MASTER THESIS

Shallow tunnels and caverns in urban areas

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Abstract

This master thesis is dealing with tunneling, more precisely with shallow tunneling and underground constructions, and the existing chances and problems especially occurring in urban areas.

Different cultures started to build tunnels in early years for different purposes. But nearly all had one in common, providing infrastructure and increasing life standard.
Tunnels can be used for a lot of purposes and are a vital part of modern civilization. Some purposes could be water and waste water transport, transportation like railroads, Highways, Subways or scientific usage like the CERN in Switzerland.

Tunneling became more important and a big topic all over the world in the last two centuries.
Therefore the reader will get an overview about the history of tunneling at whole and more precise in Europe as well as in North America. More specified the tunneling in Austria and the reason for its big Know How will be considered.

Shallow tunnels bring a lot of questions with them. Not just regarding managing the site and logistics, but also how to excavate the bores, how to stabilize the soil and which foundation works should be carried out. Due to the lack of space and the sensitive surroundings these problems are challenging the engineers and so they are improving their common methods and establishing new ones. The paper will point out these methods and find out what is state of the art today.

When talking about shallow tunnels in urban areas, you also have to mention caverns. Like shallow tunnels these are devices to solve the above mentioned problems in urban areas. May it concern the construction progress and process or the use as stations, their importance is significantly increasing. So a short overview about caverns, how to build them and how to use them in advantage will be given.

An important part of the paper is about how earthquakes are influencing a tunnel. This is an interesting topic because when talking about underground constructions, seismic design is practically not mentioned in Austria and in most parts of Europe. In contradiction to that, it is a big deal in California and a lot of places in the United States and North America. To illustrate how such seismic design could be applied to underground structures the most important equations will be given.

Many cities and governments are looking for alternative ways reducing traffic in highly populated areas. So current and future projects and plans will be considered and compared. Differences and similarities between Europe and the American way of tunneling, as far as they are consisting and decisive will be pointed out. These differences and similarities will consider newly invented methods and construction philosophies.

Keywords: tunnel, urban, shallow, comparison USA and Austria, construction methods, seismic design

Kurzfassung

Diese Diplomarbeit befasst sich mit den Besonderheiten im oberflächennahen Tunnelbau und Untertagekonstruktionen im urbanen Gebiet.

Der Tunnelbau hat eine lange Tradition und seine Geschichte geht zurück auf die verschiedensten Kulturen dieser Welt. Schon damals hatten sie den Zweck die Infrastruktur zu verbessern sowie für einen besseren Lebensstandard zu sorgen. Heutzutage sind Tunnel ein nicht mehr wegzudenkender Teil unseres täglichen Lebens. Sie werden für die verschiedensten Zwecke wie zum Beispiel zum Transport von Schmutz- und Frischwasser, als Einrichtungen zur Personenbeförderung jeglicher Art, für wissenschaftliche Einrichtungen oder auch zum Schutze sensibler Objekte genutzt.

Der Bau von oberflächennahe Tunneln, noch dazu in dicht besiedelten Gebieten, birgt einige Besonderheiten und Herausforderungen in sich. In vielen Fällen muss man mit eingeengten Platzverhältnissen welche zusätzlich von sensiblen Gebäuden umgeben sind zurechtkommen. Diese Bedingungen fordern sowohl die beteiligten Ingenieure als auch stätige Weiterentwicklungen sowie Innovationen in sämtlichen Bereichen des Tief-, Grund- und Tunnelbaus. Diese weiterentwickelten Methoden und Innovationen werden in dieser Arbeit herausgearbeitet und aufgezeigt.

Spricht man heutzutage über Tunnel in besiedelten Gebieten, sollte man auch Kavernen erwähnen. Diese können ebenso wie Tunnel einen erheblichen Beitrag in der Entwicklung von modernen Städten spielen, sei es als Knotenpunkt für den öffentlichen sowie privaten Verkehr, Raum für spezielle Zweige der Industrie oder auch als Teil der Baustelleneinrichtung um einen optimaleren Bauprozess zu ermöglichen.

In den letzten Jahrzehnten gewann der Tunnelbau quer über den Globus immer mehr an Bedeutung. Neben dem geschichtlichen Überblick, vor allem über Österreich und die Vereinigten Staaten, werden Gründe für die derzeitige Position der beiden Länder im Tunnelbau erläutert.

Ein weiterer Teil der Arbeit beschäftigt sich mit dem Thema Erdbeben und deren Auswirkungen auf Tunnel. Ist dies in unseren Breitengraden ein eher vernachlässigbares Thema, wird man in Kalifornien und anderen Teilen der Vereinigten Staaten sehr intensiv damit konfrontiert. Grundsätzliche Berechnungen werden angeführt und erläutert.

Es werden aktuelle und zukünftige Projekte betrachtet, um einzelne Themen besser erläutern und deren Wichtigkeit hervorzuheben zu können. Außerdem werden dadurch verschiedene Intentionen sichtbar, welche möglicherweise vorhandene Unterschiede der amerikanischen und europäischen Kultur im Tunnelbau aufzeigen.

Stichworte: Tunnel, urbaner Raum, oberflächennah, Vergleich USA mit Österreich, Baumethoden, Erdbebenberechnung

Declaration

"I declare that this paper is my own work and was written without literature other than the sources indicated in the bibliography. Information used from the published or unpublished work of others has been acknowledged in the text and has been explicitly referred to in the given list of references. This paper has not been submitted in any form for another degree or diploma at any university or other institute of tertiary education."

Acknowledgments

First of all I am truly indebted and thankful to my family and above all my parents who made my studies possible and supported me wherever possible, especially those times I went abroad.

I am grateful to the Construction Management Department of the Californian Polytechnic State University for accommodating me and providing me the chance to write this thesis in the United States, as well as making me feeling welcome and comfortable there from the first second on.
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I want to thank my former colleagues, Martin Zmölnig and Peter Herzog for imparting me a lot during my internship and providing me with information, ideas and suggestions for my thesis.

Furthermore I owe my deepest gratitude to Mike Mühlhauser and my brother Jürgen Sturm for helping me in so many ways and situations and being real friends.

Last but not least I am obliged to all the persons who I met and participated along my way and made me, and also this thesis, what it is today.

Table of contents

1 Background Information & Introduction

To understand the background and the purpose of this thesis, it has to be mentioned that this thesis was written on an intercultural basis involving Austria and the United States. The supervision was undertaken primary by the FH Joanneum Graz, University for Applied Sciences and secondary by the Construction Management Department of the California Polytechnic State University San Luis Obispo.

Several parts of the paper are comparing, dealing with and referencing to Europe and the United States as well as sometimes pointing out more precise content relating to Austria and the State of California.
To highlight the intercultural purpose of this thesis all specifications are given in North American as well as Austrian (European) standards. Indications are primarily stated in Austrian standards and subsequent the North American ones are listed in brackets.

The profession of tunneling is more than many other professions internationally very close related and connected. Many researches are carried out on an international basis and presented at international congresses with participating members from all over the world. Not just as a result of this fact the transfer of knowledge is quite encouraged.
Anyways differences are still occurring and will occur in the future. These differences are related to the environmental surroundings, the elementary requirements and the ethics and philosophies of different cultures and projects.

Regarding the development and importance of tunnels and underground structures Parker[1] is stating:

> • *Tunnels play a vital environmental role by conveying clean water to urban areas and by conveying wastewater out. Most major urban areas depend on tunnels for these services, which function with a minimum of maintenance. (Few people appreciate how water gets to their home: out of sight, out of mind.)*
>
> • *The usable space of a parcel of land can, in some cases, be almost be doubled by adding floor space or bulk storage below the ground surface. Life-cycle cost analysis may reveal the underground alternatives to be much more cost-effective.*
>
> • *It has been demonstrated by several recent events that tunnels behave very well in earthquakes. If urban planners want an important lifeline to survive earthquakes, they should go out of their way to use tunnels.*

[1] Parker, Harvey W.: Tunneling, Urbanization and Sustainable Development: The Infrastructure Connection. In: Tunnelling and Underground Space Technology Vol. 11 No. 2 (1996), pp. 133-134

• The underground is the only safe location for storage of nuclear waste and other hazardous or undesirable materials.

• In transit systems, tunnels provide safe, environmentally sound, very fast, and unobtrusive transportation for people in all walks of life in both developed and developing countries.

• Underground space is being used increasingly for industrial, office and even residential facilities.

