Metro de Santiago development is the speed by which construction methods have evolved. Construction started in the mid-1970s. Of the existing 40 km network more than 23 km is underground, mainly in Open-Cut works with some 6 km, elevated and another 5 km at grade. It was the mounting objection to Open-Cut disruption and the increasing cost of relocating services that persuaded Metro in the late 1980s that non-disruptive methods would be needed in future.

With that in mind, the last 2 km of the Phase 1 Line 5 construction was converted from Open-Cut to a mined tunnel alternative. Located under a public park, this was a suitable location to experiment with the mined alternative and with a length of 2 km, any risk to schedule would be limited.

The running tunnel experiment was carried out in 1993 with a 55 m^2 (6.5 m high x 9.6 m wide) single tube, double-track configuration in a very favorable geology. Design support comprised 300 mm of dry mix shotcrete reinforced to full load-bearing requirements using lattice girders and rebar rather than wire mesh, and finished with a 200 mm thick, strongly reinforced in-situ concrete final lining. The experiment was largely a success. It proved that, despite being about 20% more expensive per km than Cut-and-Cover in direct construction costs, mined tunnels were a safe, technically feasible, cost effective alternative when including cost savings in surface reinstatement, social costs and service diversions.

The one drawback was that attention to settlement control, across the park and under the shallow cover fixed by the original Cut-and-Cover design, was limited. No registered settlement readings were logged and settlement of up to 100 mm was estimated. For the next extension – a 2.8 km continuation of Line 5 from this first mined tunnel experiment, beneath a main city street and adjacent to the city's 300 year old Cathedral and other old, historic buildings – anything less than tight control on surface settlements would be unacceptable. Instrumentation expertise, ground movement monitoring, and the implementation of design criteria, construction methods and construction sequences, to limit settlement and prevent damage to adjacent structures, was required.

In early 1998 work started on the 2.8 km extension of single-tube, double-track running tunnels between three Open-Cut stations. Working in the very heart of the city, a robust design was adopted for the NATM tunnels to avoid any considerable surface settlements. The 35 m^2 full-face top headings of the running tunnels were excavated in 0.8 m – 1.4 m rounds with the bench and closed invert no more than seven rounds behind the top heading.

The scope for the advancement in tunneling technology from Cut-and-Cover to NATM was evident, but local engineers and contractors had, and still have, strong opinions about engineering theory and practice based on extensive experience of foundations and Open-Cut techniques with the ground conditions in the city. But acquiring the confidence to using a new construction technique for the first time in the heart of the capital has been achieved remarkably fast by the tunneling community in Santiago.

In early 2001, following successful completion of the Line 5 extension, plans were adopted to extend Lines 2 and 5 and to construct a 33 km long, 27-station Blue Line 4. The estimated US$ 2bn investment would almost double the network and bring services to another 1.8 million (or 40%) of Santiago's population.

For these new projects, Metro introduced several major advances. One of the most significant is the selection of mined underground stations. Although some of the adjacent Open-Cut access points are large, there are no more Open-Cut station boxes in the city streets. Two other major changes were made: There are no in-situ concrete final linings (single shell support) and the instrumentation has been optimized.

The cost of building the current Line 5 extension is approximately 60% of those building the previous Line 5 extension. Both are about the same in length, about 3 km, and both have three new stations. The differences are that the current extension is through better ground conditions than the first; it is through an area of mostly low rise residential buildings; and – the most significant change of all – the stations on the new extensions are all mined as opposed to expensive open boxes. [9, 10]

6. Example: Subway Station

6.1 General

In this notional example, a subway station was designed using the Cut-and-Cover construction method and in NATM. In detail, the following three alternatives have been investigated:

- Alternative 1: Open-Cut construction
- Alternative 2: Top-Down construction
- Alternative 3: Mined tunneling construction (NATM)

The station design is based on an existing project and is of typical size and depth. The geology was assumed to be favorable for all three alternatives, for example stable sandstone.

The running tunnels between the stations were assumed to be excavated using a TBM (Tunnel Boring Machine). All station alternatives are designed to allow the skid-through of the TBM during the construction. However, it was abstained from a detailed investigation of the construction sequence concerning the time of the skid-through.

The station consists of two levels: The concourse and the platform level. Passengers enter via one of three entrance tunnels and get to the concourse level, where the turnstiles, ticket vending machines, station control room etc. are located. From there they can take either an elevator or an escalator down to the platform level.

The entrance tunnels, constructed in Cut-and-Cover method are the same for all three alternatives and are therefore not included in the comparison.

All assumptions made in this example are general, in order to allow an easy comparison and interpretation. The scope of this example is to demonstrate the economic and environmental pros and cons of the different construction alternatives, rather than to make a comparison concerning the constructability. Even if the alternatives are designed to be basically feasible, for a "real" application a detailed investigation from the technical point of view would be necessary.

6.2 Description of the Alternatives

6.2.1 Alternative 1: Open-Cut Construction

The Open-Cut construction was designed using a slurry wall as pit enclosure and part of the tunnel wall. The pit box is 175 m long and 20 wide and has a depth of 19 m. Each floor provides a gross area (including all walls of the interior) of 3,500 m², consequently the entire station offers 7,000 m².

The slurry walls are one meter thick and enclosed by guide walls to lead the clamshell-type bucket of the excavator into the trench and to ensure surface stability.

The first step of the construction is the relocation of the utilities. After the site installation and the traffic diversion is completed, the slurry walls are installed. Then the excavation can be carried out in five steps, interrupted by the installation of the temporary strut layers one meter above ground each time. The steel struts provide additional stiffening and minimize settlements on the surface.

When the pit is excavated to the final level of –19 m, the base slab is poured. A layer of lean concrete is placed at the bottom, followed by the waterproofing membrane and a protective layer of concrete. The base slab has an average thickness of 1.50 m.

After removing the temporary strut layer IV and erecting the scaffolding and the formwork, the concourse slab can be installed with a thickness of 0.55 m and in the same manner eventually the roof slab with a thickness of 1 m. After the waterproofing membrane is placed on top and the protection and slope concrete are poured, the space between roof slab and street level can be backfilled, leaving only two 12.5 m long openings. The surface of the backfilled area can be reinstated and the traffic redirected. As soon as the interior is finished, the remaining openings can be closed, too.

In order to decrease the construction duration and to reduce the construction cost, the pit is subdivided into two parts, one with a length of 95 m; the other one with 80 m. Cross sections and a plan view of Variant 1 are shown in Figures 6.1, 6.3 and 6.4.

6.2.2 Alternative 2: Top-Down Construction

This method is commonly used, for example for the metro construction in Vienna (Austria). It has the same pit size as alternative 1 and the final constructions are similar. The difference is the sequence of construction, which allows an earlier backfill of the pit and therefore causes shorter interruption time.

For the Top-Down construction, excavation takes place identically to the Open-Cut construction to a depth of –7 m, which is the elevation of the bottom of the roof slab. A layer of plywood is placed at the bottom of the pit before the roof slab is poured. The plywood simplifies the subsequent excavation by separating the roof slab and the underlying ground.

Then the opening can be backfilled and the surface reinstated, leaving only two 12.5 m long openings. Through those openings, excavation continues horizontally underneath the roof slab, similar to mined tunneling excavation with shafts to the surface. The plywood of the bottom of the roof slab is removed and a smooth concrete surface is visible.

After excavating 5 m underneath the roof slab, the concrete slab is installed on grade, in the same way as the roof slab. Then the rest of the pit is excavated and a second temporary strut layer is installed to brace the pit walls. The base slab is poured in the same way as for alternative 1. As soon as the base slab has reached sufficient strength , the temporary strut layer II can be removed.

When the interior is finished, the two remaining openings can be backfilled. Cross sections and a plan view of Variant 2 are shown in Figures 6.2, 6.3 and 6.4.

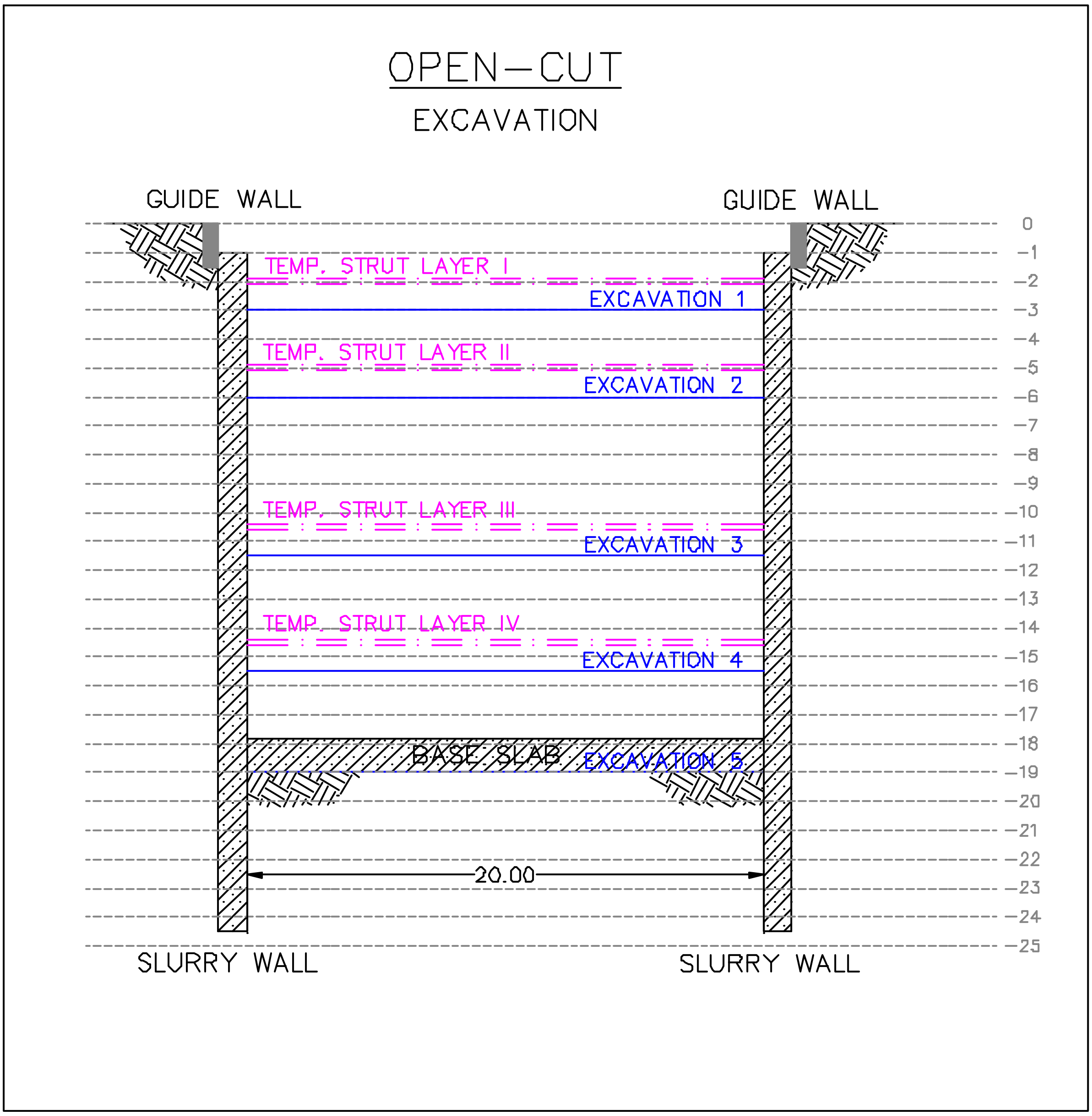


Figure 6.1: Excavation cross section Alternative 1 (Open-Cut construction)

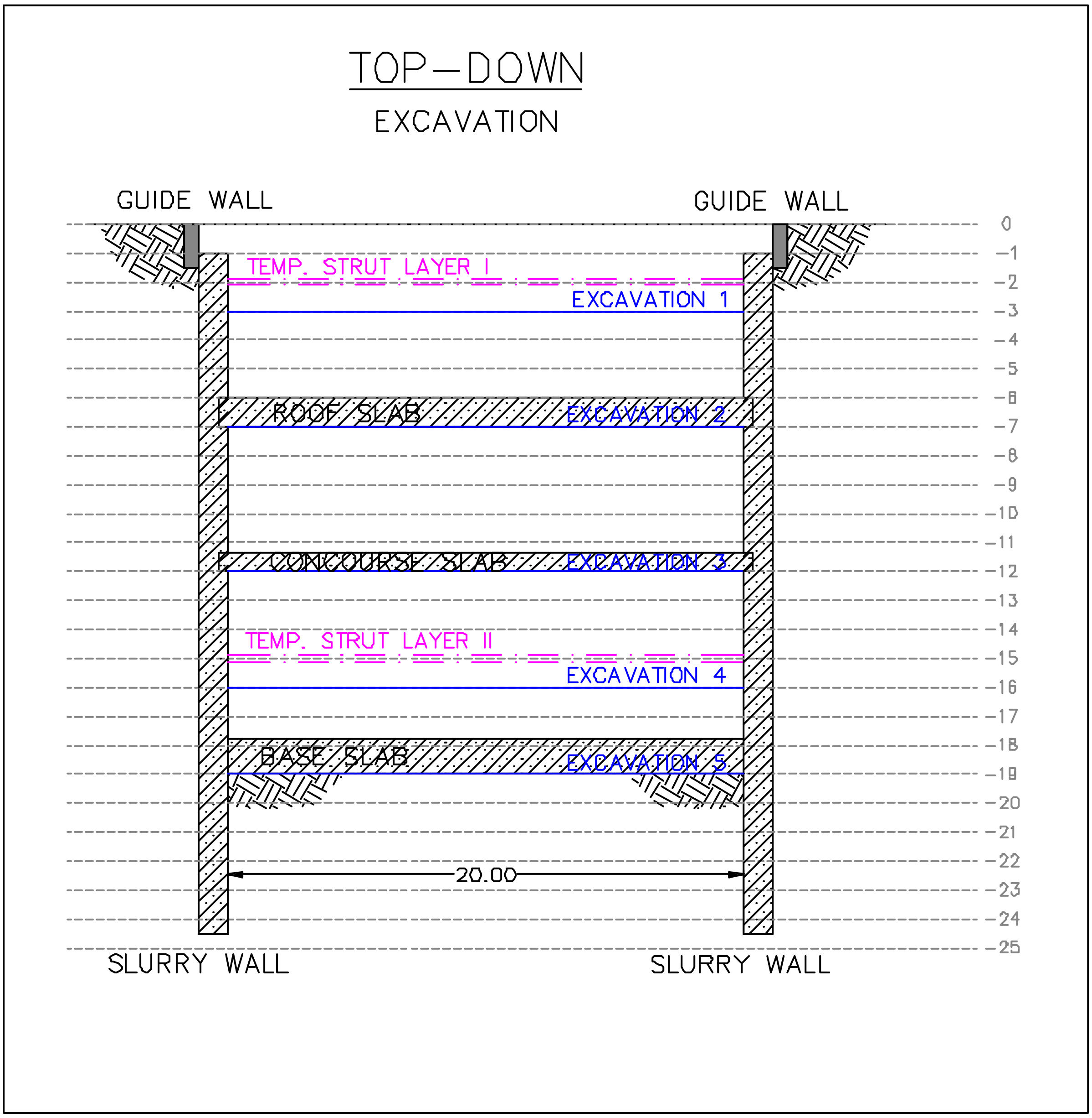


Figure 6.2: Excavation Cross Section Alternative 2 (Top-Down construction)

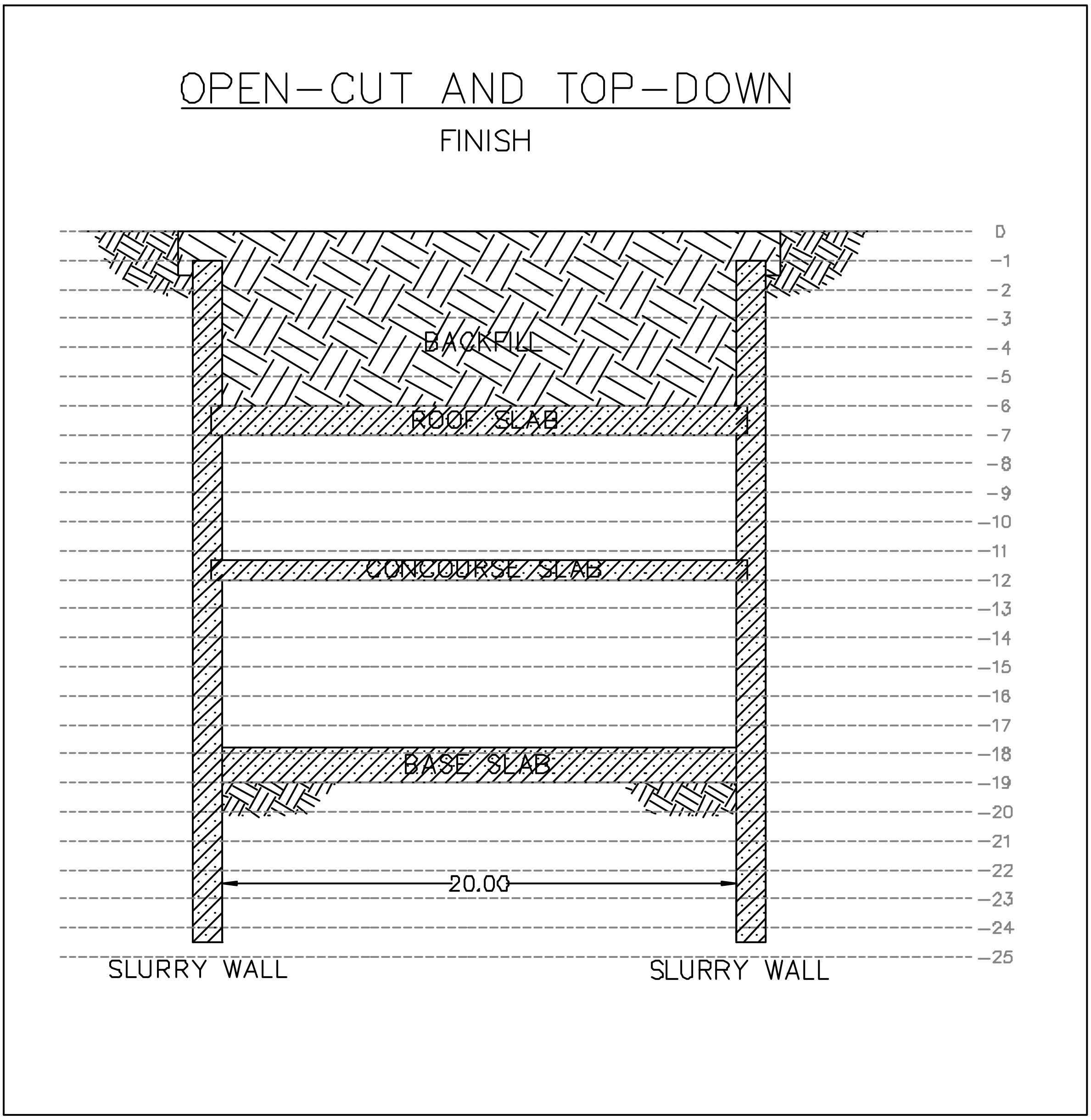


Figure 6.3: Finish Cross Section Alternative 1 and Alternative 2 (Open-Cut and Top-Down)