• Underground space for bulk storage of food, liquids, and gas has gained increasing acceptance in various areas of the world.

• Congestion in urban areas has been dramatically reduced by use of the underground.

This gives a good overview about purposes of tunnels and underground constructions and how they can influence our life in a positive way.

1.1 Key Figures USA & Austria

To demonstrate and understand the importance of tunnels, especially in urban areas, as well as being able providing proper conclusions it is important to know some background information.

1.1.1 Demographical Data

One attempt to compare the basic differences between two or more countries is to compare their demographical data. In the following paragraphs the demographical data of Austria and the United States, emphasizing California, are given.
As long as no other source is stated, the statistical data are provided by Wikipedia[2].

1.1.1.1 Austria

- Area: 83.871 km² (32.383 sq mi)
- Inhabitants: 8,356 Mio
- Density: 99 / m² (257 / sq mi)
- Mean elevation: 910 m (2986 ft)[3]

[2] Wikipedia, the free encyclopedia: http://en.wikipedia.org/ (September 2009)
[3] Food and Agriculture Organization of the United Nations: http://www.fao.org/forestry/country/18310/en/aut/ (September 2010)

- Three biggest Metropolitan areas:
  Vienna: 1,98 Mio people
  Graz: 255.000 people
  Linz: 280.000 people

1.1.1.2 United States

- Area: 9.826.675 km² (3.794.101 sq mi)

- Inhabitants: 310,314 Mio

- Density: 32 / m² (83 / sq mi)

- Mean elevation: 762 m (2500 ft)[4]

- Three biggest Metropolitan Areas (2000 Census[5]):
  New York (Northern New Jersey, Long Island): 21.199.865 people
  Los Angeles (Riverside, Orange County): 16.373.645 people
  Chicago (Gary, Kenosha): 9.157.540 people

1.1.1.3 California

- Area: 423.970 km² (163.696 sq mi)

- Inhabitants: 36,962 Mio.

- Density: 90.5 / km² (234 / sq mi)

- Mean elevation: 884 m (2.900 ft)

- Three biggest Metropolitan areas (2000 Census[6]):
  Los Angeles (Riverside, Orange County): 16.373.645 people
  San Francisco (Oakland, San Jose): 7.039.362 people

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[4] Infoplease: Encyclopedia: http://www.infoplease.com/ipa/A0001792.html (September 2010)
[5] U.S. Census Bureau American Fact Finder: http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=%200%201000US&-_box_head_nbr=GCT-PH1-R&-ds_name=DEC_2000_SF1_U&-format=US-10S (September 2010)
[6] U.S. Census Bureau American Fact Finder: http://www.census.gov/population/www/cen2000/briefs/phc-t3/tables/tab03.txt (September 2010)

San Diego: 2.813.833 people

1.1.2 Infrastructural Data

1.1.2.1 Austria

- Highways[7]: 2178 km (1353 mi)

- Highway Tunnels[8]: 142 Tunnels
  Total length: 331 km (206 mi) and 130 km (81 mi) in planning

- Railroads[9]: 5650 km (3519 mi)

- Railroad Tunnels[10/11]: 280 (47 in construction)
  Total length: 173 km (107 mi) and 293 km (182 mi) in construction

1.1.2.2 USA

- Highways: 350.180 km (217.592 mi) (including rural and urban principal arterial roads)
  93.480 km (58.086 mi)[12] (excluding rural and urban principal arterial roads)

- Highway Tunnels[13]: 366 Tunnel

- Railroads[14]: +257.495 km (+160.000 mi)

- Railroad Tunnels: No exact data available

1.1.2.3 California

- Highways[15]: 22.502 km (13.982 mi) (including rural and urban principal arterial roads)
  6.432 km (3.997 mi) (excluding rural and urban principal arterial roads)

- Highway Tunnels: 61[16] Tunnel / 29 Tunnel[17]

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[7] Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft: http://www.asfinag.at (September 2010)
[8] Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft: http://www.asfinag.at (September 2010)
[9] ÖBB-Holding AG: Geschäftsbericht 2009. Wien: ÖBB-Holding AG
[10] ÖBB-Holding AG: Geschäftsbericht 2009
[11] Eisenbahn-Tunnel in Österreich: http://www.eisenbahntunnel.at (September 2010)
[12] Federal Highway Administration: https://international.fhwa.dot.gov/policyinformation/statistics/2008/ (September 2010)
[13] Federal Highway Administration: http://www.fhwa.dot.gov/bridge/tunnel/management/summary.cfm (September 2010)
[14] The American Railroads: http://www.american-rails.com/railroad-history.html (September 2010)
[15] Federal Highway Administration: https://international.fhwa.dot.gov/policyinformation/statistics/2008/ (September 2010)

- Railroads[18]: 9320 km (5791 mi)

- Railroad Tunnels: No exact data available

1.1.3 Urban Transportation Networks

Metropolitan Regions and their transportation network (As long as no other source is stated, data is provided by urbanrail.net[19]):

Region	Total Network [km (mi)]	Underground [km (mi)]	Underground Ratio [%]
Austria			
Vienna[20]	70 (43,5)	35 (22)	50
Total	**70 (43,5)**	**35 (22)**	**50**

Table 1: Metropolitan Regions in Austria and their transportation network

Region	Total Network [km (mi)]	Underground [km (mi)]	Underground Ratio [%]
USA			
New York	337 (234)	223 (138,5)	66
Washington	171 (106)	85 (53)	50
San Francisco (Bay Area)[21]	167 (104)	60 (37)	36
Chicago	137 (85)	18 (11)	13
Los Angeles	127 (79)	32 (20)	25
Boston	101 (63)	28 (17,5)	28
Philadelphia	89 (55,5)	33 (20,5)	37
Atlanta	81 (50,5)	14 (9)	17
Baltimore	25 (15,5)	10 (6)	40
Seattle	25 (15,5)	7 (4,5)	28
Buffalo	10,5 (6,5)	9 (5,5)	85
Total	**1270,5 (789,5)**	**519 (322,5)**	**41**

Table 2: Metropolitan Regions in the US and their transportation network

1.1.4 Data Analysis

When comparing the two countries of Austria and USA there are huge differences. As the size of the United States is 117 times bigger than Austria there are just 37 times more inhabitants, which means a three times higher density in Austria than in the US. The size of California is five times bigger than those of Austria, while the population density is nearly the same. Also regarding the mean elevation,

[16] Federal Highway Administration: http://www.fhwa.dot.gov/bridge/tunnel/management/summary.cfm (September 2010)
[17] Federal Highway Administration: https://international.fhwa.dot.gov/bridge/nbi/strtyp09.cfm (September 2010)
[18] The American Railroads: http://www.american-rails.com/california-railroads.html (September 2010)
[19] urbanrail.net > metro – subway – light rail: http://urbanrail.net/index.html (September 2010)
[20] The Vienna Metro: http://homepage.univie.ac.at/horst.prillinger/metro/english/index.html (September 2010)
[21] Bay Area Rapid Transit: http://www.bart.gov (September 2010)

California seems more comparable to Austria. While those of Austria is 910 m (2986 ft), those of California is 884 m (2900 ft) and those of the whole US is 762 m (2500 ft).
This could lead to the assumption that Austria and California are also comparable regarding the infrastructure, but the big differences in the geography of the countries are detaining that. California has a lot of elevations but, compared to its size, not that many high alpine mountains. In addition to that, most times the landscape provides enough space to bypass the existing hills and mountainous areas. In Austria therefore 60% of the country are mountainous and only 32% are lower than 500 m (1640 ft). Due to the many narrow valleys there are often no other option than going through a mountain.

When taking a look at the numbers of tunnels, there are a total of 142 highway tunnels and about 280 railroad tunnels in Austria. Regarding highway tunnels this means a 2,3 higher amount than in California and still more than a third than in the whole United States. This data should also take into relation the total amount of Highway miles. Including the principal arterial roads, the US Highway system consists of 350.180 km (217.592 mi) which means 160 times more than Austria. The comparison with California shows that there are 10 times more highways.
Sadly there are no reliable data about Railway tunnels, although a report is saying that there are about 800 over whole the United States. Other sources are stating that there are just 80 proper railroad tunnels throughout the US and about 30 in California.