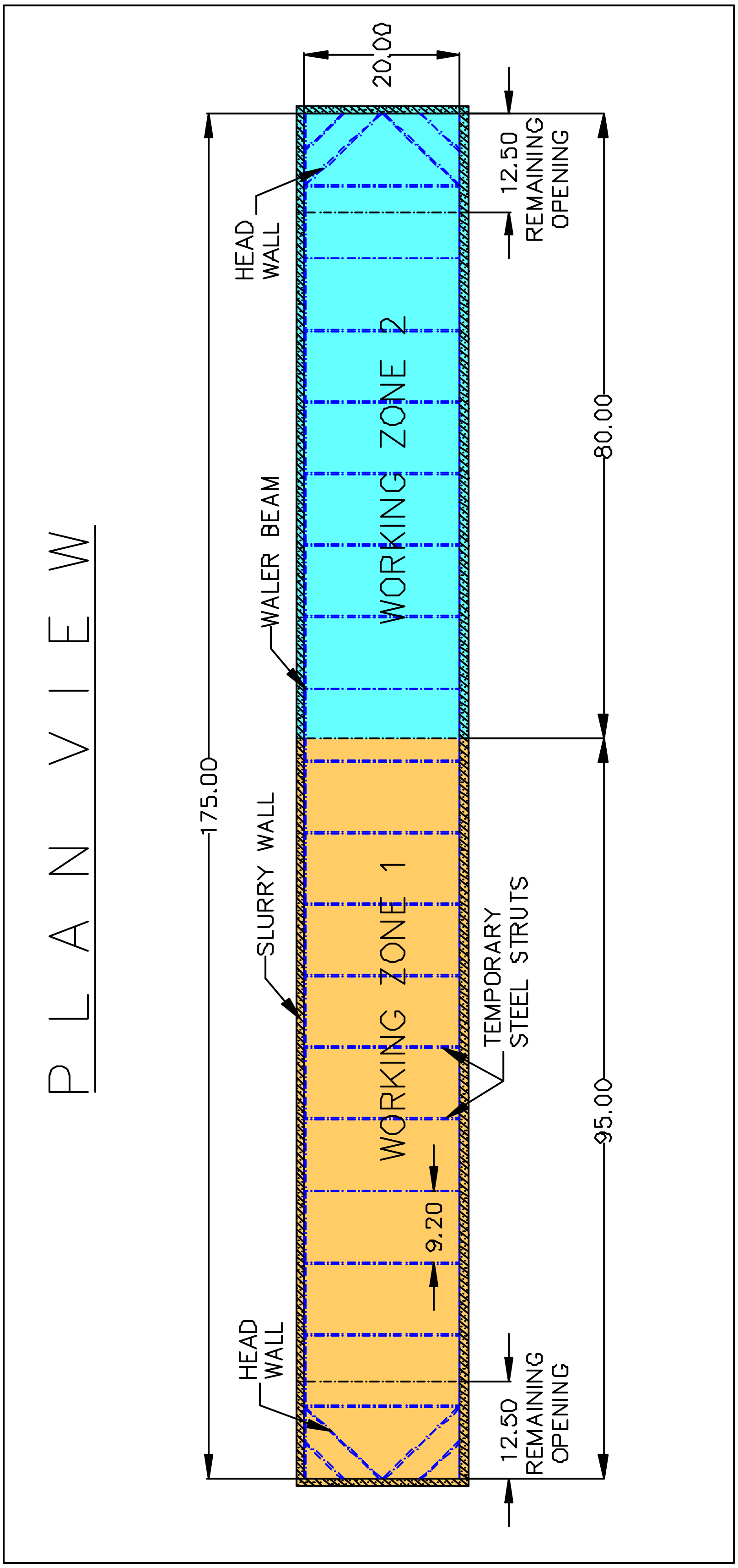


Figure 6.4: Plan View Alternative 1 and Alternative 2 (Open-Cut and Top-Down)

6.2.3 Alternative 3: Mined Tunneling Construction (NATM)

The mined station was designed in a way to serve the same purpose as the Cut-and-Cover alternative. The platform length is identical and the top of rail (TOR) is situated at the same level. The station consists of a concourse level and of a platform level. The concourse level provides a gross area (including all walls of the interior fit-out) of about 3,440 m² and the platform level has an area of about 3,650 m², which results in 7,090 m² - compared to a total area of 7,000 m² for alternative 1 and alternative 2.

Passengers can enter from three entrances and walk through the Cross Adit Tunnel to the Concourse Tunnel, from where they can go down to the platform level either by taking the elevator or an escalator. The concourse level also provides room for utilities (air-conditioning plant, tunnel ventilation equipment, transformers etc.)

The platform level consists of one wide tunnel, which is made up of three single tunnels (one Platform and two Station Tunnels). It provides a central platform with a train track on each side. In the Platform Tunnel two lateral supporting walls are installed for structural reasons, before the Station Tunnel is excavated. Wherever necessary, openings in the wall are foreseen to provide access from the platform to the train and vice versa.

The connection between the concourse level and the platform level is constructed via a breakthrough from the Concourse Tunnel to the Platform Tunnel, big enough that the escalators can be accommodated. The same applies to the elevator shaft.

The TBMs may be skid through the station as soon as the initial linings of the Station Tunnels exist or after the final linings of the Station Tunnels have been finished. It would be impossible to skid the TBM through in a straight way without damaging the support walls between the Platform Tunnel and the Station Tunnels. For that reason the machine has to be diverted to the outmost wall of the Station Tunnel. The redirection happens within the Connector Tunnel, which is the connection between the Running Tunnel and the Station Tunnel (see Figure 6.6).

Two access shafts establish the connection to the surface during the construction. From both shafts different crews can work independently without interfering each other. The shafts may serve as elevator location once the construction is finished and can also be used as additional utility rooms for ventilation.

The construction commences at the platform level. Starting from the shafts, the Cross Adit Tunnels are excavated and subsequently the Platform and Station Tunnel and also the Connector Tunnels. Once, the platform level tunnels are excavated from one shaft, a working platform is installed in the shaft at the same elevation as the concourse level. Beginning at the Cross Adits, the Concourse and Utility Tunnels are excavated. Simultaneously, the waterproofing and final lining take place at the platform level and later at the concourse level. The Cross Adits at the platform level are only used during construction and are therefore backfilled. The shafts are backfilled up to concourse level.

Plans and a cross section of the station design is shown on Figures 6.5, 6.6 and 6.7. Figures 6.8a and 6.8b show the different tunnel cross sections with the detailed excavation steps.

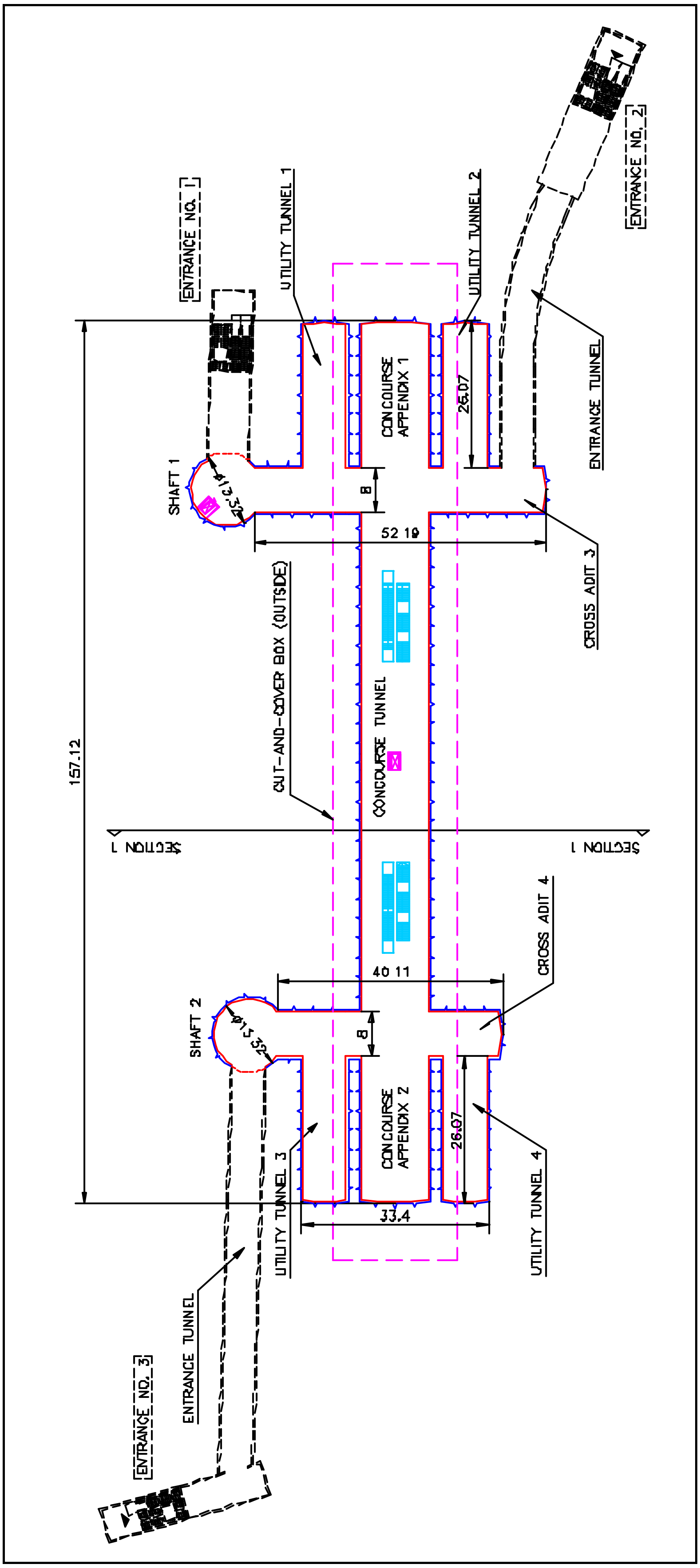


Figure 6.5: Plan View Alternative 3 (NATM), Concourse Level

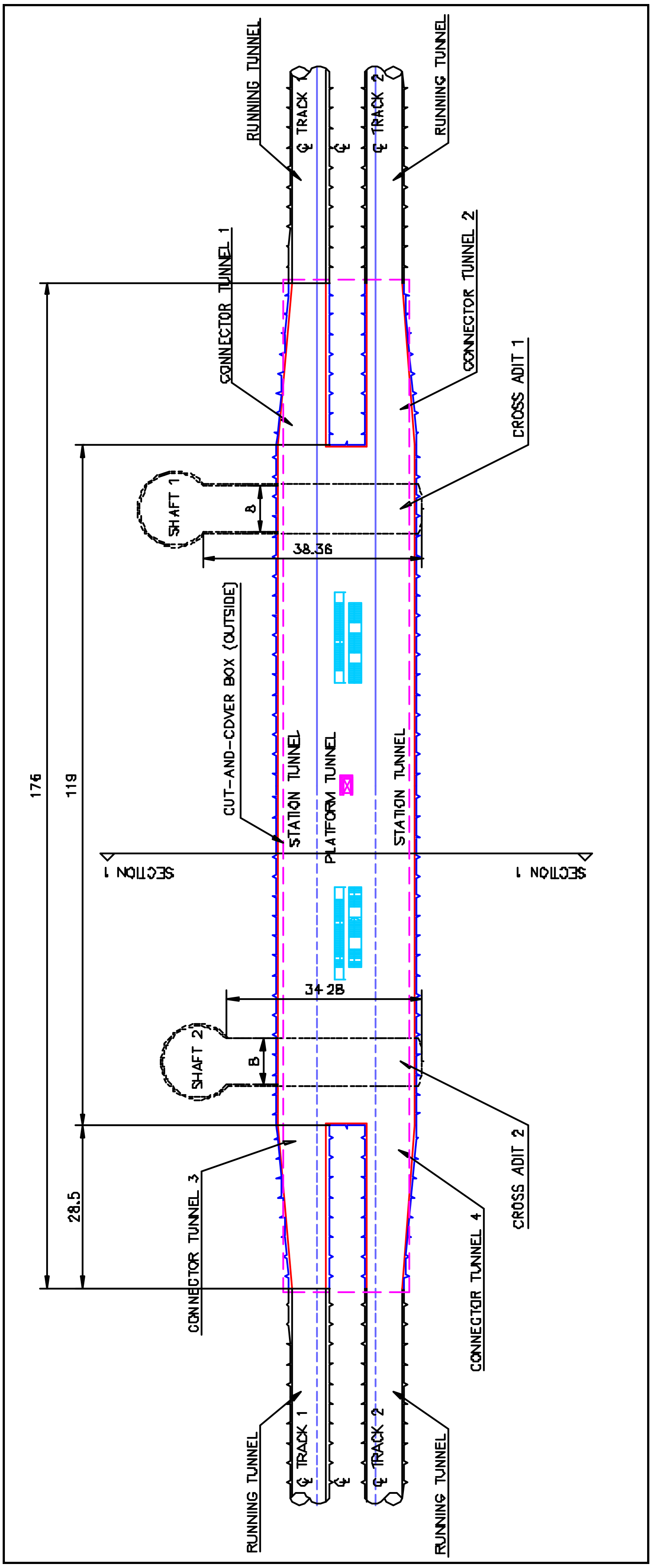


Figure 6.6: Plan View Alternative 3 (NATM), Platform Level

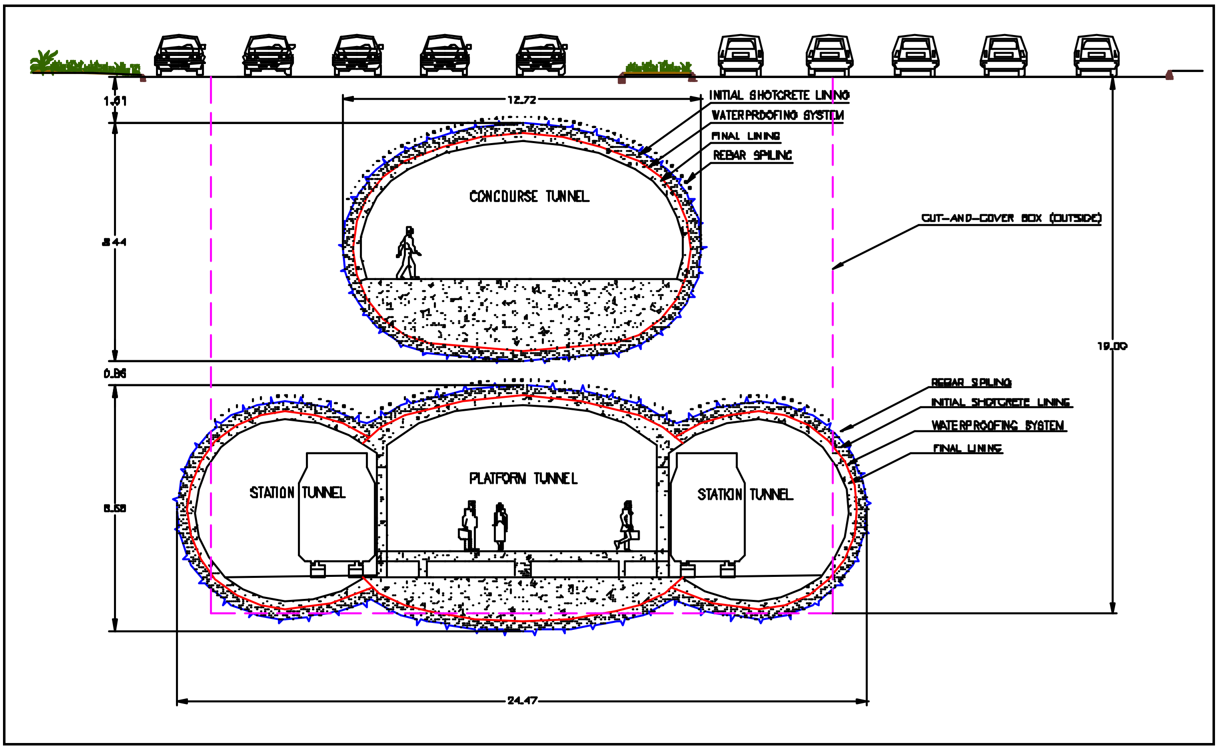


Figure 6.7: *Cross Section 1, Alternative 3 (NATM)*

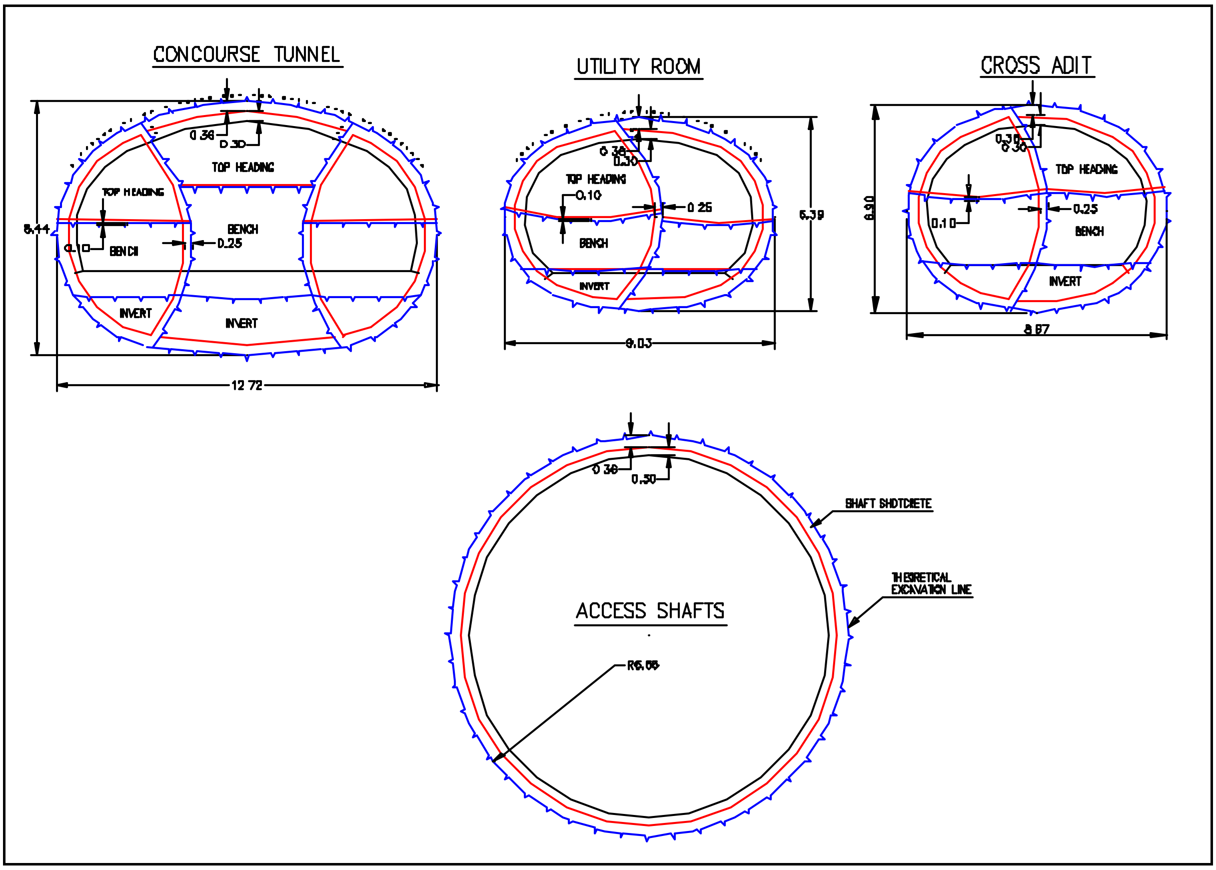


Figure 6.8a: *Tunnel Sections, Alternative 3 (NATM), Drawing 1 of 2*

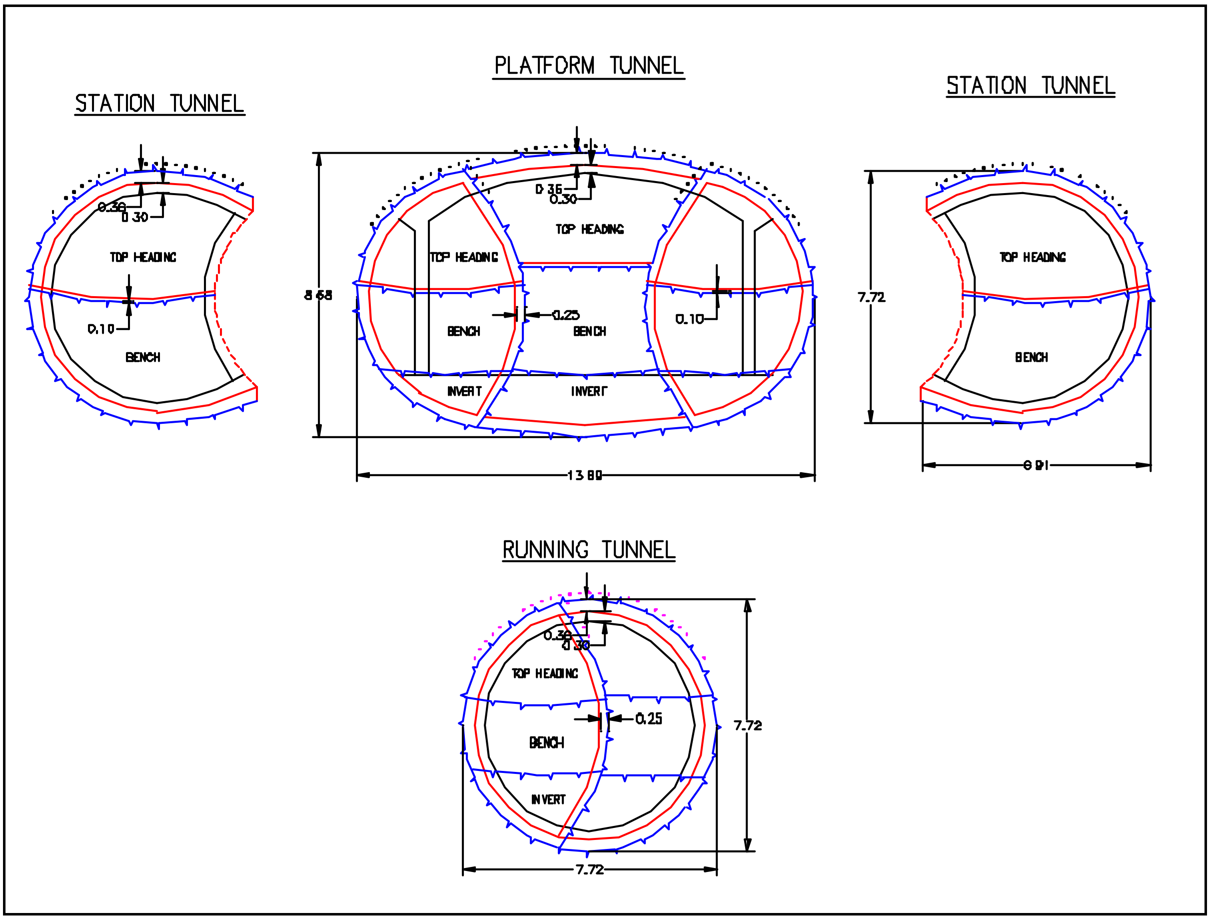


Figure 6.8b: Tunnel Sections, Alternative 3 (NATM), Drawing 2 of 2

6.3 Calculation of Quantities

The quantities of the main construction materials, like concrete, reinforcement, shotcrete, excavation material etc. have been calculated for all three alternatives. As the final construction of alternative 1 and 2 is identical, the quantities of the main items are similar, except the temporary steel struts.

6.3.1 Quantities for Alternative 1 and Alternative 2

The calculation of the quantities is shown in the Appendix, Table A.1.

6.3.2 Quantities for Alternative 3

	Excavation [m³]	Shotcrete [m³]	CIP Concr. [m³]	Backfill [m³]	Waterproofing [m²]	Lattice Girder [ton]	Wire Mesh [ton]	Rebar Spiles [ton]	Final Lin. Reinf. [ton]	Steel total [ton]
Concourse Tunnel	13,832	3,226	4,632	0	5,040	126	61	168	185	539
Utility Tunnels	4,891	1,300	1,001	0	2,357	42	27	11	40	120
Cross Adits	7,917	2,095	988	1,032	3,711	67	43	18	40	167
Access Shafts	5,572	584	464	2,786	1,584	0	13	0	19	32
Platform Tunnel	11,869	2,796	2,463	0	2,697	122	49	27	99	297
Station Tunnels	9,082	1,841	1,909	0	4,120	41	40	10	76	168
Connector Tunnel	5,882	1,485	1,083	0	2,690	49	30	10	43	132
Total	**59,045**	**13,327**	**12,539**	**3,818**	**22,198**	**447**	**262**	**245**	**502**	**1,455**

Table 6.9: Calculation of Quantities, Alternative 3 (NATM)

6.4 Construction Schedules

Construction schedules have been elaborated for all three alternatives. The assumptions and performance rates were chosen in accordance with experienced engineers who have been working on underground stations worldwide. However, production rates can differ considerably depending on location, labor, circumstances etc. Hence, the values used can only be considered as average numbers.

6.4.1 Construction Schedules for Alternative 1 and Alternative 2

The performance rates and the detailed calculation of durations are shown in Table A.2 and Table A.3 of the Appendix.

The construction of the slurry wall takes place successively in working zone one and two. Due to the expensive equipment necessary and the possibility of using the second zone longer as public area a simultaneous construction is less favorable.

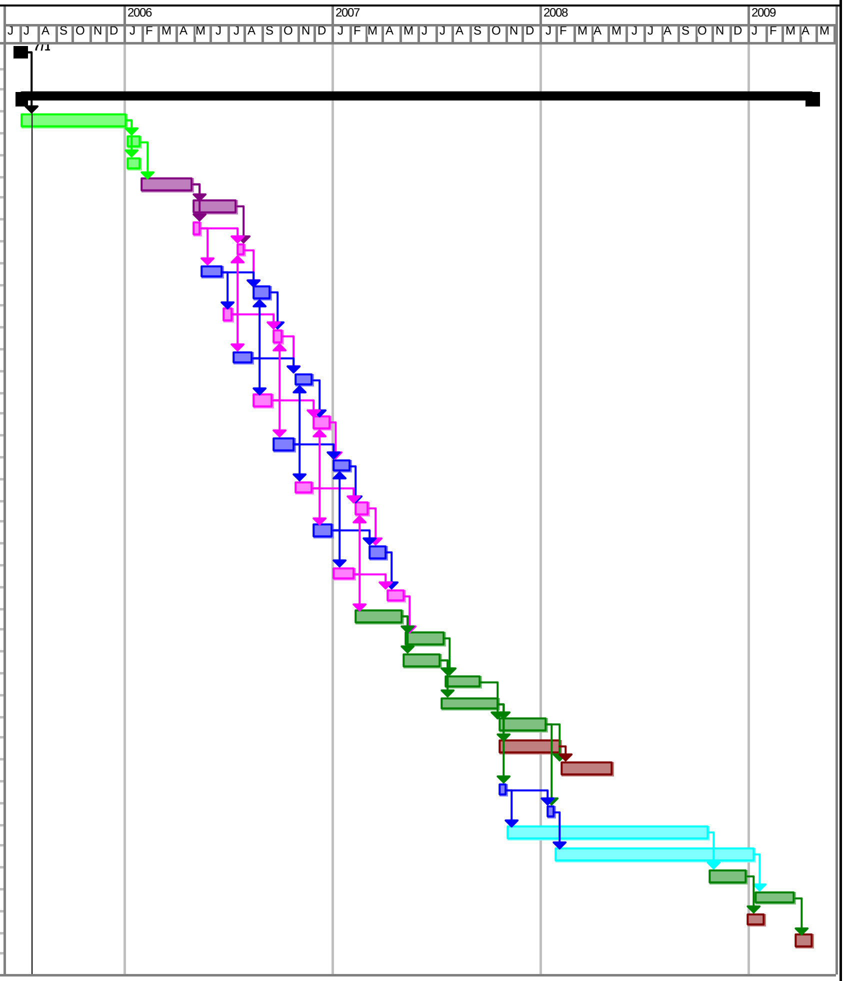
The excavation capacity is reduced with the increasing depth of the pit. Reasons for that are the more difficult working conditions and denser ground at depth. In the Top-Down method the excavation capacity underneath the roof slab is severely affected. The limited space requirements, longer transport distances, the difficult excavation under the slab and the necessity of cleaning the underside of the slab are responsible for the reduction of capacity.

Due to the more restricted space during the erection of the concourse and roof slabs for the Top-Down alternative, the advance rates are lower for the underground works.

The time for the utility relocation was estimated at 6 months. Mobilization and site installation takes 3 weeks, likewise traffic diversions. The time for the interior finish was estimated to take one year. During this period all columns, walls, screeds, wall panels, ventilations etc. are installed.

The working time is "normal", i.e. five days per week with ten hours daily. The detailed construction schedules of alternative 1 and alternative 2 are shown in Table 6.10 and Table 6.11.

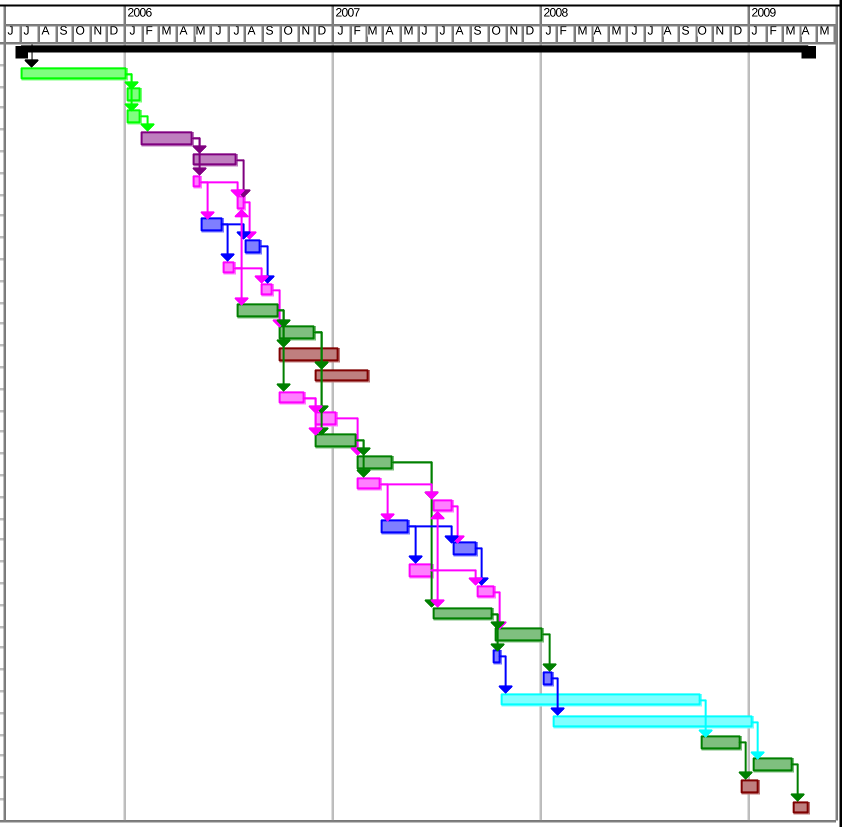
ID	Task Name	Duration
1	**SUBWAY STATION - EXAMPLE**	0 days
2		
3	**VARIANT 1: OPEN-CUT**	**995 days**
4	Utility Diversions	131 days
5	Mobilization & Site Installation	21 days
6	Traffic Diversions	21 days
7	Slurry Wall, Zone 1	64 days
8	Slurry Wall, Zone 2	55 days
9	Excavation I, Zone 1	11 days
10	Excavation I, Zone 2	10 days
11	Temporary Strut Layer, Zone 1	26 days
12	Temporary Strut Layer I, Zone 2	22 days
13	Excavation II, Zone 1	13 days
14	Excavation II, Zone 2	11 days
15	Temporary Strut Layer II, Zone 1	26 days
16	Temporary Strut Layer II, Zone 2	22 days
17	Excavation III, Zone 1	26 days
18	Excavation III, Zone 2	22 days
19	Temporary Strut Layer III, Zone 1	26 days
20	Temporary Strut Layer III, Zone 2	22 days
21	Excavation IV, Zone 1	22 days
22	Excavation IV, Zone 2	18 days
23	Temporary Strut Layer IV, Zone 1	26 days
24	Temporary Strut Layer IV, Zone 2	22 days
25	Excavation V, Zone 1	27 days
26	Excavation V, Zone 2	22 days
27	Base Slab, Zone 1	59 days
28	Base Slab, Zone 2	50 days
29	Concourse Slab, Zone 1	51 days
30	Concourse Slab, Zone 2	45 days
31	Roof Slab, Zone 1	70 days
32	Roof Slab, Zone 2	61 days
33	Waterproofing,Backfill & Reinstatement, Zone 1	78 days
34	Waterproofing,Backfill & Reinstatement, Zone 2	68 days
35	Waterproofing & Inner Lining, Zone 1	11 days
36	Waterproofing & Inner Lining, Zone 2	10 days
37	Interior Finishing Works, Zone 1	252 days
38	Interior Finishing Works, Zone 2	252 days
39	Slabs Remaining Opening, Zone 1	50 days
40	Slabs Remaining Opening, Zone 2	50 days
41	Waterpr., Backf. & Reinstat. Remaining, Zone 1	23 days
42	Waterpr., Backf. & Reinstat. Remaining, Zone 2	23 days
43		



Task | Milestone | External Tasks
Split | Summary | External Milestone
Progress | Project Summary | Deadline

Table 6.10: Construction Schedule, Variant 1 (Open-Cut)

ID		Task Name	Duration
44		**VARIANT 2: TOP-DOWN**	**990 days**
45		Utility Diversions	131 days
46		Mobilization & Site Installation	21 days
47		Traffic Diversions	21 days
48		Slurry Wall, Zone 1	64 days
49		Slurry Wall, Zone 2	55 days
50		Excavation I, Zone 1	11 days
51		Excavation I, Zone 2	10 days
52		Temporary Strut Layer I, Zone 1	26 days
53		Temporary Strut Layer I, Zone 2	22 days
54		Excavation II, Zone 1	17 days
55		Excavation II, Zone 2	14 days
56		Roof Slab, Zone 1	54 days
57		Roof Slab, Zone 2	46 days
58		Waterproofing,Backfill & Reinstatement, Zone 1	76 days
59		Waterproofing,Backfill & Reinstatement, Zone 2	66 days
60		Excavation III, Zone 1	32 days
61		Excavation III, Zone 2	27 days
62		Concourse Slab, Zone 1	53 days
63		Concourse Slab, Zone 2	46 days
64		Excavation IV, Zone 1	30 days
65		Excavation IV, Zone 2	26 days
66		Temporary Strut Layer II, Zone 1	34 days
67		Temporary Strut Layer II, Zone 2	29 days
68		Excavation V, Zone 1	29 days
69		Excavation V, Zone 2	24 days
70		Base Slab, Zone 1	75 days
71		Base Slab, Zone 2	61 days
72		Waterproofing & Inner Lining, Zone 1	11 days
73		Waterproofing & Inner Lining, Zone 2	10 days
74		Interior Finishing Works, Zone 1	252 days
75		Interior Finishing Works, Zone 2	252 days
76		Slabs Remaining Opening, Zone 1	50 days
77		Slabs Remaining Opening, Zone 2	50 days
78		Waterpr., Backf. & Reinstat. Remaining, Zone 1	22 days
79		Waterproofing,Backfill & Reinstatement, Zone 2	22 days



Task	Milestone	External Tasks	
Split	Summary	External Milestone	
Progress	Project Summary	Deadline	

Table 6.11: Construction Schedule, Variant 2 (Top-Down)

6.4.2 Construction Schedule for Alternative 3

Two shafts are available from where excavation advances simultaneously. The excavation advance rate was estimated for each tunnel, depending on its size and the performance of excavation. The rates refer to the excavation of the whole tunnel and do not differentiate the advance rates of the different drifts (top heading, bench, invert, side-wall drift, etc.).

The assumed advance rates and lengths of round of the different tunnels are:

Tunnel	Length Total	Excavation Area	Advance Rate	Length of Round
Concourse Tunnel	157 m	88.1 m²	1.2 m/day	1.2 m
Utility Tunnels	104 m	46.9 m²	1.5 m/day	1.5 m
Cross Adits	165 m	48.0 m²	1.5 m/day	1.5 m
Platform Tunnel	119 m	99.7 m²	1.0 m/day	1.0 m
Station Tunnels	238 m	38.2 m²	2.0 m/day	2.0 m
Connector Tunnels	114 m	51.6 m²	1.5 m/day	1.5 m
Shafts	40 m	139 m²	0.5 m/day	

The waterproofing and final lining is installed in blocks of 10 m length. The advance rate was estimated to be about three blocks in two weeks, or in other words 4 working days per 10 m. The final lining of the Platform Tunnel takes longer, as the supporting wall has to be installed, so an advance rate of 1.65 m per working day was assumed.