As the United States just have a small amount of highway and railroad tunnels another big part of going underground are the urban transportation networks. While in Austria just Vienna has a metro system operating underground there are about almost 15 cities in the US. The total amount of kilometers of underground constructions is more than 520 (323 mi). The interesting thing about these numbers is that it is not possible to get any clues out of it regarding the philosophy of building such systems. If taking a look to the three biggest Metropolitan areas of the US and California, 66% of New York's Metro is underground, just 25% of Los Angeles's Metro, 13% of Chicago's Metro and 36% of San Francisco's Metro are beneath the surface. San Diego as the third biggest Metropolitan Area in California has no urban transportation system beneath the ground. Washington should be mentioned here, because it has about 50% of its system underground. This shows a big difference between the cities and over the country. Very interesting seems the fact that all of these cities and areas are much bigger than Vienna (1,4 to more than 11 times) which has about 50% underground structures and as mentioned later on in this paper a city with more than 1 million inhabitants justify a underground transportation system.

1.2 Geotechnical Basics

When dealing with tunneling and underground constructions you are automatically dealing with ground interactions and therefore with geotechnical and soil mechanical issues. This chapter is giving a basic understanding of what ground is and other important information about it.

1.2.1 Definitons

- Ground

"Part of the earth's crust, composed of rock and/or soil, frequently with anisotropic properties, including discontinuities, and voids filled with liquids or gases." [22]

- Rock

Rock means that the ground is a coherent discontinuum.
It is an *"Aggregate, consisting of mineral components, developed from natural processes, characterized by the types and amount of the minerals and grain structure" or a*
"Mineral aggregate, whose properties predominantly are determined by the physical/chemical bond."[23]

Rock is described by the following characteristics and parameters according to Eurocode 7[24]:

- Mineralogy
- Petrography
- Weight density
- Porosity
- Water content
- Swelling
- Uniaxial compressive strength

- Soil

Soil means that the ground is a not coherent continuum, it is consisting of particle or grains.
It is an *"Accumulation of anorganic solid varigrained particels with occasional organic admixtures. The properties are predominately governed by the granulometric composition, the compaction, and the water content."*[25]

[22] Austrian Society for Geomechanics: Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation. Salzburg: ÖGG 2010
[23] Austrian Society for Geomechanics: Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation.
[24] Österreichisches Normungsinstitut: Eurocode 7: Geotechnical design Part 1: General rules. Wien: Österreichisches Normungsinstitut 2006

Soil is described by the following characteristics and parameters according to Eurocode 7[26]:

- Grain size distribution
- Weight density
- Porosity
- Water content
- Density index
- Swelling
- Degree of compaction

- Rock mass

It is the composition of larger amounts of rock, including, and described by, structural discontinuities like shear zones and joints. Regarding joints the following characteristics are crucial and should be considered:[27]

- Spacing
- Orientation
- Persistence
- Aperture

- Shear strength [τ]

The shear strength gives the magnitude of the shear stress which the soil can withstand. It is a parallel or tangential stress. In soil the shear strength is based on the interlocking between particles. Parameters which are influencing the shear strength according to Eurocode 7[28]:

- The stress level imposed on the soil
- Anisotropy of strength, especially in clays of low plasticity
- Fissures, especially in stiff clays
- Strain rate effects
- Very large strains where these may occur in a design situation
- Pre-formed slip surfaces
- Time effects
- Sensitivity in cohesive soil
- Degree of saturation

[25] Austrian Society for Geomechanics: Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation.
[26] Österreichisches Normungsinstitut: Eurocode 7: Geotechnical design Part 1: General rules.
[27] Österreichisches Normungsinstitut: ÖNORM B 2203-1 Untertagebauarbeiten – Werkvertragsnorm Teil 1: Zyklischer Vortrieb. Wien: Österreichisches Normungsinstitut 2001
[28] Österreichisches Normungsinstitut: Eurocode 7: Geotechnical design Part 1: General rules.

1.2.2 Soil Classes

- Soil classes[29]

The triangle below shows the classification of soil depending on its proportional parts of the different soil types.

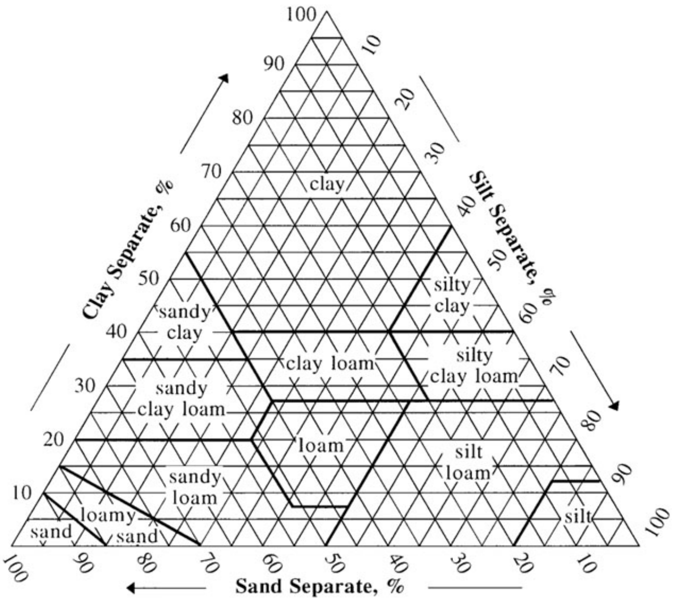

Figure 1: Classification of soil

The following table shows the classification of soil types regarding their particle size and different North American systems as well:

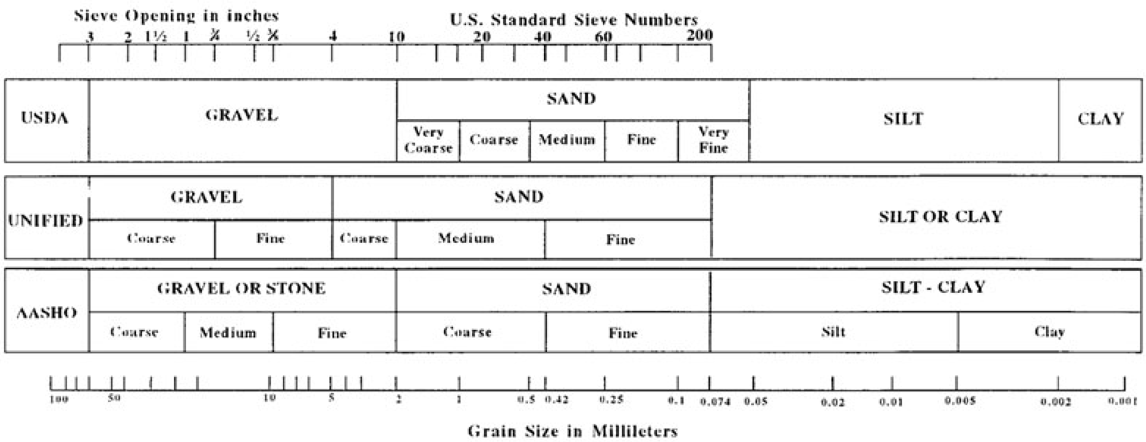

Table 3: Classification of soil

USDA … United States Department of Agriculture

UNIFIED … Unified Soil Classification System (Most common in North America)

AASHO … American Association of State Highway and Transportation Officials

[29] United States Department of Agriculture: http://soils.usda.gov/technical/handbook/images/Part618Exhibit8_hi.jpg (September 2010)

1.3 Tunneling Basics

1.3.1 General

Tunneling is one of the most exciting professions in the field of construction engineering and construction management. Every project is unique, rather be every round length is unique.
For almost no other type of construction the predictions and the foreseeing of the advancement is so difficult.