The erection time for the working platform in the shafts was estimated at 18 working days. For the concrete works 3 month were taken into account and for waterproofing, backfilling and reinstatement of the shafts 23 working days.

Due to the fact, that the shafts are located in convenient locations, the required time for utility relocation is estimated to be one month only. The duration of mobilization and site installation is two months and traffic diversion takes one month. Similar to variants 1 and 2 the duration for the interior finish was assumed to be one year.

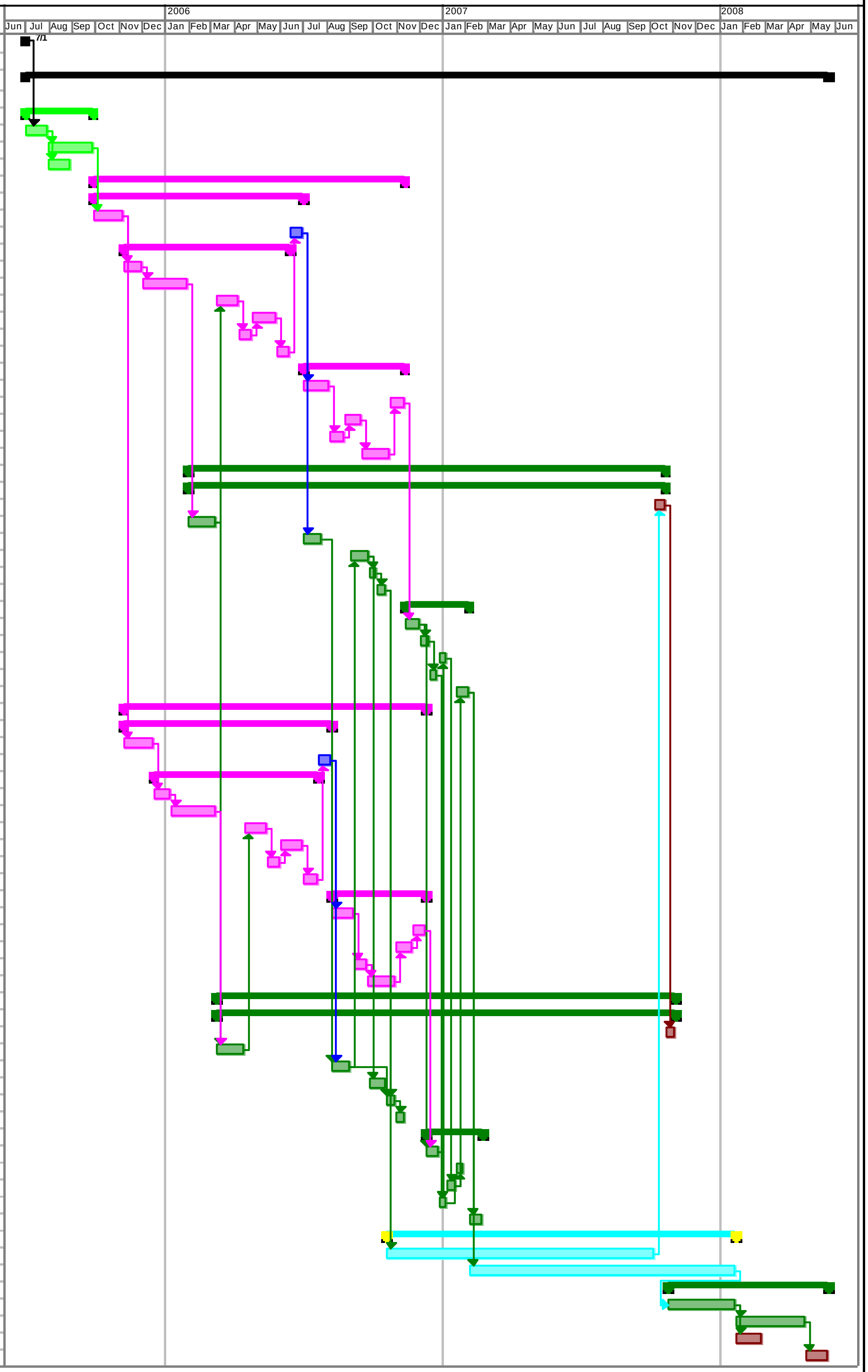
For excavation & support and waterproofing & final lining a nonstop working schedule was assumed. This leads to a faster, cheaper and safer excavation, because the tunnel face does not have to be sealed and subsequently broken up again, if there are no substantial working interruptions. All other works, like utility relocation, site installation, backfilling and the interior finishing take place under "normal" working schedule, i.e. 5-day week, 10-hour days.

The construction schedule of alternative 3 is shown in Table 6.12.

Example: Subway Station

Master's Thesis
Eva Greifeneder
October 2003

ID	Task Name	Duration
1	**SUBWAY STATION - EXAMPLE**	0 days
2		
3	**VARIANT 3 - NATM**	756 days
4		
5	**Utility & Traffic Diversions, Mobilization**	63 days
6	Utility Diversion for Shafts	21 days
7	Mobilization & Site Installation	42 days
8	Traffic Diversions	21 days
9	**Excavation & Support Shaft 1**	411 days
10	**Shaft 1**	278 days
11	Shaft 1 - Platform Level	40 days
12	Shaft 1 - Working Platform	18 days
13	**Platform Level - Shaft 1**	220 days
14	Cross Adit 1	26 days
15	Platform (1)	60 days
16	Station 1 (1)	30 days
17	Station 2 (1)	30 days
18	Connector 1	19 days
19	Connector 2	19 days
20	**Concourse Level - Shaft 1**	133 days
21	Cross Adit 3	35 days
22	Utility Tunnel 1	19 days
23	Concourse Appendix 1	22 days
24	Utility Tunnel 2	19 days
25	Concourse (1)	38 days
26	**Waterproofing & Final Lining Shaft 1**	628 days
27	**Platform Level**	628 days
28	Cross Adit 1 (backfilling)	13 days
29	Platform (1)	36 days
30	Station 1 (1)	24 days
31	Station 1 (2)	24 days
32	Connector 1	12 days
33	Connector 2	12 days
34	**Concourse Level**	85 days
35	Cross Adit 3	21 days
36	Utility Tunnel 1	11 days
37	Concourse Appendix 1	11 days
38	Utility Tunnel 2	11 days
39	Concourse (1)	18 days
40	**Excavation & Support Shaft 2**	399 days
41	**Shaft 2**	275 days
42	Shaft 2 - Platform Level	40 days
43	Shaft 2 - Working Platform	18 days
44	**Platform Level - Shaft 2**	217 days
45	Cross Adit 2	23 days
46	Platform (2)	60 days
47	Station 1 (2)	30 days
48	Station 2 (2)	30 days
49	Connector 3	19 days
50	Connector 4	19 days
51	**Concourse Level - Shaft 2**	124 days
52	Cross Adit 4	28 days
53	Utility Tunnel 3	18 days
54	Concourse Appendix 2	22 days
55	Utility Tunnel 4	18 days
56	Concourse (2)	38 days
57	**Waterproofing & Final Lining Shaft 2**	605 days
58	**Platform Level**	605 days
59	Cross Adit 2 (backfilling)	14 days
60	Platform (2)	36 days
61	Station 1 (2)	24 days
62	Station 2 (2)	24 days
63	Connector 3	12 days
64	Connector 4	12 days
65	**Concourse Level**	75 days
66	Cross Adit 4	17 days
67	Utility Tunnel 3	11 days
68	Concourse Appendix 2	11 days
69	Utility Tunnel 4	11 days
70	Concourse (2)	18 days
71	**Interior Finishing Works**	329 days
72	Interior Finishing Works Platform Level	252 days
73	Interior Finishing Works Concourse Level	252 days
74	**Concrete Works Shafts & Reinstatement**	151 days
75	Concrete Works Shaft 1	64 days
76	Concrete Works Shaft 2	64 days
77	Waterproofing,Backfill&Reinstatement Shaft 1	23 days
78	Waterproofing,Backfill&Reinstatement Shaft 2	23 days



Task	Progress	Summary	External Tasks	Deadline
Split	Milestone	Project Summary	External Milestone	

Table 6.12: Construction Schedule, Variant 3 (NATM)

6.5 Cost Estimates

The cost estimates are restricted locally to the station only (without entrances) and objectively to the bare construction without interior fit-out. Cost for mobilization, site installation and traffic diversion and overhead cost were not included.

These cost estimates are created for comparison purposes only and does not provide an exact prediction of the construction cost of similar projects.

Costs for material, labor and equipment can differ widely, depending on location, season, market situation, executing company etc. An attempt was made to use common and average cost, typical for Austria. Of course fluctuations exist, but due to the fact, that for all three alternatives the same values are used, the results of the comparison will not be significantly influenced by the base cost.

The costs are derived from different sources, namely the Dr. G. Sauer Corporation in Herndon, Virginia, USA (in the following called "DSC"), the Austrian specification of construction machinery "Österreichische Baugeräteliste" (ÖBGL) [20] and the script "Ausgewählte Bauverfahren" (selected construction methods) of the Institute of Construction Management and Economics at the Vienna University of Technology [21]. The numbers in parenthesis in Table A.6 (Appendix) refer to the item number of the ÖBGL respectively the page number of the script.

Where a conversion of EURO into US-$ was necessary, a conversion factor of 1 EURO = 1.168 US-$ was used. The equipment costs, which were derived from the ÖBGL, were calculated in the following manner:

Monthly cost for write-off and interest acc. to ÖBGL x 0.5
\+ Monthly cost for repair work acc. to ÖBGL x 0.6
\+ Monthly cost for diesel (kWh x 0,3 l/kWh x 1.0 $/l x 172 h/month x 1.1 lubricant factor)
or: + <u>Monthly cost for electr. power (kWh x 0.2 $/kWh x 172 h/month x 1.1 lubricant factor)</u>
Monthly equipment cost

Tables A.4, A.5 and A.6 of the Appendix summarize the unit cost for material, labor and equipment for all three variants.

6.5.1 Cost Estimate for Alternative 1

For the cost estimate the material cost was calculated by multiplying the required amount with the cost per unit. Then the construction sequence was subdivided into different steps, like excavation, strutting and decking, concrete works or backfilling. The durations of these working steps are taken from the construction schedule. The working days for every step were added.

Time-dependent cost like labor and equipment cost were calculated by multiplying the durations of each working step with the cost per day of the corresponding labor unit respectively equipment unit. An investigation into how many working crews are actually hired and the distribution of the existing work to the various crews did not take place. However, that does not affect the total cost, as long as every working day is considered in the calculation.

The cost for utility diversion and road rebuilding could only be estimated, as it depends a lot on the location. The detailed cost estimate is shown on Table A.7 in the Appendix. Table 6.13 (below) gives a summary of the cost.

COST ESTIMATE SUMMARY - OPEN-CUT STATION (ALTERNATIVE 1)

Material		$	10,705,553
Labor		$	10,417,200
Equipment		$	2,850,198
Subtotal		$	23,972,951
Utility Diversion		$	3,000,000
Surface reinstatement and Traffic Diversion		$	500,000
Net Construction Cost		$	27,472,951
Monitoring	2%	$	549,459
Dewatering	2%	$	549,459
Project Management		$	1,000,000
Contingencies, e.g. obstacles, bad weather	10%	$	2,747,295
Total Construction Cost, ALT. 1		**$**	**32,319,164**

Table 6.13: Summary of Cost Estimate, Alternative 1 (Open-Cut)

6.5.2 Cost Estimate for Alternative 2

The cost estimate for alternative 2 is shown on Table A.8 of the Appendix. A short summary gives Table 6.14.

COST ESTIMATE SUMMARY - TOP-DOWN STATION (ALTERNATIVE 2)

Material		$ 10,223,313
Labor		$ 10,882,400
Equipment		$ 2,876,880
Subtotal		$ 23,982,593
Utility Diversion		$ 3,000,000
Surface reinstatement and Traffic Diversion		$ 500,000
Net Construction Cost		$ 27,482,593
Monitoring	2%	$ 549,652
Dewatering	2%	$ 549,652
Project Management		$ 1,000,000
Contingencies, e.g. obstacles, bad weather	10%	$ 2,748,259
Total Construction Cost, ALT. 2		**$ 32,330,156**

Table 6.14: Summary of Cost Estimate, Alternative 2 (Top-Down)

6.5.3 Cost Estimate for Alternative 3

For the NATM cost estimate, in a first step the material cost for each tunnel was calculated on a separate table. The tables are shown in the Appendix, A.9.

Subsequently, for each construction step a working crew was considered. Consequently, the daily labor cost for excavation, concrete works, backfill etc. could be calculated as shown on Table A.10 of the Appendix.

In the same way, the daily equipment cost was calculated, as shown in Table A.11 of the Appendix. Only the major equipment was considered, less important and inexpensive machinery is part of the contingencies.

In a summary sheet (Appendix, Table A.12) the total material cost is calculated by multiplying the length of each tunnel with the cost per meter and adding the results. Thereafter, the durations of each construction step were added, using the construction schedule (Table 6.12). The total cost for labor and equipment could be calculated by multiplying the duration of each step with the cost per day. The equipment also contains parts which are written-off to a certain percentage, which is shown directly on the summary table.

10% contingencies are added to the sum of material, labor and equipment cost. They include the items, which have not been calculated in detail, like the break-through from the concourse to the platform level, but also difficulties due to ground conditions worse than expected.

Table 6.15 shows a summary of the NATM cost estimate.

COST ESTIMATE SUMMARY - NATM STATION (ALTERNATIVE 3)

Material		$ 9,966,244
Labor		$ 11,621,280
Equipment		$ 2,369,819
Net Construction Cost		$ 23,957,344
Monitoring	2%	$ 479,147
Dewatering	2%	$ 479,147
Project Management		$ 1,000,000
Contingencies, e.g. worse ground conditions	10%	$ 2,395,734
Total Construction Cost, ALT. 3		**$ 28,311,372**

Table 6.15: Summary of Cost Estimate, Alternative 3 (NATM)

6.6 Results

6.6.1 Comparison of Quantities

When comparing the quantities, no differentiation needs to be made between Open-Cut and Top-Down method, because the numbers are equal, except the amount of temporary steel struts. However, quantities of the NATM alternative differ considerably to the Cut-and-Cover methods.

Table 6.16 summarizes the quantities of the NATM station (Alternative 3) and the Cut-and-Cover stations (Alternative 1 and Alternative 2).

	UNIT	OPEN-CUT AND TOP-DOWN	%	NATM	%
Excavation Material	m³	76,060	100%	59,050	78%
Backfill	m³	21,000	100%	3,820	18%
CIP Concrete	m³	21,780	100%	12,540	58%
Shotcrete	m³	0	0%	13,330	100%
Reinforcement	ton	3,570	100%	1,460	41%
Waterproofing	m²	11,600	100%	22,200	191%
Temporary Steel Struts	ton	1,100 / 550	100%	0	0%

Table 6.16: Comparison of Quantities

Figure 6.17 illustrates the differences graphically.

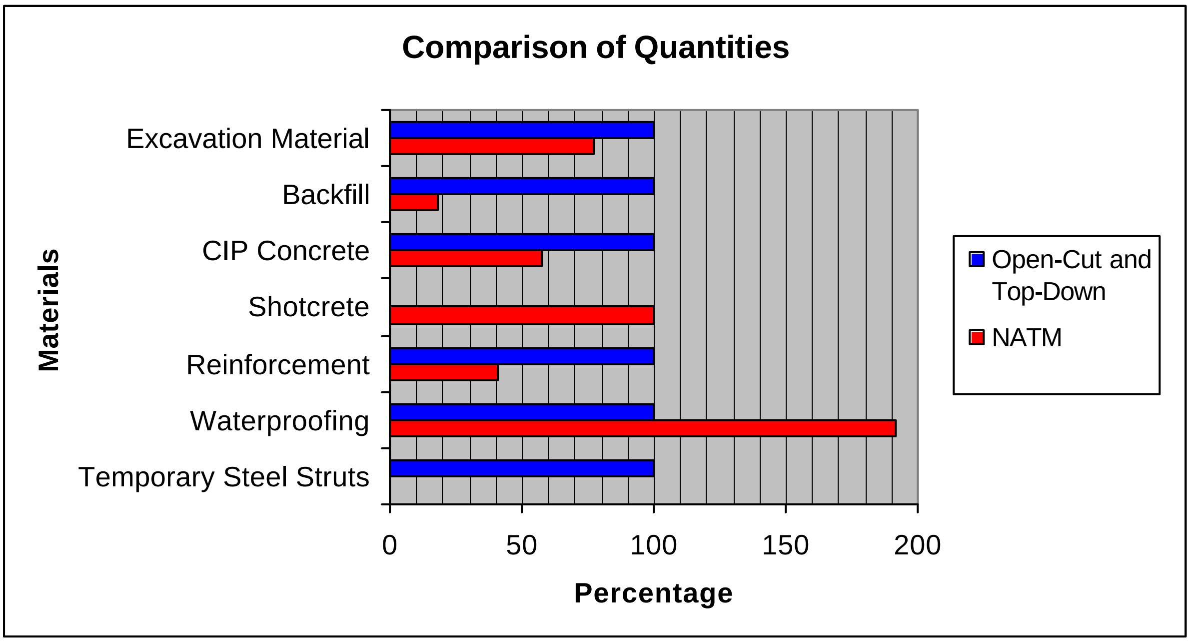


Figure 6.17: Comparison of Quantities

For the NATM station, only minor quantities (18% compared to Cut-and-Cover) have to be backfilled. Consequently, more volume has to be excavated for the Cut-and-Cover alternatives to provide the same station area as the NATM station.

The reinforcement consumption of the NATM construction is considerably less, compared to the Cut-and-Cover alternatives. Reasons for that are the structurally optimized shapes of the NATM tunnels, which do not require excessive reinforcement. In order to withstand buoyancy and to allow the wide span, the concrete slabs of the Cut-and-Cover methods need a certain minimum thickness and reinforcement. NATM tunnels have a primary lining of shotcrete. Therefore they do not require a high amount of CIP concrete for the inner lining. However, the sum of shotcrete and CIP concrete of the NATM station is 119% of the amount of CIP concrete of the Cut-and-Cover constructions.

The required area of waterproofing membrane is almost double as much for the NATM station. Decisive for that is the much higher inner surface area of the NATM tunnels compared to the surface area of the Cut-and-Cover station. However, this does not affect the cost significantly, because the waterproofing membrane is a low cost item.

Temporary steel struts are only required for the Cut-and-Cover construction. For the Open-Cut alternative twice as many struts are needed as for the Top-Down method, because the previously installed concrete slabs provide additional bracing.

6.6.2 Schedule Comparison

The construction durations of the Open-Cut and the Top-Down method differ only slightly. The NATM station can be constructed faster and is finished 11 months before the Cut-and-Cover alternatives. This is due to the fact that a nonstop working schedule is used for excavation and support, waterproofing, and final lining. Also the required time for utility diversion is much shorter for NATM, and backfilling can be done faster and the interior finishing work can start sooner.

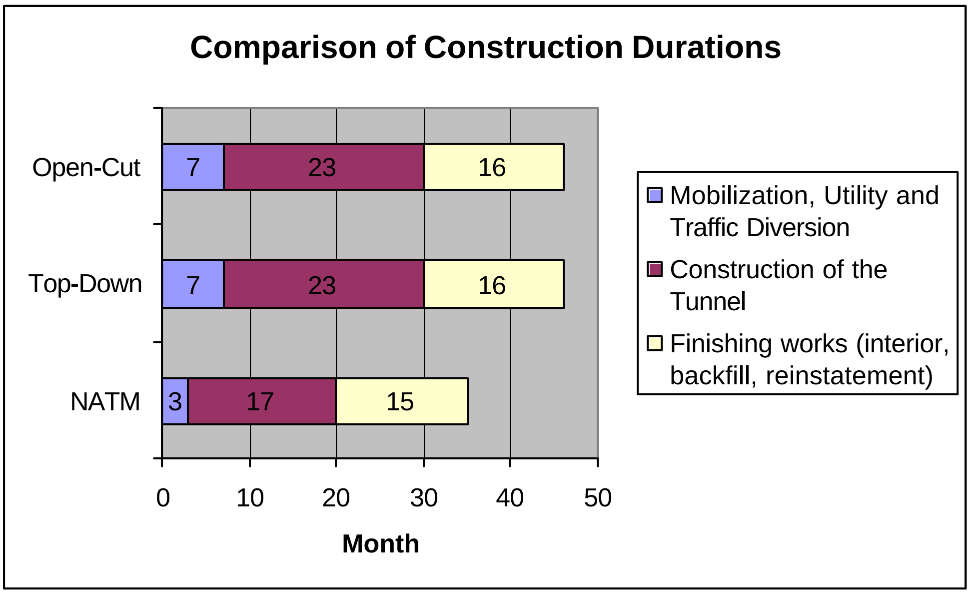


Figure 6.18: Comparison of Construction Durations

6.6.3 Cost Comparison

The costs of the different station variants are summarized in Table 6.19.

	OPEN-CUT	%	TOP-DOWN	%	NATM	%
Material	$ 10,705,550	100%	$ 10,223,310	95%	$ 9,966,240	93%
Labor	$ 10,417,200	100%	$ 10,882,400	104%	$ 11,621,280	112%
Equipment	$ 2,850,200	100%	$ 2,876,880	101%	$ 2,369,820	83%
Utility Diversion	$ 3,000,000	100%	$ 3,000,000	100%	$ -	0%
Surface Reinst. & Traffic Div.	$ 500,000	100%	$ 500,000	100%	$ -	0%
Net Construction Cost	$ 27,472,950	100%	$ 27,482,590	100%	$ 23,957,340	87%
Other	$ 4,846,210	100%	$ 4,847,570	100%	$ 4,354,030	90%
Total Construction Cost	**$ 32,319,160**	**100%**	**$ 32,330,160**	**100%**	**$ 28,311,370**	**88%**

Table 6.19: Cost Comparison

Figure 6.20 shows the cost relationship graphically and in Figure 6.21 the cost units of the three variants are compared to each other.

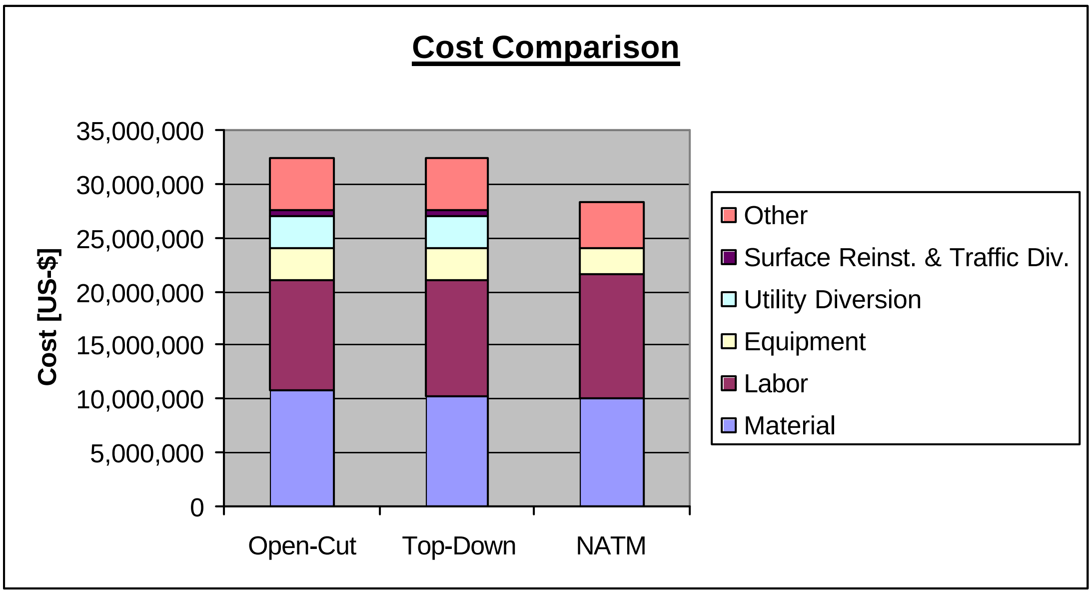


Figure 6.20: Cost Comparison

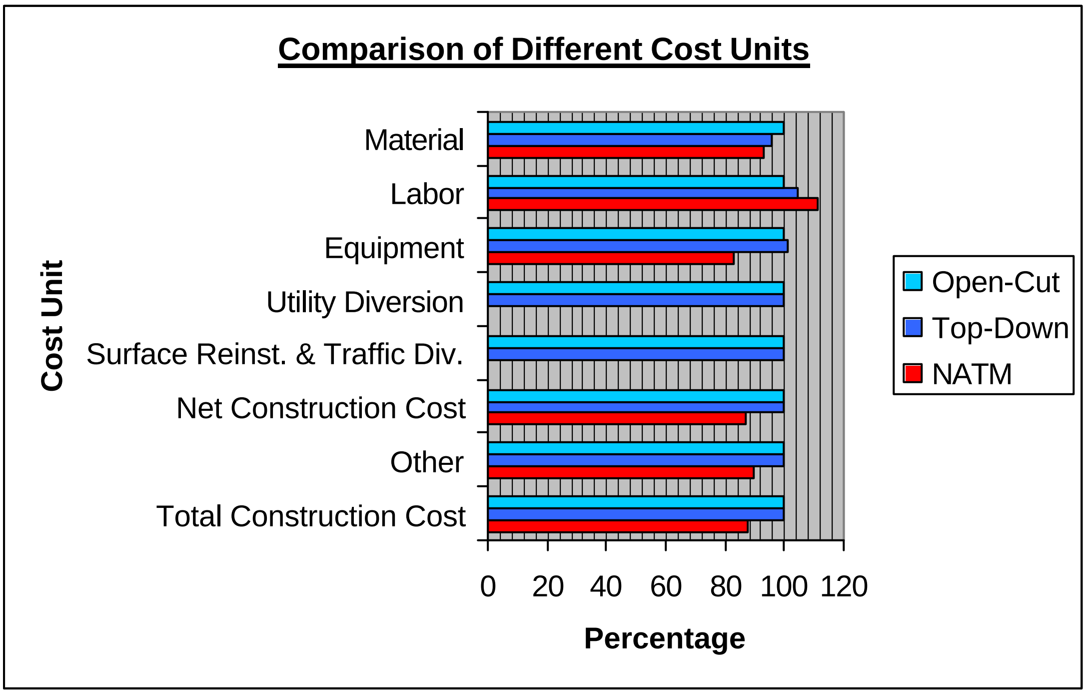


Figure 6.21: Comparison of Different Cost Units

The tables above show that the NATM station is more economical than the Open-Cut and Top-Down alternatives. The material cost is lower for the NATM station, especially because less excavation material needs to be loosened and disposed and less steel is required for reinforcement and bracing. The required backfilling material is negligible for NATM.

The labor cost is higher for the NATM station construction, whereas the equipment cost is lower, which indicates that NATM is a more labor-intense construction. Costs for utility diversion, surface reinstatement and traffic diversion are much lower for NATM and are insignificant for the comparison.

The "Other" costs, which consist of monitoring, dewatering, project management and contingencies, are mainly defined as percentage of the net construction cost. Therefore, these costs are proportionally lower for the NATM alternative.

The total construction cost is 12% cheaper using NATM compared to the costs of the Open-Cut and the Top-Down method which are almost equal. Differences exist only in the structure of the cost: As expected, material cost is lower at Top-Down construction (only 50% temporary steel struts), on the other hand costs for labor and equipment are higher due to the more difficult working conditions.

Figures 6.22 through 6.24 show the structure of the cost for the three different construction alternatives.

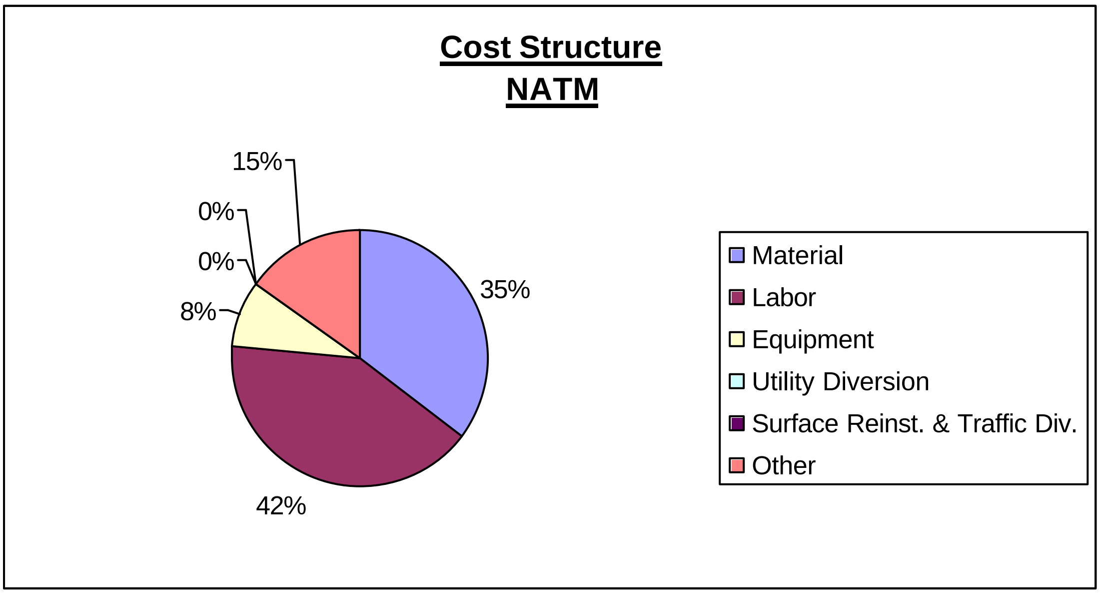


Figure 6.22: Cost Structure NATM

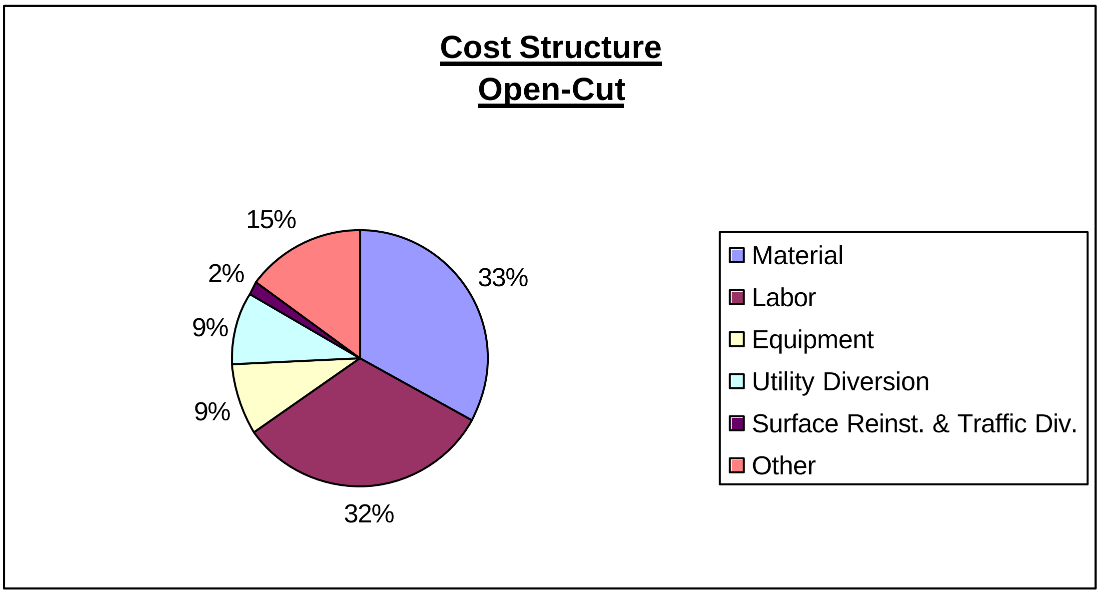


Figure 6.23: Cost Structure Open-Cut

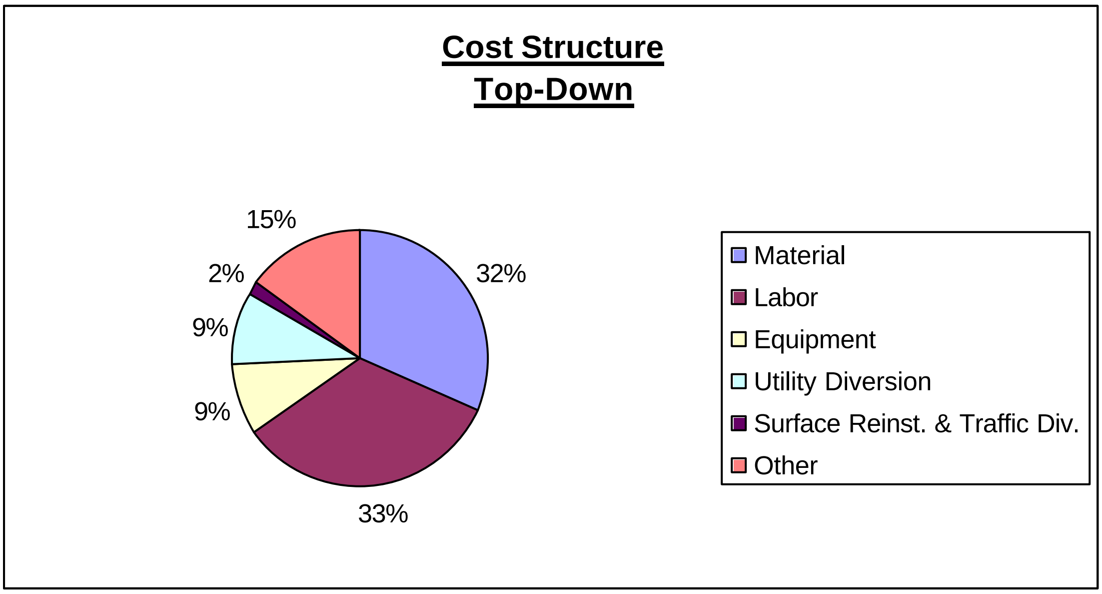


Figure 6.24: Cost Structure Top-Down

7. Conclusions

In urban tunneling usually both, NATM and Cut-and-Cover tunneling methods are feasible, if shallow overburden is present. Today, for the construction of running tunnels of subway lines, the Cut-and-Cover method is used only very rarely, because of the obvious disadvantages, especially the surface disturbance. Therefore underground excavation by means of a Tunnel Boring Machine (TBM) or the New Austrian Tunneling Method (NATM) is preferred. For subway stations however, the Cut-and-Cover method is still commonly used. NATM has a reputation of being more expensive, especially when shallow overburden is present and of involving higher construction risks.

General advantages and disadvantages of the methods have been analyzed. The comparison reveals the advantages of NATM. They include the alignment, which may be chosen more independently, the surface interruption, which is limited to the shaft areas only and the less extensive utility relocation. Also the surface settlements are less problematic. Other advantages of NATM are the irrelevance of weather and the near absence of buoyancy, noise and vibration problems. However, on the other hand NATM requires highly specialized planning and execution personnel and it is more dependant upon the ground conditions.

The risk comparison shows, that Cut-and-Cover tunneling is not a priori chancier than NATM but may involve - quite the contrary - higher risks than NATM. The crucial factor for the amount of risk of a construction method is rather a careful planning and execution of the project.

Several investigations concerning competitiveness of NATM and Cut-and-Cover tunneling method have been performed in the past. The cost analysis carried out in 1982 in Bochum (Germany) revealed, that the bid prices of NATM railway tunnels were lower than those of Cut-and-Cover tunnels in every investigated case. The analyzed tunnel sections were: two single track tunnels, a twin-track tunnel, a triple-track tunnel and a station with central platform. For the smaller section sizes NATM was up to 50% cheaper. Even for the station construction the bid price was only 93% of that of Cut-and-Cover.

If a temporary pit decking was required for the Cut-and-Cover construction in order to reduce the negative impact on the surface traffic, the price difference was even higher. In this case the NATM cost for the smaller section sizes amounted to 40.8% compared to Cut-and-Cover construction. The NATM station construction cost was 32.5% cheaper than Cut-and-Cover.

The average cost for the relocation of utility lines was investigated. For NATM construction the cost was only about one fifth that of Cut-and-Cover construction.

Other studies have shown that NATM-constructed stations are often cheaper than Cut-and-Cover constructed ones, even without considering the cost savings by leaving the surface almost unaffected. A study carried out in 1978 by the German research organization for underground traffic structures (STUVA) revealed, that NATM stations are usually the cheaper alternative.

An example of a project, where both alternatives were analyzed and a cost comparison was carried out is shown. The pedestrian tunnel at an airport was calculated to be 25% cheaper using NATM.

For a fair comparison, the secondary and indirect costs also have to be considered. They are usually not paid by the client, but affect retailers, road users, pedestrians and residents of the affected areas and are caused by the loss of public space and the impacts due to noise, dust and other inconveniences. Since these are intangible costs, they are very difficult or even impossible to calculate.

As an example a subway station was designed in three different ways: using Open-Cut, Top-Down and New Austrian Tunneling Method. The provided space, the tunnel alignment and the ground conditions were considered equal for all three alternatives. After specifying the design, construction schedules were developed for the different methods. Average performance rates and general assumptions were used. For the Top-Down and the Open-Cut method a 5-day working week with 10 working hours per day were assumed. The NATM station construction schedule is based on a nonstop working schedule, as this is favorable for the construction. The comparisons of the construction durations of the three different methods show that the NATM station can be constructed faster than the Cut-and-Cover alternatives.