There is a long history in tunneling and mining and it all started thousands of years ago. Engineers and miners developed and used quite impressive methods and technologies at those times.
But progress in tunneling didn't continue that way, over a lot of centuries miners only exploited resources but almost no progress in tunneling was made.
Due to the industrial revolution a huge step in technical improvements was made and had led to an increase of knowledge in tunneling. The most inventions in tunneling were made over the last two centuries.
Tunnels became a lifeline of cities and society and are in direct interaction with the rise of the Metropolises and contrariwise. In the year 2000 already 21 cities have grown to so called megacities with a population of more than 10.000.000 people.[30]

When talking about underground construction there are some specific terms and meanings. While in some cases the German language provides exact terms for different underground constructions or its purposes, the English terms can be used for a broader or different range of meaning. The same problem can occur vice versa.
Therefore the attempt to work out proper and exact translations for providing a list of words with exactly the same signification failed.
An example is the German word 'Tunnel', which is nowadays defined as a horizontal underground structure for the purpose of railroad, automobile or pedestrian traffic with two portals. So this is a quite clear definition. In English the word tunnel just stands for *"an essentially horizontal underground passageway"* So that also includes waste water and other non-human traffic or it could also be an adit.
At this point is has to be mentioned that the word tunnel was inherited in the 18th century from the English language and over the decades many different definitions emerged, till todays definition, still not agreeing with everyone's opinion, was established.[31]

[30] Parker: Tunneling, Urbanization and Sustainable Development: The Infrastructure Connection.
[31] Grewe, Klaus: Licht am Ende des Tunnels - Planung und Trassierung im antiken Tunnelbau. Mainz am Rhein: von Zabern 1998

1.3.2 Types of Tunneling

There are not just many ways of using a tunnel, but also many ways to construct them as well as to differentiate them. The following table gives a quick overview.

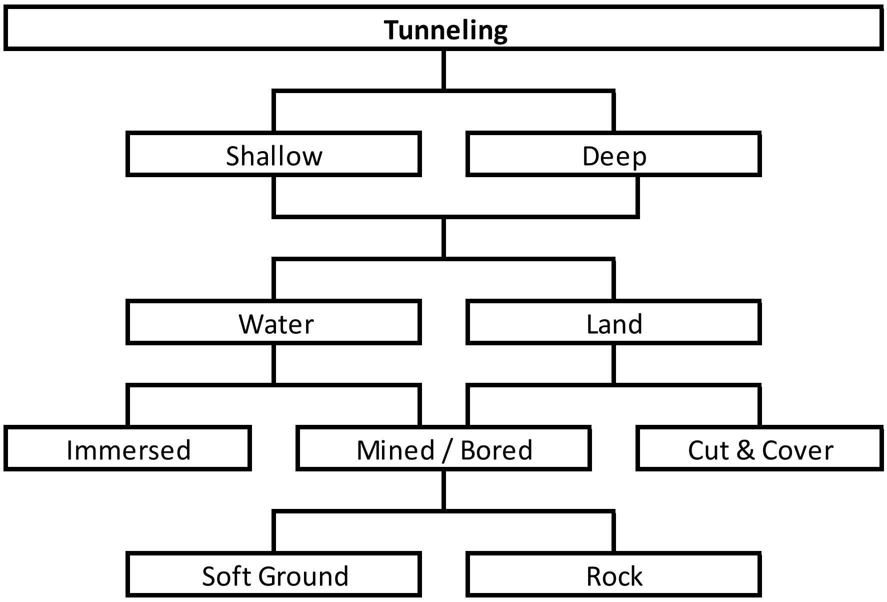

Table 4: Types of Tunnels

1.3.2.1 Divided into Site

- Shallow Tunnel

There is no standartized or official definition, stating where the line between a shallow and a deep-set tunnel is.

A few thoughts about shallow tunnels have a quite similar outcome. One of these outcomes is that a shallow tunnel has to carry all the loads from the ground above. This is closely related to the idea that shallow tunnels are built above bedrock and therefore can't use the ground as a structural element. Another thought is that as long as a tunnel is directly influencing the surface, and the objects above the surface it is a shallow tunnel. This brings us back to the statement, that the artificial structure has to carry all the loads from above.[32/33]

- Deep-Set Tunnel

Opposed to the shallow tunnels, deep-set tunnels do not directly interfere with the surface. Normally the rock stresses are just influencing the surroundings of the bore in a proper way. The nearer to the

[32] Britannica - The Online Encyclopedia: http://www.britannica.com/ (September 2010)
[33] Leca, Eric / New, Barry: ITA/AITES Report 2006 on Settlements induced by tunneling in Soft Ground. In Tunnelling and Underground Space Technology 22 (2007), pp.119–149

surface the stresses are measured the more they are decreasing. Since this is a general attempt of defining a deep set tunnel, it may not be correct in every case.

1.3.2.2 Divided into Construction Method

- Immersed Tunnel

Immersed tunnels are built beneath water and exist of precast tunnel segments which are mostly made of reinforced concrete and sometimes steel. These segments are produced in a dry dock which then are shipped or floated to their designated location. Once they arrive, every segment gets immersed and placed in an excavated trench. When placed, they get connected and sealed to the already immersed segments. These steps continue till all segments are connected to a whole tunnel.

- Mined / Bored Tunnel

A mined tunnel is a bore or a tube which is totally excavated beneath the surface. There are one or more portals, shafts or caverns where the excavation starts from. Regarding the excavation there are many ways of proceeding. Excavation could for example be done by digging, blasting or boring. More about the construction methods can be found in *Chapter 3 - (Shallow) Tunneling Methods*.
Compared to Immersed and Cut and Cover tunnels, the bored or mined tunnels are the true types of tunnels which are in need of the classical mining techniques.

- Cut and Cover Tunnel

Cut and Cover means in a very simple way, that first a trench is excavated from the surface. When the ground is removed the “tunnel” is erected. One possibility is doing that by placing precasted elements or by constructing the tunnel-frame in-situ. The in-situ construction can be done using an tunnel-form-work or by erecting ordinary concrete walls and slabs. Once the tunnel structure is finished the remaining trench is refilled with soil, until the whole structure is covered and buried.

1.3.2.3 Divided in ground conditions:

Different ground conditions need different construction methods, geological investigations, surveillance methods and construction sequences. Therefore one of the most important points regarding tunneling is a very good knowledge about the ground. In terms of the ground conditions, there can be two mayor distinctions made.

- Soft Ground

Soft ground is defined by its “*mechanical properties, grain size distribution, density, mineral composition, parameters of the soil components, matrix parameters, water content and hydraulic properties”*[34]*.*

Tunneling in soft ground brings quite different problems and requirements than hard rock tunneling with it. In most cases the ground is not able to be structural part, and excavation rounds are need to kept short. Often shields are used to prevent the tunnel from collapsing.

- Hard Rock

Rock is defined by “*mechanical properties (intact rock - rock mass), discontinuity, characteristics and properties, rock type, rock- and rock mass conditions and hydraulic properties”*[35].

When tunneling in hard rock, the rock is used as a part of the structure. Normally quite less support measures need to be carried out and the open face area can be quite larger than in soft ground.

[34] Austrian Society for Geomechanics: Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation.

[35] Austrian Society for Geomechanics: Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation.

2 Historical Development and Inventions

The historical development of tunneling dates back thousands of years to ancient times. The first tunnels were used to connect caves and later on for irrigating the fields with so called qanates.

Although the disciplines of tunneling and mining are closely related since ancient times, there are some important distinctions.

Regarding tunneling, the underground construction itself is the purpose of the excavation, and the arising spoil is just a byproduct, often without use. The tube itself needs to be stable, safe and accessible for the designed use.

Whereas the main purpose of mining is to recover minerals. In this context the construction itself is just a necessity for the main goal, the recovery of the minerals and used for bringing worker to the material and the material out of the mine. That means normally less support and smaller cross sections. Anyway the work-steps needed to be carried out to reach both purposes are quite the same, just in a different way.

2.1 Timeline

2.1.1 Ancient Times[36/37]

The first underground constructions are dating back to 5000 BC in Malta and had the purpose to connect some caves. First mines date back to the 24th century BC in Norfolk / Great Britain[38]. In this Neolithic mine flint was exploited and used for weapons and tools.

The first historical known pedestrian tunnel dates back to the 22th century BC and was erected by the Babylonians beneath the Euphrates River. It was about 900 m (3000 ft) long.

Salomon, King of Israel started to build tunnels for water transport in Jerusalem about 1000 BC.

About 600 BC Nebuchadnezzar was building the first arched traffic tunnel. Its length was about 1 km (3280 ft) and the dimensions were about 3,6 to 4,7 m (11,8 to 15,4 ft). A historical innovation of this tunnel was the first proofed use of iron made tools.

Also about 600 BC the Eupalinos Tunnel was built in Samos. It had a length of about 1040 m (3400 ft) and was the second, historically proofed, tunnel which was dug from two portals.

[36] Svoboda, Willibald: Die geschichtliche Entwicklung des Tunnelbaus. [Dissertation, Graz: 1994]
[37] Britannica - The Online Encyclopedia (September 2010)
[38] West, Graham: Innovation and the rise of the tunneling industry. Cambridge: Cambridge University Press 1988.

The Pausilippo Tunnel near Naples was constructed in 36 BC. It was 1460 m (4800 ft) long, 7,6 m (25 ft) wide and 9,1 m (30 ft) high. The mayor invention regarding this tunnel was the introduction of proper surveying methods.
At another Roman Tunnel, the Lacus Fucinus built in 41 AD, 30.000 workers were digging about 10 years before completing the 6 km (3,5 mi) long tunnel.
A quite common method to crush the stone at this time was the so called Fire-Quenching, where the rock gets heated by fire, and suddenly quenched with water. Because of the arising stresses the rock crushs.
The Egypts, Greeks and Romans forced slaves, prisoners, prisoners of war and other outcasts to work in their mines and underground constructions. This led to a bad reputation of miners.
The middle European countries therefore employed freeman, which were more skilled and also had a lot more respect in the society. This is proofed by some historical diggings in Hallstatt, Austria where since 2500 BC salt was exploited. In this mines a lot more attention was paid to ventilation and safety measures.

2.1.2 Middle Ages[39]

During the middle ages from about 600 to 1500 there was nearly no progress in proper tunneling. At this time almost all underground constructions were used as mines.
A metal mining industry was arising in the area of South Germany, Austria, Czech, Slovakia and Hungary. There were some technical advances but no mayor innovations. The only change was the picture of the job miner.

2.1.3 Resurrection of Tunneling

After a period of inactivity in tunneling, the French renewed this profession in the 17th century. Why France is easily explained by the political situation, which were consisting of many quarrelling dynasties in most European countries. Just France was politically quite stable and allowed its engineers and scientists to develop and research without restrictions and political barriers. Out of this France began to build and establish a quite good infrastructure. The only nation at this time who could compete with the France and even had a better infrastructure was the Austrian-Hungary Empire.[40]

The most important tunnels constructed and inventions at this time have been:

[39] West: Innovation and the rise of the tunneling industry.
[40] Svoboda: Die geschichtliche Entwicklung des Tunnelbaus.

1627 Schemnitz (Slovakia): In the Schemnitz or Selmecbanya mines gunpowder was introduced. Although it was already tested in some German mines, Selmecbanya was the first mine using it properly to exploit the minerals.

1666 Canal du Midi (France): The Canal du Midi had a length of about 157 m (515 ft) and is supposed to be the first tunnel with mayor use of blasting gunpowder. It was also one of the first tunnels after centuries of stagnation.

1678 Malpas Tunnel (F): The Malpas Tunnel is also one of the first tunnels after time of stagnation. It was about 157 m (515 ft) long and at first build without lining. The cross-section with more than 8 m (26 ft) was also very impressive.

1761 Bridgewater Canal Tunnel (Great Britain): The Bridgewater Canal Tunnel was part of a canal system built for boat traffic shipping coal from the Worsley Mine to Manchester. It was the first modern tunnel in Great Britain.

1770 Tunnel de Gier (F): After the Malpas Tunnel was build, it took 90 years till another big and challenging tunnel project was started. It was the 522 m (1.700 ft) long Tunnel de Gier, part of the railroad track between St. Etienne and Lyon.

2.1.4 Industrial Age

1803 Canal of St. Quentin (F): The Tunnel of Tronquoy as part of the Canal of St. Quentin was a big step into modern tunneling. It was one of the first tunnels with a diameter of about eight meter (26 ft) in squeezing rock. The engineers decided to excavate the tunnel profile in multiple sections. So a separate lining in each of the sections was possible which reduced the stresses. Once all lining works were finished the core of the tunnel was removed safely.
This tunnel was the beginning of a new age in tunneling, because it was the first tunnel using proper engineering principles.

1824 Tunnel of Pouilly (F): The Tunnel of Pouilly is another important tunnel in France which was also built using the above mentioned Core-Method.

1825 Wapping-Rotherhithe Tunnel (GB): The Wapping-Rotherhithe Tunnel was the first tunnel using a tunnel shield, developed by Bruce, and his son Isambard, Brunel. The tunnel was built under the River Thames and became the first subaqueous tunnel. Because of several floodings the work stoped for several years. In 1841, after a construction time of nine years, the 365 m (1.200 ft) long tunnel was finally finished.[41]

1831 Staple Bend Tunnel (USA): The Staple Bend Tunnel was part of the Allegheny Portage Railroad System and the first railroad tunnel in the United States. Its length was about 275 m (901 ft) and the height was about 5,8 m (19 ft).[42]

1836 / 1837 (Germany): The first and second Railroad tunnels in Germany were constructed.

1839 Gumpoldskirchen (Austria): Near Gumpoldskirchen the first railroad tunnel in Austria was built as a part of the railway line between Vienna and Trieste.

1840 Woodhead Tunnel (GB): The Woodhead Tunnel was part of the railroad line between Sheffield and Manchester. With its length of about 4.840 m (3 mi) it was one of the longest railroad tunnels at this time.

1849 Semmering Tunnel (A): It was about 1400 m (4600 ft) long. More than 1200 men were working at this tunnel, which was part of the first European mountain standard railway.

1855 Hoosac Tunnel (USA)[43]: The Hoosac Tunnel was part of the canal system between Boston and Albany and about 7,3 km (4,5 mi) long. It took about 22 years to construct the 6,4 m (21 ft) high and 7,3 m (24 ft) wide bore. It was the first time dynamite and electric firing explosives were used in tunneling. Another big impact for the whole construction industry was the invention and use of power drills with air, which gave the impulse for the development of the whole compressed air technology.

1857 Mount Cenis (F): The Mount Cenis Tunnel near Frejus in the French Alps was the first tunnel forced by a mechanical tunneling machine. It took about 14 years to built this 13,7 km (8,5 mi) long tunnel and it is a milestone in tunneling. Innovations like rail mounted drills, hydraulic ram air compressors and more advanced boring technology were introduced, and led to much better forcing rates. Furthermore better methods of ventilation and surveying were used. Another novelty was the construction of houses and camps for the miners, including housing for their families, schools and hospitals.

[41] Britannica - The Online Encyclopedia
[42] Citizendium: http://en.citizendium.org/ (September / October 2010)
[43] The Hoosac Tunnel: http://www.hoosactunnel.net/ (September 2010)

1872 St. Gotthard (Swiss): The St. Gotthard is a 15 km (9 mi) long railway tunnel through the Swiss Alps. About 3.000 workers needed about seven and a half year to finish the tunnel. The tunnel was one of the most impressive constructions at his time but also turned the small villages at the portals into worker-towns with awful living conditions. The Gotthard is probably one of the most famous tunnels.

1880 Hudson Tunnel (USA): The Hudson Tunnel was the first attempt to force a tunnel with just compressed air. After mayor fatalities the project was stopped.

Second half of 19th century: London Subway (GB): At this time the city of London started to build the first underground railway system in the world. The amount of underground tubes continued steadily during the second half of the 19th century.

1898 Simplon Tunnel (CH): With its length of 19,3 km (12 mi) the Simplon Tunnel was the longest mountain tunnel for over 70 years. Like at the Gotthard tunnel the working conditions were pretty bad and a lot of workers died under the harmful conditions.

1901 Tauern Tunnel (A): Construction of the Tauern Railroad Tunnel with a length of 8550 m (5,3 mi)

1906 Loetschberg Tunnel (CH): The Loetschberg Tunnel is also located in the Swiss Alps. It is 14,6 km (9,1 mi) long and is inglorious famous for the death of 26 workers because of an inflow of water and gravel on a length of 1.500 m (4.900 ft). The surface above this area settled about 3 m (10 ft).

1906 Detroit Tunnel: The central Michigan Railway Tunnel or Detroit Tunnel was the first modern immersed tunnel. It is about 2.560 m (1,6 mi) long and still connects the American city Detroit with the Canadian city Windsor under the Detroit River.

1927 Holland Tunnel (USA): The Holland Tunnel is connecting the cities New York and New Jersey below the Hudson River. It was named after the chief-engineer Clifford Holland and the first automotive tunnel ever built. For its purpose of automotive traffic it was in need of a proper ventilation system to blow the exhausts out of the tunnel and fresh air into it.

1954 Oahe Dam (USA): At the Oahe Dam in South Dakota the first use of a mechanical rotary excavator, named the Mittry Mole, was conducted.