The quantities of all main positions, like excavation, cast-in-place concrete, shotcrete, reinforcement and backfill were calculated for every station alternative and subsequently compared. It is evident, that more excavation material is produced for the Top-Down and the Open-Cut stations. Furthermore, 82% less backfilling material is required for the NATM station. Cast-in-place concrete and reinforcement are necessary in a much higher quantity for the Cut-and-Cover constructions than for the NATM construction. On the other hand, shotcrete is only required for the NATM station, which also requires a larger quantity of waterproofing membrane. However, the temporary steel struts are only necessary for the Open-Cut construction and – to a lower degree – for the Top-Down construction.

After establishing average costs for material, labor and equipment, cost estimates have been developed for the three different alternatives. NATM is the favorable option also from the economical point of view. The station construction is about 12% cheaper, compared to the Open-Cut and the Top-Down construction, which are similar in cost. The financial savings with the NATM station derive partially from the fact, that utility diversion, surface reinstatement and traffic diversion are negligible. Also the cost for material is lower for the NATM station, because the quantities of the main items are lower. As could be expected, labor cost is higher for the NATM station, due to the fact that it involves more manual work. The equipment of the Cut-and-Cover alternatives is costlier than the NATM construction equipment.

The described advantages of an NATM station construction, together with the potential cost savings, led to a rethinking in many countries, where Cut-and-Cover station construction was historically the logical way of building urban underground stations. In Germany, the mutation happened in the 1970's. Fast progress in NATM construction technique and experience made the method competitive to the conventional methods and it was increasingly used for subway construction in München and Bochum.

In Chile, twenty years later a similar development took place. Before 1993 the Metro of Santiago built its tunnels only by TBM and Cut-and-Cover method. After a successful NATM experiment running tunnels were built with the new method for first time. The application was so convincing and offered so substantial cost savings, that Metro built the next extension stations using NATM.

A tendency to construct underground stations using NATM is becoming apparent all over the world. Reasons are explained above - low surface interruption and cost advantages are only two of them. Cut-and-Cover construction will always have its justified field of application and is favorable under certain conditions. These can be the presence of a very low overburden and the fact, that huge surface openings do not cause major annoyances and cost and critical surface settlements are not expected. But due to the fact, that urban tunneling usually involves high restrictions and difficulties and rarely provides perfect conditions, NATM is increasingly an appreciated alternative.

Conversion Table

	English units		SI units
Length	1 mile	= 5280 ft	1.60930 km
	1 foot (ft or ')	= 12 in	0.3048 m
	1 inch (in or ")		2.54 cm
	1 yard (yd)	= 3 ft	0.9144 m
Area	1 ft^2		0.092903 m^2
	1 in^2		6.4516 cm^2
	1 yd^2		0.8361274 m^2
Volume	1 in^3		16.38706 cm^3
	1 ft^3		0.028317 m^3
	1 yd^3		0.7645549 m^3
Mass	1 lbs (pound)		0.4535924 kg
Density	1 lbs/ft^3		16.01846 kg/m^3
Pressure	1000 psi (pound/in^2)		0.7030696 kg/mm^2 = 6.89712 N/mm^2

Vocabularies and Notation

English	**German**
Advance rate	Vortriebsleistung
Barrel Vault	Rohrinjektionsschirm (RIS)
Barrel Vault Method	Tonnengewölbeverfahren
Bench	Strosse
"Berlin Construction Method" = Soldier Pile Wall with Timber Lagging	Berliner Bauweise = (Trägerbohlwand mit Holzverpfählung)
Bored Pile	Bohrpfahl
Cast-in-Place (CIP) Concrete	Ortbeton
Cut-and-Cover Tunneling	Offene Tunnelbauweise
Diaphragm Wall	Überbegriff für durchgehende Stützwände aus Stahlbeton o.ä. (Schlitzwände, Bohrpfahlwände etc.)
Doorframe Slab Method	Türstock-Deckel-Bauweise
Drilled Pile Wall	Bohrpfahlwand
Driven Pile	Rammpfahl
Formwork	Schalung
"Hamburg Construction Method"	Hamburger Bauweise
Invert	Sohle
Lattice girder	Tunnelgitterbögen
Length of round	Abschlagslänge
Mined tunneling	Bergmännische Tunnelbauweise
NATM (New Austrian Tunneling Method)	NÖT (Neue Österreichische Tunnelbau-weise
Open-Cut Excavation	Offene Tunnelbauweise mit verbleibender Baugrubensicherung (z.B. Schlitzwand)
Reinforcement	Bewehrung

Top-Down Construction Method = "Milan Construction Method"	Deckelbauweise = Mailänder Bauweise
Top heading (= crown)	Kalotte
Tremie Method	Kontraktorverfahren
Tube Umbrella Method	Rohrschirmbauweise
Scaffolding	Rüstung
Secant Pile Wall	Tangierende oder überlappende Bohrpfahlwand
Sheet Pile Wall	Spundwand
Shoring Wall	Stützwand (Baugrubeneinfassung)
Shotcrete	Spritzbeton
Slurry Wall	Schlitzwand
Soldier Pile and Tremie Concrete (SPTC) Wall	Trägerbohlwand mit Kontraktorbeton-verfüllung
Soldier Pile Wall	Trägerbohlwand
Wire mesh (= Welded wire fabric)	Baustahlgitter

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Table A.1: Calculation of Quantities, Alternative 1 and Alternative 2 (Open-Cut and Top-Down)

EXCAVATION		
Pit		
Length		175 m
Depth		19 m
Width		20 m
Excavation volume		**66,500 m³**
Slurry Walls, Zone 1		
Length	[95*2+20]	210 m
Depth		24.5 m
Width		1 m
Excavation volume		**5,145 m³**
Slurry Walls, Zone 2		
Length	[80*2+20]	180 m
Depth		24.5 m
Width		1 m
Excavation volume		**4,410 m³**
EXCAVATION VOLUME TOTAL		**76,055 m³**
BACKFILL		
Backfill Volume, Zone 1	[95*20*6]	11,400 m³
Backfill Volume, Zone 2	[80*20*6]	9,600 m³
Backfill Volume Total		**21,000 m³**
Backfill Volume, Remaining openings	[12.5*20*6]	1,500 m³
CIP CONCRETE		
Slurry Walls		
Length total	[2*175+2*20]	390 m
Depth		24.5 m
Width		1 m
Concrete volume		**9,555 m³**
Guide Walls		
Length total	[2*175+2*20]*2	780 m
Depth		1.5 m
Width		0.5 m
Concrete volume		**585 m³**

Roof Slab		
Length		175 m
Width		20 m
Height		1.00 m
Concrete volume		**3,500 m³**
Slope & protection conc.	[((0.05+0.10)/2+0.05)*20*175]	**438 m³**
Concourse Slab		
Length		175 m
Width		20 m
Height		0.55 m
Concrete volume		**1,925 m³**
Base Slab		
Length		175 m
Width		20 m
Height		1.50 m
Concrete volume		**5,250 m³**
Lean conc. & protection conc.	[20*(0.10+0.05)*175]	**525 m³**
CONCRETE VOLUME TOTAL		**21,778 m³**

REINFORCEMENT

Slurry Walls	
Concrete volume	9,555 m³
180 kg/m³	**1,720 to**
Guide Walls	
Concrete volume	585 m³
40 kg/m³	**23 to**
Roof Slab	
Concrete volume	3,500 m³
200 kg/m³	**700 to**
Concourse Slab	
Concrete volume	1,925 m³
120 kg/m³	**231 to**
Base Slab	
Concrete volume	5,250 m³
170 kg/m³	**893 to**
REINFORCEMENT MASS TOTAL	**3,567 to**

WATERPROOFING

Roof Slab		
Length		175 m²
Width		21 m²
Membrane area		**3,675 m²**
Base Slab		
Length		175 m²
Width		23 m²
Membrane area		**4,025 m²**
Side Walls		
Length	[(175+20)*2]	390 m²
Height	[4.5+5.5]	10 m²
Membrane area		**3,900 m²**
WATERPROOFING AREA TOTAL		**11,600 m²**

TEMPORARY STEEL STRUTS

Pit Length		175 m
Strut distance		9 m
Strut number		18
Strut mass per number		14 to
Strut mass per layer		**252 to**
Mass head walls per layer	[2*11]	**22 to**
MASS PER STRUT LAYER		**274 to**
OPEN-CUT		
Number of strut layers		4
Mass of strut layers total		**1,096 to**
TOP-DOWN		
Number of strut layers		2
Mass of strut layers total		**548 to**

Table A.2: Calculation of Durations, Alternative 1 (Open-Cut)

CALCULATION OF DURATIONS
ALTERNATIVE 1: OPEN-CUT CONSTRUCTION

EXCAVATION

	Length	Width	Depth	Volume	Capacity per day	Duration
Excavation 1, Zone 1	95 m	20 m	3.0 m	5,700 m³	500 m³	**11 d**
Excavation 1, Zone 2	80 m	20 m	3.0 m	4,800 m³	500 m³	**10 d**
Excavation 2, Zone 1	95 m	20 m	3.0 m	5,700 m³	450 m³	**13 d**
Excavation 2, Zone 2	80 m	20 m	3.0 m	4,800 m³	450 m³	**11 d**
Excavation 3, Zone 1	95 m	20 m	5.5 m	10,450 m³	400 m³	**26 d**
Excavation 3, Zone 2	80 m	20 m	5.5 m	8,800 m³	400 m³	**22 d**
Excavation 4, Zone 1	95 m	20 m	4.0 m	7,600 m³	350 m³	**22 d**
Excavation 4, Zone 2	80 m	20 m	4.0 m	6,400 m³	350 m³	**18 d**
Excavation 5, Zone 1	95 m	20 m	3.5 m	6,650 m³	250 m³	**27 d**
Excavation 5, Zone 2	80 m	20 m	3.5 m	5,600 m³	250 m³	**22 d**

TEMPORARY STEEL STRUTS

Zone 1		
Strut number	10	
Duration per strut installation	2 d	
Duration strut installation total		20 d
Installation Waler Beams		2 d
Installation Head Wall		4 d
Duration per strut layer installation		**26 d**
Zone 2		
Strut number	8	
Duration per strut installation	2 d	
Duration strut installation total		16 d
Installation Waler Beams		2 d
Installation Head Wall		4 d
Duration per strut layer installation		**22 d**

SLURRY WALLS AND CONCRETE WORKS

ZONE 1

Slurry Wall			
Area	[(95*2+20)*24.5]	5,145 m²	
Capacity per day		80 m²	
Duration			64 d

Base Slab			
Connection to Slurry Wall			15 d
Dressing & Lean Concrete			5 d
Waterproofing & Protection Concrete			5 d
Reinforcement mass	[893/175*95]	485 to	
Capacity per day	[100 kg/manhr. * 200 manhr./day]	20.0 to	
Reinforcement installation duration			24 d
Formwork and concrete installation	[5 blocks * 2 days/block]		10 d
Duration total			**59 d**
Concourse Slab			
Connection to Slurry Wall			15 d
Removal of temp. strut layer IV			2 d
Scaffolding			10 d
Formwork			5 d
Reinforcement mass	[231/175*95]	125 to	
Capacity per day	[90 kg/manhr. * 150 manhr./day]	13.5 to	
Reinforcement installation duration			9 d
Formwork and concrete installation	[5 blocks * 2 days/block]		10 d
Duration total			**51 d**
Roof Slab			
Connection to Slurry Wall			15 d
Removal of temp. strut layer III			2 d
Scaffolding			10 d
Formwork			5 d
Reinforcement mass	[700/175*95]	380 to	
Capacity per day	[90 kg/manhr. * 150 manhr./day]	13.5 to	
Reinforcement installation duration			28 d
Formwork and concrete installation	[5 blocks * 2 days/block]		10 d
Duration total			**70 d**
Waterproofing, Backfill & Reinstatement			
Removal of temp. strut layer I and II			4 d
Waterproofing			7 d
Backfill	[(11,400-1500) / 200 m³/day]		50 d
Reinstatement			17 d
Duration total			**78 d**
Waterproofing, Backfill & Reinstatement - remaining opening			
Removal of temp. strut layer I and II			2 d
Waterproofing			3 d
Backfill	[1500 / 200 m³/day]		8 d
Reinstatement			10 d
Duration total			**23 d**

ZONE 2

Slurry Wall

Area	[(80*2+20)*24.5]	4,410 m²	
Capacity per day		80 m²	
Duration			55 d

Base Slab

Connection to Slurry Wall			12 d
Dressing & Lean Concrete			5 d
Waterproofing & Protection Concrete			5 d
Reinforcement mass	[893/175*80]	408 to	
Capacity per day	[100 kg/manhr. * 200 manhr./day]	20.0 to	
Reinforcement installation duration			20 d
Formwork and concrete installation	[4 blocks * 2 days/block]		8 d
Duration total			**50 d**

Concourse Slab

Connection to Slurry Wall			12 d
Removal of temp. strut layer IV			2 d
Scaffolding			10 d
Formwork			5 d
Reinforcement mass	[231/175*80]	106 to	
Capacity per day	[90 kg/manhr. * 150 manhr./day]	13.5 to	
Reinforcement installation duration			8 d
Formwork and concrete installation	[4 blocks * 2 days/block]		8 d
Duration total			**45 d**

Roof Slab

Connection to Slurry Wall			12 d
Removal of temp. strut layer III			2 d
Scaffolding			10 d
Formwork			5 d
Reinforcement mass	[700/175*80]	320 to	
Capacity per day	[90 kg/manhr. * 150 manhr./day]	13.5 to	
Reinforcement installation duration			24 d
Formwork and concrete installation	[4 blocks * 2 days/block]		8 d
Duration total			**61 d**

Waterproofing, Backfill & Reinstatement

Removal of temp. strut layer I and II			4 d
Waterproofing			7 d
Backfill	[(9,600-1500) / 200 m³/day]		41 d
Reinstatement			16 d
Duration total			**68 d**

Waterproofing, Backfill & Reinstatement - remaining opening

Removal of temp. strut layer I and II		2 d
Waterproofing		3 d
Backfill	[1500 / 200 m³/day]	8 d
Reinstatement		10 d
Duration total		**23 d**

Table A.3: Calculation of Durations, Alternative 2 (Top-Down)

CALCULATION OF DURATIONS
ALTERNATIVE 2: TOP-DOWN CONSTRUCTION

EXCAVATION

	Length	Width	Depth	Volume	Capacity per day	Duration
Excavation 1, Zone 1	95 m	20 m	3.0 m	5,700 m³	500 m³	**11 d**
Excavation 1, Zone 2	80 m	20 m	3.0 m	4,800 m³	500 m³	**10 d**
Excavation 2, Zone 1	95 m	20 m	4.0 m	7,600 m³	450 m³	**17 d**
Excavation 2, Zone 2	80 m	20 m	4.0 m	6,400 m³	450 m³	**14 d**
Excavation 3, Zone 1	95 m	20 m	5.0 m	9,500 m³	300 m³	**32 d**
Excavation 3, Zone 2	80 m	20 m	5.0 m	8,000 m³	300 m³	**27 d**
Excavation 4, Zone 1	95 m	20 m	4.0 m	7,600 m³	250 m³	**30 d**
Excavation 4, Zone 2	80 m	20 m	4.0 m	6,400 m³	250 m³	**26 d**
Excavation 5, Zone 1	95 m	20 m	3.0 m	5,700 m³	200 m³	**29 d**
Excavation 5, Zone 2	80 m	20 m	3.0 m	4,800 m³	200 m³	**24 d**

TEMPORARY STEEL STRUTS

Zone 1		
Strut number	10	
Duration per strut installation	2 d	
Duration strut installation total		20 d
Installation Waler Beams		2 d
Installation Head Wall		4 d
Duration for strut layer I installation		**26 d**
Difficulty factor for strut layer II	1.3	
Duration for strut layer II		**34 d**
Zone 2		
Strut number	8	
Duration per strut installation	2 d	
Duration strut installation total		16 d
Installation Waler Beams		2 d
Installation Head Wall		4 d
Duration for strut layer I installation		**22 d**
Difficulty factor for strut layer II	1.3	
Duration for strut layer II		**29 d**

SLURRY WALLS AND CONCRETE WORKS

ZONE 1

Slurry Wall			
Area	[(95*2+20)*24.5]	5,145 m²	
Capacity per day		80 m²	
Duration			**64 d**
Roof Slab			
Connection to Slurry Wall			15 d
Dressing & Lean Concrete & Plywood			10 d
Reinforcement mass	[700/175*95]	380 to	
Capacity per day	[100 kg/manhr. * 200 manhr./day]	20.0 to	
Reinforcement installation duration			19 d
Formwork and concrete installation	[5 blocks * 2 days/block]		10 d
Duration total			**54 d**
Concourse Slab			
Connection to Slurry Wall			15 d
Dressing & Lean Concrete & Plywood			10 d
Reinforcement mass	[231/175*95]	125 to	
Capacity per day	[80 kg/manhr. * 200 manhr./day]	16.0 to	
Reinforcement installation duration			8 d
Formwork and concrete installation	[5 blocks * 3 days/block]		15 d
Additional: Transportation			5 d
Duration total			**53 d**
Base Slab			
Connection to Slurry Wall			15 d
Dressing & Lean Concrete			5 d
Waterproofing & Protection Concrete			5 d
Reinforcement mass	[893/175*95]	485 to	
Capacity per day	[80 kg/manhr. * 200 manhr./day]	16.0 to	
Reinforcement installation duration			30 d
Formwork and concrete installation	[5 blocks * 3 days/block]		15 d
Additional: Transportation			5 d
Duration total			**75 d**
Waterproofing, Backfill & Reinstatement			
Removal of temp. strut layer I			2 d
Waterproofing			7 d
Backfill	[(11,400-1500) / 200 m³/day]		50 d
Reinstatement			17 d
Duration total			**76 d**

Waterproofing, Backfill & Reinstatement - remaining opening

Removal of temp. strut layer I			1 d
Waterproofing			3 d
Backfill	[1500 / 200 m³/day]		8 d
Reinstatement			10 d
Duration total			**22 d**

ZONE 2

Slurry Wall

Area	[(80*2+20)*24.5]	4,410 m²	
Capacity per day		80 m²	
Duration			**55 d**

Roof Slab

Connection to Slurry Wall			12 d
Dressing & Lean Concrete & Plywood			10 d
Reinforcement mass	[700/175*80]	320 to	
Capacity per day	[100 kg/manhr. * 200 manhr./day]	20.0 to	
Reinforcement installation duration			16 d
Formwork and concrete installation	[4 blocks * 2 days/block]		8 d
Duration total			**46 d**

Concourse Slab

Connection to Slurry Wall			12 d
Dressing & Lean Concrete & Plywood			10 d
Reinforcement mass	[231/175*80]	106 to	
Capacity per day	[80 kg/manhr. * 200 manhr./day]	16.0 to	
Reinforcement installation duration			7 d
Formwork and concrete installation	[4 blocks * 3 days/block]		12 d
Additional: Transportation			5 d
Duration total			**46 d**