2.1.5 Nowadays

A lot of progress in tunneling was made in the second half of the 20th century. Today more and more tunneling projects are superlatives and it doesn't matter if these are projects in urban areas or deep in the mountains.
Regarding urban tunneling should be said that in the 1980s about 63 cities were constructing or planning an underground transportation system.[44]

1971 – 1988 Seikan Tunnel (Japan): The Seikan Tunnel is a 53.85 km (33.46 mi) long construction located in Japan. 23.3 km (14.5 mi) of the tunnel are built up to 240 m (790 ft) beneath sea-level. Till 2010 it was the longest tunnel in the world.

1980 – 1987 (Second Tube 1998 – 2003) Plabutsch Tunnel (A): The Plabutsch Tunnel in the southern part of Austria is about 10 km (6,2 mi) long and the second longest twin-tube motorway tunnel in Europe.

1988 – 1994 Channel Tunnel (GB / F): The Channel Tunnel connects Great Britain and France under the Strait of Dover. It is 50.5 km (31.4 mi) long, which makes it the longest underwater tunnel in the world, and has a maximum depth of 75 m (250 ft) below sea-ground. About 15.000 workers were employed in peak times and 10 fatalities happened during construction.

1996 - 2010 Gotthard Base Tunnel (CH): The Gotthard Base Tunnel is the longest tunnel in the world. With the cut-through in 2010 it reached a continuous length of 57 km (35,4 mi). The whole system is consisting of 151,84 km (94,3 mi) of underground constructions like tunnels, shafts and passages.

[44] West: Innovation and the rise of the tunneling industry.

2.2 Outcome

The timeline shows that tunneling and mining was always a big deal in Europe and the region of the Alps. In Austria the first mines for exploiting salt are dating back to 2500 BC.
When tunneling became reinvented in the 17^{th} and 18^{th} century Middle Europe was the center of knowledge and innovations.
Later the US made some very important inventions and was particularly successful in tunneling. They made some mayor inventions like the compressed air-driller, the use of nitroglycerine in tunnels, the development of immersed tunnels and TBMs. But it seems like although the US often made the first step, they didn’t continue to push their technologies forward. Instead other countries adapted and developed them further, leaving the US behind. When now thinking about the newest innovations or technologies regarding tunneling from the US you have to go back many years. Almost all of nowadays progress in tunneling was made by Europe or Japan.
One reason for the recent lack could be the adversarial approach between contractors and engineers. This is creating a reluctance of the engineers and they do not want to take the risks of innovations.[45]
Also the public funding regarding tunneling should be increased to provide more research.
When taking a look at the American infrastructure, it seems like a tunnel is something special, nothing usual like in Europe. Therefore also constructing a tunnel is something unusual. It also appears that the United States are a country which prefers building elevated instead of underground structures. It is obvious when travelling through the United States that bridges are their way to solve infrastructural problems. Even metro transportation systems are built as high raised constructions instead of putting them underground.

In Austria there are some big tunneling projects in progress. One reason is the attempt of establishing a transeuropean transportation system, which has mayor routes through Austria. Examples are the Brenner Base Tunnel with a planned length of 56 km (35 mi) with many related underground constructions and the Koralm Tunnel in the eastern part of Austria. Another reason are the accidents happened at the end of the last and beginning of the new decade. These accidents in the Tauern Tunnel, the Mont Blanc Tunnel and the Gotthard Tunnel caused mayor fatalities and led to a rethinking of tunnel safety. So the European Union as well as the Austrian government started pushing safety measures in tunnels forward. Many mayor road tunnels were turned into two-tube one way traffic tunnels.
Regarding the urban planning and construction, nowadays more of the transportation systems are getting at least partly transferred into the underground.

[45] West: Innovation and the rise of the tunneling industry.

The construction philosophy concerning tunnels is also different in Austria. Problems mentioned before occurring in the United States are mostly eliminated by the relationship between contractor and engineer.[46] This relationship is based on cooperation, control and knowledge between the involved parties.

Also in terms of research Austria is a big player. The Technical Universities of Graz, Vienna and Innbruck as well as the University of Leoben are well known for their research in tunneling and mining. This commitment continues with the work in international research groups and the participation at international congresses. A research project concerning tunneling, called TUNCONSTRUCT[47], co-financed by the European Commission and with a total investment of 26 million Euro was led by the Graz University of Technology.

The international support of this work can be seen as a credit to the Austrian tunneling community.

[46] Galler, R.: NATM – The Austrian Practice of Conventional Tunnelling. In: Zlámal, Jaromír: Transport and city tunnels - proceedings of the 11th International Conference Underground Constructions, Prague 2010. Prague: Czech Tunnelling Ass. ITA-AITES 2010

[47] TunConstruct: http://www.ifb.tugraz.at/tunconstruct/ (October 2010)

3 (Shallow) Tunneling Methods

Tunneling as a whole can be divided in many subsections. This chapter gives an overview about shallow tunneling methods, explains them and points out their differences.
Because of the sometimes difficult distinction between shallow or deep tunneling, some of the methods mentioned in this chapter are equally adoptable for deep tunneling. Nevertheless this chapter will consider the methods from a shallow tunneling point of view.

Underground constructions are always a challenge, even more if they are constructed in urban areas where sensitive buildings and infrastructure need to be considered.
Just small settlements can be a big problem and especially in highly populated areas end in a disaster. So it is obvious that adapted and newly innovated construction methods are needed.

3.1 Cut and Cover Tunnels[48]

The principle of the Cut and Cover method is to dig the tunnel from the surface in a trench and avoid the more challenging underground works.
Cut and Cover needs more space on the surface, and there may not be any obstacles. In depth from about 10 - 12 m (30 – 40 ft) the Cut and Cover method is normally more economical, but of course depending on project parameters like ground conditions, available space, objectives on the surface and influences of existing traffic.
Regarding the trench there are two different ways of digging and stabilizing it. Depending on the available space an open cut slope or a permanent or temporary structure is used. The open cut slope is a quite cheap method, but can only be used if slopes in a proper angle can be erected. If the space is tight and sensible objects are surrounding the trench, the trench needs to be supported by permanent or temporary structures. Temporary support can be sheet piles, soldier piles or lagging walls. Most common for permanent support are slurry walls or pile walls. Important is to consider the dewatering of the trench and the deflection of the permanent or temporary support walls.

3.1.1 Bottom Up

There are two different kinds of constructing a Cut and Cover Tunnel; the more common method is called Bottom Up. A trench is excavated from the surface till the bottom of the prospected tunnel. Then a foundation slab is poured in place whereon later the tunnel frame is erected. This is

[48] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034 - Technical Manual for Design and Construction of Road Tunnels - Civil Elements. Washington D.C.: 2009

commonly done by the use of ordinary framework and reinforced concrete, although pre casted steel or concrete elements are used sometimes. As soon as the structure is able to carry loads the trench is refilled with soil. The following figure from the FHWA - Technical Manual[49] visualizes this process.

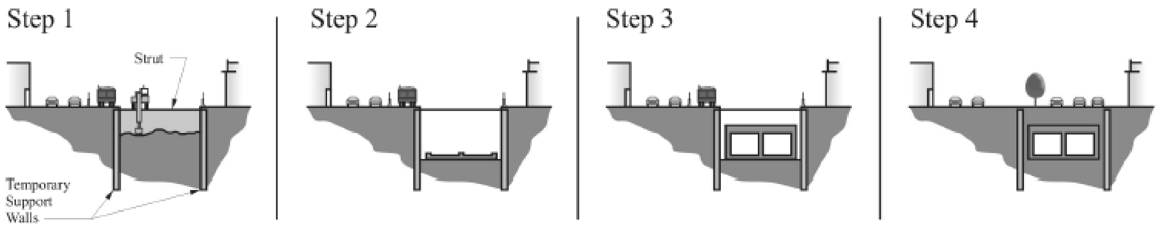

Figure 2: Principle of the Bottom Up method

A very interesting Project using this method was carried out in the Austrian Alps. The small village of Serfaus, a ski resort in Tyrol, had to deal with too many cars on the small dead-end main street. So they decided to keep cars out of the village by erecting the smallest underground in the world. Because of the lack of space, the existing old buildings and the site of the village it was a very challenging project. In 1984 the construction of the four stations and 1280 m (4200 ft) long underground air cushion funicular transport system began. After its official inauguration in 1986 it started being a big success.

On the following pictures the erection of a Bottom Up tunnel located at the new Brenner railroad track can be seen. The pictures, Figure 3 to 5, are taken and provided by the ARGE BEG H4-3 Stans.

Figure 3: Use of Bottom Up at the Brenner railroad track

[49] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

Figure 4: Use of Bottom Up at the Brenner railroad track

Figure 5: Use of Bottom Up at the Brenner railroad track

3.1.2 Top Down

The second method to construct a Cut and Cover tunnel is the so called Top-Down method, which is rather the opposite of the Bottom up method. When applying this method just a shallow trench is excavated. Subsurface walls or columns, mostly slurry walls, are built in advance and are proposed for a later use as load bearing walls. These walls are constructed to the designed depth of the tunnel. Once the walls are finished, in the excavated shallow trench, a concrete slab is poured in place. The slab itself is commonly erected on a layer of sand and without any framework. As soon as the concrete of the slab has reached a proper strength it is covered with soil to establish an immediate use of the area above. The next step is the excavation beneath the slab. Excavators are digging their way beneath the slab till the designed height is reached. Then another slab is concreted and, if necessary, digging starts again. This process continuous till the final depth or amount of stories of the structure is reached.

If there are crucial objects or infrastructure on the surface, which cannot be relocated, it is possible to push the topmost slab through the ground. When this process is finished excavation can start.

Top Down means a minimum interruption on the surface. As soon as the first slab is finished normal conditions can return to the surface, while beneath the works are going on.
The following figure[50] shows the principle of this method.

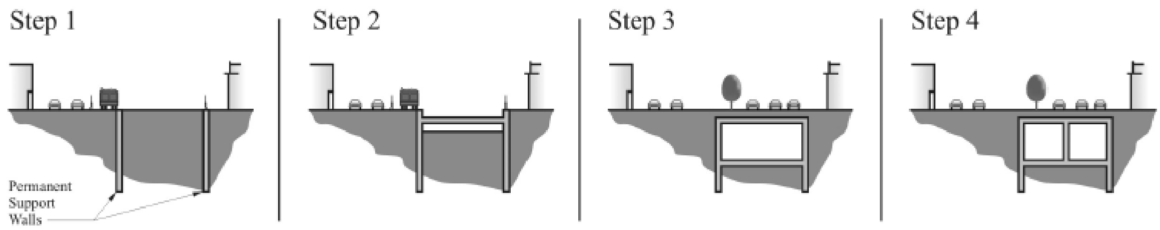

Figure 6: Principle of the Top Down method

[50] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

3.2 Immersed Tunnels[51]

Immersed tunnels are structures consisting of pre casted segments placed under water. The segments are pre-casted on a floodable basin or a dry dock and have a sealed bulkhead on each end. While most immersed tunnels in Europe are consisting of concrete, the immersed tunnels in the United States are made of steel.

Regarding concrete the segment length is limited by the weight and the hydration heat to about 20 m (60 ft). Steel segments therefore can have a length up to 130 m (400 ft). The problem with steel segments is the deformation.

Figure 7 to 10 are images from the very interesting Oresund Project. [52]

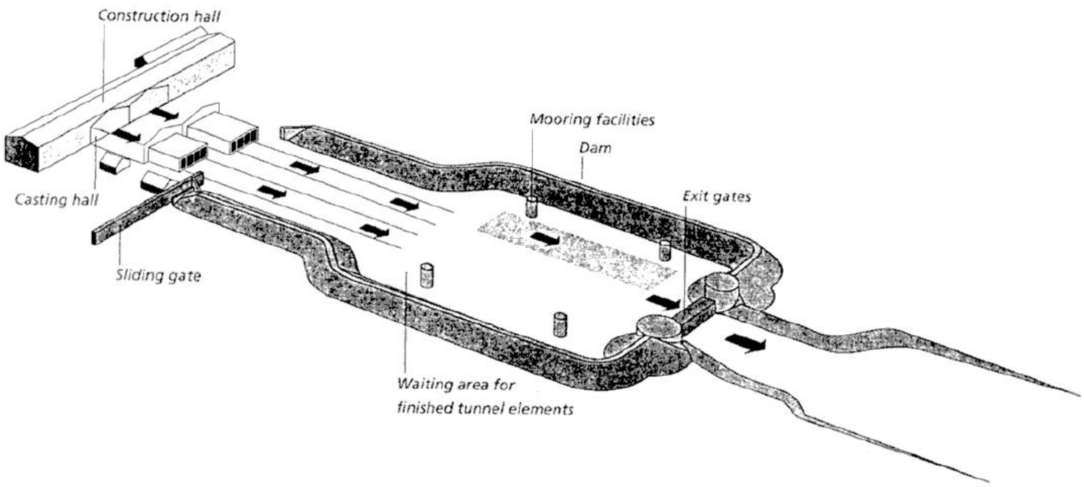

Figure 7: Principle of a dry dock

After the construction of one segment the dock or construction place is flooded. While steel segments are starting to float earlier, concrete segments need to be complete under water to float and need a higher water depth on the shipping route than steel segments.

Once floating the segments are towed to the site where they are be put in place. Before the segments arrive a trench needs to be excavated to provide a proper layer for them. The digging of the trench is a critical part of the construction, because it can have a big impact on the sea ground and furthermore the whole environment. Creatures living there and fish populations can be harmed quite seriously.

[51] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

[52] Ben C. Gerwick, Inc. - Construction of Elements for the Oresund Immersed Tunnel: http://gerwick.com/PDF/oresund_link.pdf (November 2010)

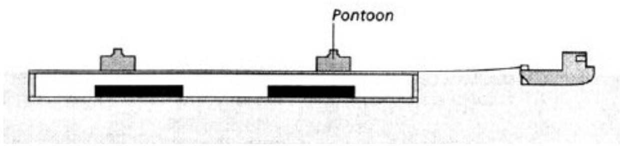

Figure 8: Towing of a finished tunnel segment

The next step are the foundation works. Foundations for an immersed tunnel can either be a continuous bedding foundation, consisting of a 0,5 to 1,4 m (1,6 to 4,5 ft) thick layer of gravel, or more rarely an individual support foundation, consisting of driven piles.

Once the segments arrive on site they are lowered by using ballast. The ballast can be water tanks or other components with extra weight and can be placed on the exterior or interior of the segments. The lowering process is one of the most crucial parts. Considerations about the weather and its influences to the lowering process as well as tides and other maritime and environmental parameters are absolutely necessary.

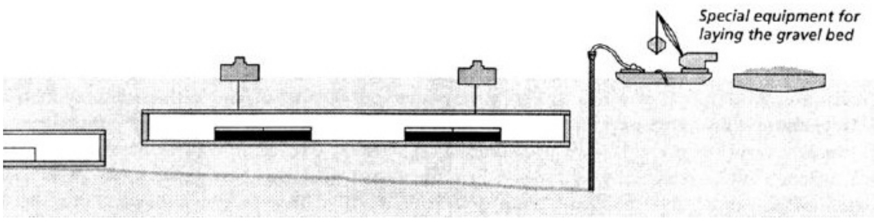

Figure 9: Foundation works for the immersed segment

Is the segment finally in place, it is connected with the other placed segments. This connection needs to be totally watertight. When this is ensured, the space between the bulkheads of the two segments is cleared of water.

Then the trench is backfilled. This backfill consists of the following parts:[53]

- *Selected locking fill to secure the elements laterally*
- *General backfill to the sides and top of the tunnel structure, also providing an impact-absorbing / load-spreading layer above the tunnel*
- *A rock protection blanket generally above and adjacent to the tunnel to provide scour protection*
- *Rock-fill anchor-release bands at both sides of the tunnel are sometimes provided*

[53] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

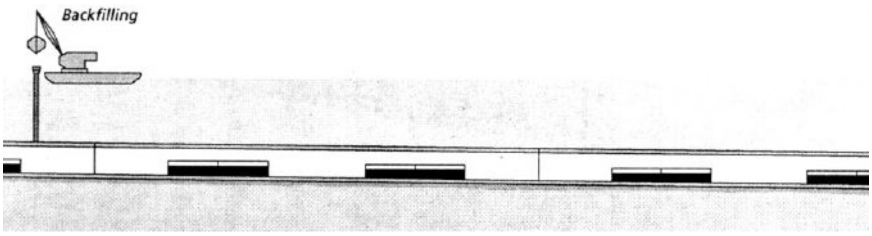

Figure 10: Backfilling of the immersed segments

For safety reasons the backfilling has to be done symmetrically. Regarding seismic design, a free-draining material should be used for lowering the pore water pressure and therefore avoiding ground liquefaction. Also an additional armor protection should be installed to protect the backfill against longtime loss.
After the backfilling process is finished, the two bulkheads between the segments can be removed.