Base Slab

Connection to Slurry Wall			12 d
Dressing & Lean Concrete			5 d
Waterproofing & Protection Concrete			5 d
Reinforcement mass	[893/175*80]	408 to	
Capacity per day	[80 kg/manhr. * 200 manhr./day]	16.0 to	
Reinforcement installation duration			26 d
Formwork and concrete installation	[4 blocks * 2 days/block]		8 d
Additional: Transportation			5 d
Duration total			**61 d**

Waterproofing, Backfill & Reinstatement

Removal of temp. strut layer I		2 d
Waterproofing		7 d
Backfill	[(9,600-1500) / 200 m³/day]	41 d
Reinstatement		16 d
Duration total		**66 d**

Waterproofing, Backfill & Reinstatement - remaining opening

Removal of temp. strut layer I		1 d
Waterproofing		3 d
Backfill	[1500 / 200 m³/day]	8 d
Reinstatement		10 d
Duration total		**22 d**

Table A.4: Material Cost used for Calculation

MATERIAL

		Unit	Unit Rate		Source
Excavation (disposal and landfill fee)					
Estimated cost for solid material		m³	**$**	**60**	estimate
Shotcrete (incl. equipment)					
Cost per m³ shotcrete		m³	$	90	DSC
Rebound	200%				
Cost incl. rebound		m³	**$**	**180**	
Backfill (incl. transport to site)					
Cost for backfilling material		m³	**$**	**25**	estimate
Lattice Girders					
Cost per meter		m	$	50	DSC
Waste	2%				
Cost per meter incl. waste		m	**$**	**51**	
Wire Mesh					
Cost per squaremeter		m²	$	3.0	DSC
Factor for waste	70%				
Cost per squaremeter incl. waste		m²	**$**	**5.1**	
Rebar Spiles, 36mm diameter					
Cost per kg		kg	$	0.57	DSC
Weight per m	8.1	kg			
Cost per meter		m	$	4.7	
Length of rebars	2.5	m			
Cost per rebar			$	11.7	
Factor for waste	10%				
Cost per rebar incl. waste		m	**$**	**12.8**	
CIP Concrete					
Cost per m³ CIP concrete, pumpable		m³	$	85	DSC
Waste	10%				
Cost incl. waste		m³	$	94	
Reinforcement					
Reinforcement cost per ton		ton	$	800	DSC
Waterproofing					
Cost membrane per m²		m²	$	17	DSC
Waste and overlapping	15%				
Cost membrane incl. waste		m²	**$**	**20**	

Temp. Steelstruts				
Cost per ton	ton	$	**2,200**	DSC
Bentonit Suspension				
Cost per m³	m³	$	**15**	[21] (II.3.6/14), rounded up

Table A.5: Labor Cost used for Calculation

LABOR

Personnel	Average gross labor cost per hour [US-$]	Source
Laborer	**$ 40**	[21] and estimate

Note:
The average gross labor cost is an average of all different professions working on the site. It includes all social and indirect costs.

Table A.6: Equipment Cost used for Calculation

EQUIPMENT

			Source
Slurry Wall Equipment			
Equipment cost per month	$ 40,000		[21] (II.3.6/14)
Equipment cost per week		$ 9,302	
Energy, fuel (550 kW) - cost per day	$ 290		
Energy, fuel (550 kW) - cost per week		$ 1,450	
Total cost per week		**$10,752**	
Excavator (120 kW)			
Cost per month	$ 12,971		[21] (3140-0250+3182-0120)
Cost per week		**$ 3,016**	
Tunneling excavator (120 kW)			
Cost per month	$ 14,140		[21] (II.4.1/25)
Cost per week		**$ 3,288**	
Drill rig (1 arm)			
Cost per month	$ 10,690		[20] (6542-0069)
Cost per week		**$ 2,486**	
Wheel loader (180 kW)			
Cost per month	$ 17,262		[21] (II.4.1/25)
Cost per week		**$ 4,014**	
Compressor			
Cost per month	$ 4,073		[20] (6103-0170)
Cost per week		**$ 947**	
Tunnel ventilation system			
Cost per hour	$ 0.5		[21] (II.4.4 5/6)
Cost per week (24/7)		**$ 86**	
Tunnel lighting			
Cost per week		**$ 100**	estimate
Crane (34 kW)			
Cost per month	$ 4,893		[20] (2120-0090)
Cost per week		**$ 1,138**	
Formwork for Cut-and-Cover			
Cost per month	$ 30,100		DSC
Cost per week		**$ 7,000**	

Roller			
Cost per month	$ 5,008		[20] (3625-0060)
Cost per week		**$ 1,168**	
Concrete pump			
Cost per month	$ 2,795		DSC
Cost per week		**$ 650**	
Scaffolding for Cut-and-Cover			
Cost per month	$ 5,160		DSC
Cost per week		**$ 1,200**	

Table A.7: Cost Estimate Alternative 1 (Open-Cut)

COST ESTIMATE - OPEN-CUT STATION (ALTERNATIVE 1)

Material

Slurry Wall (see [21], II.3.6/14)				
Bentonit suspension	15	$/m²		
Slurry Wall Area	9,555	m²		
Cost Bentonit Total			$	143,325
Excavation (disposal and landfill fee)	60	$/m³		
Quantity	9,555	m³		
Cost Excavation Material (disposal and landfill fee)			$	573,300
Concrete	85	$/m³		
Waste	20	%		
Quantity	9,555	m³		
Cost Concrete			$	974,610
Reinforcement	800	$/ton		
Reinforcement amount	0.080	t/m²		
Slurry Wall Area	9,555	m²		
Cost Reinforcement			$	611,520
Guide Walls	9	$/m²		
Guide Wall Area	1,170	m²		
Cost Guide Walls			$	10,530
Grinding surface (50cm), incl. disposal	130	$/m		
Length Slurry Wall	390	m		
Cost Grinding Surface			$	50,700
Material Cost Slurry Wall			**$**	**2,363,985**
Excavation (disposal and landfill fee)				
Quantity	66,500	m³		
Cost per m³ solid	60	$/m³		
Cost total			$	3,990,000
Concrete				
Quantity	12,252	m³		
Cost per m³ (incl. 10% waste)	94	$/m³		
Cost total			$	1,151,688
Reinforcement				
Quantity	1,848	ton		
Cost per ton	800	$/ton		
Cost total			$	1,478,400

Waterproofing				
Quantity		11,600 m²		
Cost per m² (incl. 15% waste and overlapping)		20 $/m²		
Cost total			$	232,000
Backfill				
Quantity		21,000 m³		
Cost per m³		25 $/m³		
Cost total			$	525,000
Temp. Steelstruts				
Quantity		1,096 ton		
Cost per ton		2,200 $/ton		
Write-off		0.40		
Cost total			$	964,480
TOTAL MATERIAL COST			**$**	**10,705,553**

Labor

Slurry Wall:				
Foreman	1			
Operator	1			
Laborer	7			
Total hourly cost	9	40 $/hr	$	360
Daily worktime per unit		10 hr		
Daily cost		day	$	3,600
Duration of Slurry Wall Installation		119 days		
Labor Cost Slurry Wall			**$**	**428,400**
Excavation:				
Foreman	1			
Operator	3			
Mechanics	1			
Electricians	1			
Helpers	3			
Total hourly cost per unit	9	40 $/hr	$	360
Daily worktime per unit		10 hr		
Daily cost		day	$	3,600
Duration of excavation		182 days		
Labor Cost Excavation			**$**	**655,200**

Strutting & Decking:					
Foreman	1				
Operator	1				
Welder	6				
Laborer	2				
Mechanics	1				
Electricians	1				
Helpers	5				
Total hourly cost per unit	17	40	$/hr	$	680
Daily worktime per unit		10	hr		
Daily cost			day	$	6,800
Duration of excavation		192	days		
Labor Cost Strutting & Decking				**$**	**1,305,600**
Concrete Work:					
Foreman	2				
Carpenter	10				
Concretor	5				
Steel Fixer	15				
Mechanics	1				
Electricians	1				
Helpers	4				
Total hourly cost per unit	38	40	$/hr	$	1,520
Daily worktime per unit		10	hr		
Daily cost			day	$	15,200
Duration of excavation		457	days		
Labor Cost Concrete Work				**$**	**6,946,400**
Waterproofing, Backfill & Reinstatement:					
Foreman	1				
Operator	2				
Helpers	3				
Total hourly cost per unit	6	40	$/hr	$	240
Daily worktime per unit		10	hr		
Daily cost			day	$	2,400
Duration of waterpr., backf. & reinst.		192	days		
Labor Cost Waterpr., Backf. & Reinstatement				**$**	**460,800**
Crane Operators					
Crane operator	2				
Total hourly cost	2	40	$/hr	$	80
Daily worktime		10	hr		
Daily cost			day	$	800
Duration of operation		776	days		
Labor Cost Crane Operators				**$**	**620,800**
TOTAL LABOR COST				**$**	**10,417,200**

Equipment

Equipment for Slurry Wall:					
Equipment total	1	$10,750	wk	$	10,750
Working days per week		5			
Equipment cost per working day				$	2,150
Duration of Slurry wall installation		119	days		
Equipment Cost Slurry Wall				**$**	**255,850**
Equipment for Excavation:					
Excavator	1	$ 3,020	wk	$	3,020
Loader	2	$ 4,010	wk	$	8,020
Total cost per week			wk	$	11,040
Working days per week		5			
Total cost per day			day	$	2,208
Duration of excavation		182	days		
Equipment Cost Excavation				**$**	**401,856**
Equipment for Strutting & Decking:					
Loader	1	$ 4,010	wk	$	4,010
Div. tools	3	$ 200	wk	$	600
Total cost per week			wk	$	4,610
Working days per week		5			
Total cost per day			day	$	922
Duration of strutting & decking		192	days		
Equipment Cost Strutting & Decking				**$**	**177,024**
Equipment for Concrete Work:					
Formwork	1	$ 7,000	wk	$	7,000
Scaffolding	1	$ 1,200	wk	$	1,200
Loader	1	$ 4,010	wk	$	4,010
Concrete pump	1	$ 650	wk	$	650
Div. Tools	4	$ 200	wk	$	800
Total cost per week			wk	$	13,660
Working days per week		5			
Total cost per day			day	$	2,732
Duration of concrete work		457	days		
Equipment Cost Concrete Work				**$**	**1,248,524**
Equipment for Waterproof., Backfill & Reinst.:					
Loader	1	$ 4,010	wk	$	4,010
Roller	1	$ 1,170	wk	$	1,170
Total cost per week			wk	$	5,180
Working days per week		5			
Total cost per day			day	$	1,036
Duration of waterpr., backf. & reinst.		192	days		
Equipment Cost Waterpr., Backf. & Reinst.				**$**	**198,912**

Additional Equipment:						
Crane	2	$	880	wk	$	1,760
Compressor	2	$	950	wk	$	1,900
Total cost per week				wk	$	3,660
Working days per week			5			
Total cost per day				day	$	732
Duration of waterpr., backf. & reinst.			776	days		
Surface Equipment Cost					**$**	**568,032**
TOTAL EQUIPMENT COST					**$**	**2,850,198**
Material, Labor and Equipment					**$**	**23,972,951**
Utility Diversion					$	3,000,000
Surface Reinstatement and Traffic Diversion					$	500,000
Net Construction Cost					**$**	**27,472,951**
Monitoring				2%	$	549,459
Dewatering				2%	$	549,459
Project Management					$	1,000,000
Contingencies, e.g. obstacles, bad weather, etc.				10%	$	2,747,295
TOTAL COST FOR OPEN-CUT ALTERNATIVE (ALT. 1)					**$**	**32,319,164**

Table A.8: Cost Estimate Alternative 2 (Top-Down)

COST ESTIMATE - TOP-DOWN STATION (ALTERNATIVE 2)

Material

Slurry Wall (see [21], II.3.6/14)				
Bentonit suspension	15	$/m²		
Slurry Wall Area	9,555	m²		
Cost Bentonit Total			$	143,325
Excavation (disposal and landfill fee)	60	$/m³		
Quantity	9,555	m³		
Cost Excavation Material (disposal and landfill fee)			$	573,300
Concrete	85	$/m³		
Waste	20	%		
Quantity	9,555	m³		
Cost Concrete			$	974,610
Reinforcement	800	t/m²		
Reinforcement amount	0.080	$/ton		
Slurry Wall Area	9,555	m²		
Cost Reinforcement			$	611,520
Guide Walls	9	$/m²		
Guide Wall Area	1,170	m²		
Cost Guide Walls			$	10,530
Grinding surface (50cm), incl. disposal	130	$/m		
Length Slurry Wall	390	m		
Cost Grinding Surface			$	50,700
Material Cost Slurry Wall			**$**	**2,363,985**
Excavation (disposal and landfill fee)				
Quantity	66,500	m³		
Cost per m³ solid	60	$/m³		
Cost total			$	3,990,000
Concrete				
Quantity	12,252	m³		
Cost per m³ (incl. 10% waste)	94	$/m³		
Cost total			$	1,151,688
Reinforcement				
Quantity	1,848	ton		
Cost per ton	800	$/ton		
Cost total			$	1,478,400

Waterproofing					
Quantity		11,600	m²		
Cost per m²		20	$/m²		
Cost total				$	232,000
Backfill					
Quantity		21,000	m³		
Cost per m³		25	$/m³		
Cost total				$	525,000
Temp. Steelstruts					
Quantity		548	ton		
Cost per ton		2,200	$/ton		
Write-off		0.40			
Cost total				$	482,240
TOTAL MATERIAL COST				**$**	**10,223,313**

Labor

Slurry Wall:					
Foreman	1				
Operator	1				
Laborer	7				
Total hourly cost	9	40	$/hr	$	360
Daily worktime per unit		10	hr		
Daily cost			day	$	3,600
Duration of Slurry Wall Installation		119	days		
Labor Cost Slurry Wall				**$**	**428,400**
Working Crew for Excavation:					
Foreman	1				
Operator	3				
Mechanics	1				
Electricians	1				
Helpers	3				
Total hourly cost per unit	9	40	$/hr	$	360
Daily worktime per unit		10	hr		
Daily cost			day	$	3,600
Duration of excavation		220	days		
Labor Cost Excavation				**$**	**792,000**

Working Crew for Strutting & Decking:					
Foreman	1				
Operator	1				
Welder	6				
Laborer	2				
Mechanics	1				
Electricians	1				
Helpers	5				
Total hourly cost per unit	17	40	$/hr	$	680
Daily worktime per unit		10	hr		
Daily cost			day	$	6,800
Duration of excavation		111	days		
Labor Cost Strutting & Decking				**$**	**754,800**
Working Crew for Concrete Work:					**Total**
Foreman	2				
Carpenter	10				
Concretor	5				
Steel Fixer	20				
Mechanics	1				
Electricians	1				
Helpers	4				
Total hourly cost per unit	43	40	$/hr	$	1,720
Daily worktime per unit		10	hr		
Daily cost			day	$	17,200
Duration of excavation		456	days		
Labor Cost Concrete Work				**$**	**7,843,200**
Waterproofing, Backfill & Reinstatement:					
Foreman	1				
Operator	2				
Helpers	3				
Total hourly cost per unit	6	40	$/hr	$	240
Daily worktime per unit		10	hr		
Daily cost			day	$	2,400
Duration of waterpr., backf. & reinst.		186	days		
Labor Cost Waterpr., Backf. & Reinstatement				**$**	**446,400**
Crane Operators					
Crane operator	2				
Total hourly cost	2	40	$/hr	$	80
Daily worktime		10	hr		
Daily cost			day	$	800
Duration of operation		772	days		
Labor Cost Crane Operators				**$**	**617,600**
TOTAL LABOR COST				**$**	**10,882,400**

Equipment

Equipment for Slurry Wall:					
Equipment total	1	$10,750	wk	$	10,750
Working days per week		5			
Equipment cost per working day				$	2,150
Duration of Slurry wall installation		119	days		
Equipment Cost Slurry Wall				**$**	**255,850**
Equipment for Excavation:					
Excavator	1	$ 3,020	wk	$	3,020
Loader	2	$ 4,010	wk	$	8,020
Total cost per week			wk	$	11,040
Working days per week		5			
Total cost per day			day	$	2,208
Duration of excavation		220	days		
Equipment Cost Excavation				**$**	**485,760**
Equipment for Strutting & Decking:					
Loader	1	$ 4,010	wk	$	4,010
Div. tools	3	$ 200	wk	$	600
Total cost per week			wk	$	4,610
Working days per week		5			
Total cost per day			day	$	922
Duration of excavation		111	days		
Equipment Cost Strutting & Decking				**$**	**102,342**
Equipment for Concrete Work:					
Formwork	1	$ 7,000	wk	$	7,000
Scaffolding	1	$ 1,200	wk	$	1,200
Loader	1	$ 4,010	wk	$	4,010
Concrete pump	1	$ 650	wk	$	650
Tools	4	$ 200	wk	$	800
Total cost per week			wk	$	13,660
Working days per week		5			
Total cost per day			day	$	2,732
Duration of excavation		456	days		
Equipment Cost Concrete Work				**$**	**1,245,792**
Equipment for Waterproof., Backfill & Reinst.:					**Total**
Loader	1	$ 4,010	wk	$	4,010
Roller	1	$ 1,170	wk	$	1,170
Total cost per week			wk	$	5,180
Working days per week		5			
Total cost per day			day	$	1,036
Duration of waterpr., backf. & reinst.		186	days		
Equipment Cost Waterpr., Backf. & Reinst.				**$**	**192,696**

Additional Equipment:						
Crane	2	$	880	wk	$	1,760
Compressor	2	$	950	wk	$	1,900
Tunnel ventilation system	1	$	90	wk	$	90
Tunnel lighting	1	$	100	wk	$	100
Total cost per week				wk	$	3,850
Working days per week			5			
Total cost per day				day	$	770
Duration of waterpr., backf. & reinst.			772	days		
Surface Equipment Cost					**$**	**594,440**
TOTAL EQUIPMENT COST					**$**	**2,876,880**
Material, Labor and Equipment					**$**	**23,982,593**
Utility Diversion					$	3,000,000
Surface Reinstatement and Traffic Diversion					$	500,000
Net Construction cost					**$**	**27,482,593**
Monitoring				2%	$	549,652
Dewatering				2%	$	549,652
Project Management					$	1,000,000
Contingencies, e.g. obstacles, bad weather, etc.				10%	$	2,748,259
TOTAL COST FOR TOP-DOWN ALTERNATIVE (ALT. 2)					**$**	**32,330,156**

Table A.9: Material Cost, Alternative 3 (NATM)

MATERIAL COST CONCOURSE TUNNEL	Area [m²]	Distance [m]	Tunnel length [m]	Total		Comment		Unit rate		Total
Excavation										
Total area	88.1		157	13,831.7	m³		$	60	$	829,902
Lattice girder										
Around profile		34.4	157	4,500.7	m	1 element every 1.2m	$	51	$	229,534
Temp. sidewalls (2)		16.4	157	2,145.7	m	1 element every 1.2m	$	51	$	109,429
Wire mesh										
Around profile		34.4	157	10,801.6	m²	two layers	$	5.1	$	55,088
Temp. sidewall		16.4	157	2,574.8	m²	one layer	$	5.1	$	13,131
Temp. invert		13.4	157	2,103.8	m²	one layer (at top heading)	$	5.1	$	10,729
Initial shotcrete lining										
Around profile	12.0		157	1,877.7	m³	36cm thick	$	180	$	337,990
Temp. sidewalls (2)	3.7		157	580.9	m³	25cm thick	$	180	$	104,562
Temp. inverts	1.2		157	191.5	m³	10cm thick, at top heading	$	180	$	34,477
Face (total)	88.1		157	576.3	m³	5cm thick, 1.2m advance rate	$	180	$	103,738
Rebar spiles			157	8,242.5	ea	63 pc. per round	$	13	$	105,504
Waterproofing										
Around profile		32.1	157	5,039.7	m²		$	20	$	100,794
Final lining (inc. 40kg/m³ reinforc.)										
Invert	24.1		157	3,783.7	m³		$	126	$	476,746
Arch	5.4		157	847.8	m³	30cm thick	$	126	$	106,823
Material Cost- Concourse Tunnel										**$ 2,618,448**

MATERIAL COST UTILITY TUNNELS	**Area [m²]**	**Distance [m]**	**Tunnel length [m]**	**Total**		**Comment**	**Unit rate**	**Total**
Excavation								
Total area	46.9		104	4,890.7	m³		$ 60	$ 293,444
Lattice girder								
Around profile		24.8	104	1,724.1	m	1 element every 1.5m	$ 51	$ 87,929
Temp. sidewall (1)		7.2	104	500.5	m	1 element every 1.5m	$ 51	$ 25,528
Wire mesh								
Around profile		24.8	104	5,172.3	m²	two layers	$ 5	$ 26,379
Temp. sidewall		7.2	104	750.8	m²	one layer	$ 5	$ 3,829
Temp. invert		9.1	104	948.9	m²	one layer	$ 5	$ 4,840
Initial shotcrete lining								
Around profile	8.5		104	886.4	m³	36cm thick	$ 180	$ 159,548
Temp. sidewall (1)	1.6		104	166.8	m³	25cm thick	$ 180	$ 30,033
Temp. inverts (2)	0.8		104	83.4	m³	10cm thick, at top heading	$ 180	$ 15,016
Face (total)	46.9		104	163.0	m³	5cm thick, 1.5m advance rate	$ 180	$ 29,344
Rebar spiles			104	2,919.8	ea	42 pc. per round	$ 13	$ 37,374
Waterproofing								
Around profile		22.6	104	2,356.7	m²		$ 20	$ 47,135
Final lining (inc. 40kg/m³ reinforc.)								
Invert	5.0		104	521.4	m³		$ 126	$ 65,696
Arch	4.6		104	479.7	m³	30cm thick	$ 126	$ 60,441
Material Cost - Utility Tunnels								**$ 886,535**

MATERIAL COST CROSS ADITS	Area [m²]	Distance [m]	Tunnel length [m]	Total		Comment	Unit rate		Total	
Excavation										
Total area	48.0		165	7,917.1	m³		$	60	$	475,027
Lattice girder										
Around profile		24.8	165	2,727.0	m	1 element every 1.5m	$	51	$	139,077
Temp. sidewall (1)		7.4	165	813.7	m	1 element every 1.5m	$	51	$	41,499
Wire mesh										
Around profile		24.8	165	8,181.0	m²	two layers	$	5	$	41,723
Temp. sidewall		7.4	165	1,220.6	m²	one layer	$	5	$	6,225
Temp. invert		9.4	165	1,550.4	m²	one layer	$	5	$	7,907
Initial shotcrete lining										
Around profile	8.6		165	1,418.5	m³	36cm thick	$	180	$	255,327
Temp. sidewall (1)	1.6		165	263.9	m³	36cm thick	$	180	$	47,503
Temp. inverts (2)	0.9		165	148.4	m³	36cm thick, at top heading	$	180	$	26,720
Face (total)	48.0		165	263.9	m³	5cm thick, 1.5m advance rate	$	180	$	47,503
Rebar spiles			165	4,618.3	ea	42 pc. per round	$	13	$	59,114
Waterproofing										
Around profile		22.5	165	3,711.2	m²		$	20	$	74,223
Final lining (inc. 40kg/m³ reinforc.)										
Invert	6.1		92	563.0	m³	Concourse Level only	$	126	$	70,942
Arch	4.6		92	424.6	m³	30cm thick, Conc. Lev. only	$	126	$	53,497
Backfill	48.0		22	1,032.0	m³	Platform Level to shafts	$	25	$	25,800
Material Cost - Cross Adits									**$**	**1,372,088**

MATERIAL COST SHAFTS	**Area [m²]**	**Distance [m]**	**Shaft depth [m]**	**Total**		**Comment**	**Unit rate**		**Total**	
Excavation										
Total area	139.3		40	5,572.0	m^3		$	60	$	334,320
Wire mesh										
Around profile		41.8	40	3,344.0	m^2	two layers	$	5	$	17,054
Initial shotcrete lining										
Around profile	14.6		40	584.0	m^3	36cm thick	$	180	$	105,120
Waterproofing										
Around profile		39.6	40	1,584.0	m^2		$	20	$	31,680
Final lining (inc. 40kg/m³ reinforc.)										
Arch	11.6		40	464.0	m^3	30cm thick	$	126	$	58,464
Backfill	139.3		20	2,786.0	m^3	Platform Level to shafts	$	25	$	69,650
Material Cost - Access Shafts									**$**	**616,288**

MATERIAL COST PLATFORM TUNNEL	**Area [m²]**	**Distance [m]**	**Tunnel length [m]**	**Total**		**Comment**	**Unit rate**		**Total**	
Excavation										
Total area	99.7		119.0	11,869.1	m³		$	60	$	712,144
Lattice girder										
Around profile		36.9	119.0	4,389.9	m	1 element every 1m	$	51	$	223,885
Temp. sidewalls (2)		17.5	119.0	2,077.7	m	1 element every 1m	$	51	$	105,965
Wire mesh										
Around profile		36.9	119.0	8,779.8	m²	two layers	$	5.1	$	44,777
Temp. sidewalls (2)		17.5	119.0	2,077.7	m²	one layer	$	5.1	$	10,596
Temp. inverts (3)		14.2	119.0	1,689.8	m²	one layer, at top headings	$	5.1	$	8,618
Initial shotcrete lining										
Around profile (total)	12.9		119.0	1,531.5	m³	36cm thick	$	180	$	275,675
Face (total)	99.7		119.0	593.5	m³	5cm thick, 1m advance rate	$	180	$	106,822
Temp. sidewalls (2)	4.3		119.0	516.5	m³	25cm thick	$	180	$	92,963
Temp. inverts (3)	1.3		119.0	154.7	m³	10cm thick, at top heading	$	180	$	27,846
Rebar spiles			119.0	7,021.0	ea	59 pc. per round	$	13	$	89,869
Waterproofing										
Top and bottom		22.7	119.0	2,696.5	m²		$	20	$	53,931
Final lining (inc. 40kg/m³ reinforc.)										
Invert	13.5		119.0	1,602.9	m³		$	126	$	201,969
Arch	5.8		119.0	693.8	m³		$	126	$	87,415
Walls (2)	2.8		59.5	166.6	m³	50% wall area	$	126	$	20,992
Material Cost Platform Tunnel									**$**	**2,063,466**

MATERIAL COST STATION TUNNELS	Area [m²]	Distance [m]	Tunnel length [m]	Total		Comment	Unit rate		Total	
Excavation										
Total area	38.2		238.0	9,082.1	m³		$	60	$	544,925
Lattice girder										
Around profile		18.4	238.0	2,189.6	m	1 element every 2m	$	51	$	111,670
Wire mesh										
Around profile		18.4	238.0	8,758.4	m²	two layers	$	5.1	$	44,668
Temp. invert		5.7	238.0	1,356.6	m²	one layer	$	5.1	$	6,919
Initial shotcrete lining										
Around profile	6.3		238.0	1,494.6	m³	36cm thick	$	180	$	269,035
Temp. invert	0.5		238.0	119.0	m³	10cm thick	$	180	$	21,420
Face (total)	38.2		238.0	227.1	m³	5cm thick, 2m advance rate	$	180	$	40,869
Rebar spiles			238.0	2,618.0	ea	22 pc. per round	$	13	$	33,510
Waterproofing										
Around profile		17.3	238.0	4,119.8	m²		$	20	$	82,396
Final lining (inc. 40kg/m³ reinforc.)										
Invert	4.8		238.0	1,135.3	m³		$	126	$	143,043
Arch	3.3		238.0	773.5	m³	30cm thick	$	126	$	97,461
Material Cost - Station Tunnels									**$**	**1,395,915**

MATERIAL COST CONNECTOR TUNNELS	**Area [m²]**	**Distance [m]**	**Tunnel length [m]**	**Total**	**Comment**	**Unit rate**	**Total**
Excavation							
Total area	51.6		114.0	5,882.4 m³		$ 60	$ 352,944
Lattice girder							
Around profile		25.5	114.0	1,938.0 m	1 element every 1.5m	$ 51	$ 98,838
Temp. sidewall (1)		8.4	114.0	638.4 m	1 element every 1.5m	$ 51	$ 32,558
Wire mesh							
Around profile		25.5	114.0	5,814.0 m²	two layers	$ 5.1	$ 29,651
Temp. sidewall (1)		8.4	114.0	957.6 m²	one layer	$ 5.1	$ 4,884
Temp. inverts (2)		8.4	114.0	957.6 m²	one layer, at top headings	$ 5.1	$ 4,884
Initial shotcrete lining							
Around profile	8.7		114.0	991.8 m³	36cm thick	$ 180	$ 178,524
Temp. sidewall (1)	1.9		114.0	214.3 m³	25cm thick	$ 180	$ 38,578
Temp. inverts (2)	0.7		114.0	83.2 m³	10cm thick	$ 180	$ 14,980
Face (total)	51.6		114.0	196.1 m³	5cm thick, 1.5m advance rate	$ 180	$ 35,294
Rebar spiles			114.0	2,508.0 ea	33 pc. per round	$ 13	$ 32,102
Waterproofing							
Around profile		23.6	114.0	2,690.4 m²		$ 20	$ 53,808
Final lining (inc. 40kg/m³ reinforc.)							
Invert	4.6		114.0	524.4 m³		$ 126	$ 66,074
Arch	4.9		114.0	558.6 m³	30cm thick	$ 126	$ 70,384
Material Cost - Connector Tunnels							**$ 1,013,503**

Table A.10: Daily Labor Cost, Alternative 3 (NATM)

LABOR COST

EXAVATION AND SUPPORT UNIT	AMOUNT	UNIT	UNIT RATE		COST
Foreman	1	pers.			
Operator	2	pers.			
Miner	3	pers.			
Total	6	pers.			
Total hourly cost per unit		hr	$	40	**$ 240**
Daily worktime per unit		hr		11	
Daily cost per unit		day			$ 2,640
Units per day		day		2	
Total cost per day		day			**$ 5,280**

WATERPROOFING AND FINAL LINING UNIT	AMOUNT	UNIT	UNIT RATE		COST
CONCRETING					
Foreman	1	pers.			
Operator	2	pers.			
Laborer	4	pers.			
INSTALLATION OF REINFORCEMENT		pers.			
Foreman	1	pers.			
Laborer	6	pers.			
Total	14	pers.			
Total hourly cost per unit		hr	$	40	**$ 560**
Daily worktime per unit		hr		11	
Daily cost per unit		day			$ 6,160
Units per day		day		2	
Total cost per day		day			**$ 12,320**

SURFACE WORKERS	AMOUNT	UNIT	UNIT RATE		COST
DAY					
Crane operator	2	pers.			
Mechanics	2	pers.			
Electricians	1	pers.			
Helpers	3	pers.			
Total	8	pers.			
Total hourly cost per unit		hr	$	40	$ 320
Daily worktime		hr		11	
Daily cost		day			**$ 3,520**

NIGHT						
Crane operator	1	pers.				
Mechanics	2	pers.				
Electricians	1	pers.				
Total	4	pers.				
Total hourly cost per unit		hr	$	40	$	160
Daily worktime		hr		11		
Nightly cost		day			**$**	**1,760**
Total cost per day		day			**$**	**5,280**

BACKFILL UNIT CROSS ADITS	**AMOUNT**	**UNIT**	**UNIT RATE**			**COST**
Foreman	1	pers.				
Operator	1	pers.				
Helpers	3	pers.				
Total	5	pers.				
Total hourly cost per unit		hr	$	40	$	200
Daily worktime		hr		11		
Total cost per day		day			**$**	**2,200**

BACKFILL UNIT SHAFTS	**AMOUNT**	**UNIT**	**UNIT RATE**			**COST**
Foreman	1	pers.				
Operator	2	pers.				
Helpers	2	pers.				
Total	5	pers.				
Total hourly cost per unit		hr	$	40	$	200
Daily worktime		hr		11		
Total cost per day		day			**$**	**2,200**

CONCRETE WORK UNIT SHAFTS	**AMOUNT**	**UNIT**	**UNIT RATE**			**COST**
CONCRETING						
Foreman	1	pers.				
Laborer	5	pers.				
INSTALLATION OF REINFORCEMENT		pers.				
Foreman	1	pers.				
Laborer	7	pers.				
Total	14	pers.				
Total hourly cost per unit		hr	$	40	**$**	**560**
Daily worktime per unit		hr		11		
Daily cost per unit		day			$	6,160
Units per day		day		1		
Total cost per day		day			**$**	**6,160**

Table A.11: Daily Equipment Cost, Alternative 3 (NATM)

EQUIPMENT COST

EQUIPMENT FOR EACH EXCAVATION UNIT	AMOUNT	UNIT	UNIT RATE		COST	
Tunneling excavator	1	wk	$	3,290	$	3,290
Drill rig	1	wk	$	2,490	$	2,490
Loader	1	wk	$	4,010	$	4,010
Concrete pump	1	wk	$	650	$	650
Total cost per week		wk			$	10,440
Working days per week		wk		7		
Total cost per day		day			**$**	**1,491**

EQUIPMENT FOR EACH FINAL LINING UNIT	AMOUNT	UNIT	UNIT RATE		COST	
Loader	1	wk	$	4,010	$	4,010
Concrete pump	1	wk	$	650	$	650
Total cost per week		wk			$	4,660
Working days per week		wk		7		
Total cost per day		day			**$**	**666**

ADDITIONAL EQUIPMENT	AMOUNT	UNIT	UNIT RATE		COST	
Crane	2	wk	$	1,140	$	2,280
Tunnel lighting	1	wk	$	100	$	100
Tunnel ventilation system	1	wk	$	90	$	90
Compressor	2	wk	$	950	$	1,900
Total cost per week		wk			$	2,380
Working days per week		wk		7		
Total cost per day		day			**$**	**340**

EQUIPMENT FOR BACKFILLING CROSS ADITS	AMOUNT	UNIT	UNIT RATE		COST	
Loader	1	wk	$	4,010	$	4,010
Crane	1	wk	$	1,140	$	1,140
Total cost per week		wk			$	5,150
Working days per week		wk		7		
Total cost per day		day			**$**	**736**

EQUIPMENT FOR BACKFILLING SHAFTS	AMOUNT	UNIT	UNIT RATE		COST	
Loader	1	wk	$	4,010	$	4,010
Roller, diesel, 8 to 12 ton	1	wk	$	670	$	670
Crane	1	wk	$	1,140	$	1,140
Total cost per week		wk			$	5,820
Working days per week		wk		5		
Total cost per day		day			**$**	**1,164**

EQUIPMENT FOR CONCRETE WORK SHAFTS	AMOUNT	UNIT	UNIT RATE		COST	
Crane	1	wk	$	1,140	$	1,140
Concrete pump	1	wk	$	650	$	650
Total cost per week		wk			$	1,790
Working days per week		wk		5		
Total cost per day		day			**$**	**358**

Table A.12: Cost Estimate, Alternative 3 (NATM)

COST ESTIMATE - NATM STATION (ALTERNATIVE 3)

MATERIAL	Length [m]	Cost/m	Cost total
Concourse Tunnel	157	$ 16,678	$ 2,618,448
Utility Tunnel	104	$ 8,501	$ 886,535
Cross Adit	165	$ 8,319	$ 1,372,088
Access Shafts	40	$ 15,407	$ 616,288
Platform Tunnel	119	$ 17,340	$ 2,063,466
Station Tunnel	238	$ 5,865	$ 1,395,915
Connector Tunnel	114	$ 8,890	$ 1,013,503
TOTAL COST FOR MATERIAL			**$ 9,966,244**

LABOR	Duration [work days]	Cost per work day	Cost total
Excavation and Support	678	$ 5,280	$ 3,579,840
Waterproofing and Final Lining	356	$ 12,320	$ 4,385,920
Surface Workers	513	$ 5,280	$ 2,708,640
Backfilling Cross Adits	26	$ 2,200	$ 57,200
Backfilling Shafts	46	$ 2,200	$ 101,200
Concrete Work Shafts	128	$ 6,160	$ 788,480
TOTAL COST FOR LABOR			**$ 11,621,280**

EQUIPMENT			
WRITE-OFF	**Amount**	**Cost/each**	**Cost total**
Working Platform for Shaft		$ 100,000	
Number of platforms	2		
Total cost of platforms (write-off)			**$ 200,000**
Formwork			
Conc. T. / Utility T., Cross Adits, Station T.	3	$ 150,000	$ 450,000
Platform T., Connector T.	2	$ 60,000	$ 120,000
Total cost of formworks (write-off)			**$ 570,000**
Scaffolding		$ 20,000	
Write-off	80%	$ 16,000	
Number of scaffoldings	6		
Total cost of scaffolding (write-off)			**$ 96,000**

RENT	Duration [days]	Cost per work day	Cost total
Equipment for Excavation	678	$ 1,491	$ 1,011,189
Equipment for Final Lining	300	$ 666	$ 199,714
Additional Equipment	513	$ 340	$ 174,420
Equipment for Backfilling Cross Adits	26	$ 736	$ 19,129
Equipment for Backfilling Shafts	46	$ 1,164	$ 53,544
Equipment for Concrete Work Shafts	128	$ 358	$ 45,824
TOTAL COST FOR EQUIPMENT			**$ 2,369,819**

Net Construction Cost (Material, Labor, Equipment)		**$ 23,957,344**
Monitoring	2%	$ 479,147
Dewatering	2%	$ 479,147
Project Management		$ 1,000,000
Contingencies, e.g. worse ground conditions, additional work, etc.	10%	$ 2,395,734
TOTAL COST FOR NATM STATION		**$ 28,311,372**