Considerations concerning the design of an immersed tunnel should also include topics like sunken ships or submarines colliding with the tunnel, which may sounds funny, but can cause serious damage to the structure.

3.3 Shield Tunnels

Shield tunneling means forcing a tunnel under the protection of a shield which is providing temporary support. The use of shields is common in soft ground because of the ability to control the ground and to prevent it from collapsing. Shield tunneling has a long tradition and was invented at the beginning of the 19th century when Brunel started to realize his idea. There are different kinds of using a shield in tunneling. The box jacking method for example, which is described more detailed in the next paragraph, is strictly speaking also a kind of shield tunneling. Most recognized, when talking about tunneling with shields, are fully mechanized shields often referred as TBMs - Tunnel Boring Machines.

But there are some more possibilities of using a shield in tunneling. The following paragraphs and graphics are mainly adopted from the Tunnel Manual of the FHWA:[54]

3.3.1 Non-Mechanized

At non-mechanized shields the tunnel is dug by men under the protection of a shield. The different kinds of non-mechanized shields are:

3.3.1.1 Blind Shield

A blind shield is used in very soft clays and silts and also beneath water passages. It uses the instability of the ground, which is removed by its ability of flowing. The flow of soil into the tunnel is regulated by a hole in the shield which can be adjusted. The use of a blind shield often results in proper settlements above the face.

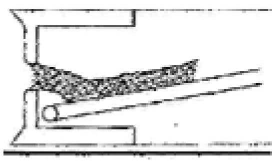

Figure 11: Blind shield

3.3.1.2 Open Face Shield

An open face shield is open over the whole cross-section of the face. With the installation of additional plates at the face some extra support can be provided. These plates have no ability to compensate the ground pressure, therefore the use is limited to short and small tunnels in non-collapsing soils. The soil is removed by men. This kind of shield is using the same principle than the one that Brunel invented 200 years ago.

[54] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

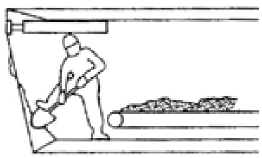

Figure 12: Open face shield

3.3.2 Semi-mechanized

Semi-mechanized shields are more common nowadays. The shield itself is similar to the open face shield, but the soil is removed by a back hoe or cutter. This shield can exist of more tables and can be additionally equipped with plates to support the face. The face can also be divided into partial segments. Problems can occur in loose or running ground but it can be combined with compressed air to reduce water inflow and improve soil stabilization.

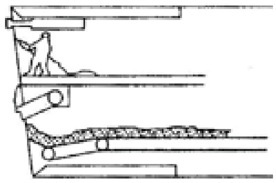

Figure 13: Semi-mechanized shield

3.3.3 Mechanized

Mechanized shields are using totally mechanized cutters, normally a full face cutter wheel or a disk cutter, to remove the ground.

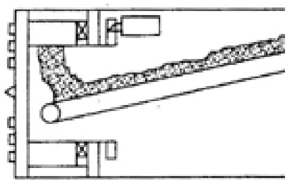

Figure 14: Mechanized shield

When speaking about mechanized shields, the term TBM - Tunnel Boring Machine is more common although not every TBM is using shield technology. Today there is a broad range of different shield TBMs.

For tunneling in rock conditions the following Shield-TBMs are available:

- Single Shield TBM
- Double Shield TBM

Because soft ground conditions are very common in shallow and urban tunneling, machines operating under these conditions are considered in the following paragraphs. [55]

3.3.3.1 *Earth Pressure Balance Shield*

Earth Pressure Balance Shields or EPB are used in soft and non-stable soils. The loosened soil is used to stabilize the tunnel face without the addition of a secondary support medium. In a closed excavation chamber the loosened soil is mixed with the already plasticized soil-water mixture. By compacting this medium with native earth- and water-pressure an equilibrium is reached. This equilibrium is kept stable by a controlled remove of the soil, accomplished by the speed of the forcing. The tunnel lining normally exists of reinforced concrete segments.

The following graphic[56] shows the areas of use for EPB and Slurry Shield machines:

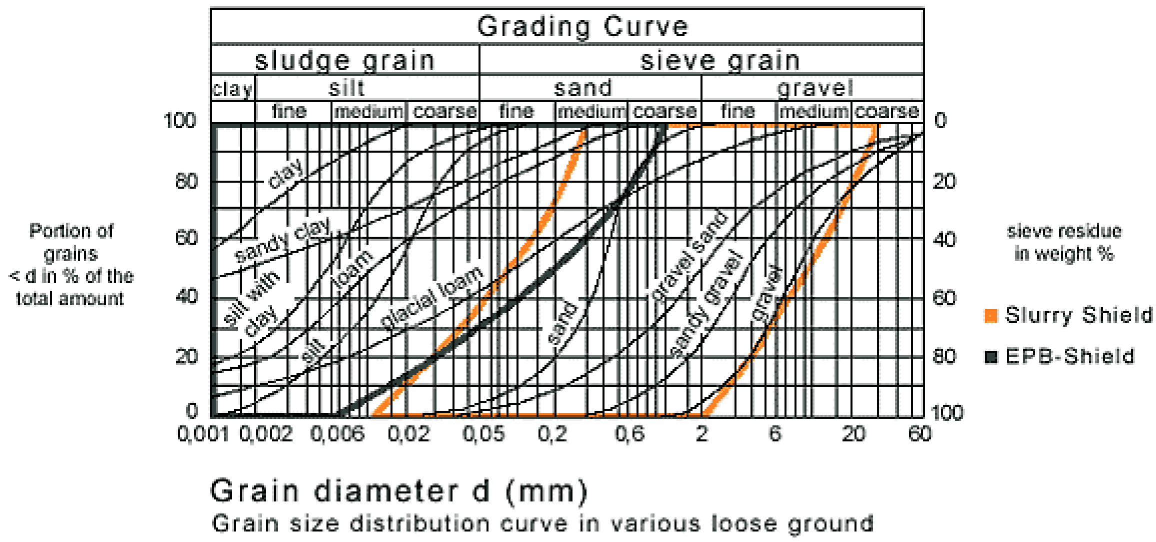

Table 5: Applicability of Slurry- and EPB-Shields

3.3.3.2 *Mix-Shield*

A Mix-Shield is used in heterogeneous and gravelly conditions as well as in mixed geological conditions with an unstable face. The cutter wheel is rotating in a bentonite suspension, creating an equilibrium by a compressible air cushion which equals the native earth pressure. Compared to the EPB Shield the support pressure is not directly controlled by the medium, but by an air cushion which allows a more flexible and better control of the pressure. This provides a more stable face and no loss of ground. Lining segments are also normally made of reinforced concrete.

[55] Herrenknecht: http://www.herrenknecht.com/ (Oktober 2010)
[56] Herrenknecht: http://www.herrenknecht.com/ (Oktober 2010)

3.3.3.3 Slurry Shield

A slurry shield is used when the tunnel face is stable, like in cohesive soils. The principle of the machine is quite similar to the Mix-Shield, but without the use of compressed air. This means the face support is controlled by the slurry itself.

3.3.3.4 Partial Face Excavation

The partial excavation shield can be used in a wide variety of geological conditions. The partial excavation of the face is done by an excavator in soft grounds or with road headers in rock.

3.4 *Jacked Tunnel*

Tunnel jacking is based on the principle of pipe jacking. Since the complexity of this method it is not used very often. Till today this method was never used in Austria and also in the United States the first mentionable application of this method was in 2003 at the Big Dig project on the I-90 in Boston, MA.

The principle of jacked box tunneling is to push a precasted tunnel segment through the ground by using a hydraulic jack. These boxes can exist of concrete or steel and either be round or rectangular, but the most common type is a rectangular box consisting of reinforced concrete.

The application of this method is limited by the ground, it is only possible in soft ground, and the length. The aim is to construct a tunnel without disrupting the surface including critical objects. The segments are jacked beneath the critical objects, starting from a jacking pit to an end-shaft.

Ground Freezing or Grouting can be used to control the ground and loss of it and provide additional stability. Appropriate dewatering methods have to be considered as well.

The construction of a jacked tunnel starts in a starting shaft, so called jacking pits. As soon as this shaft is excavated and prepared the segments are casted in it. Regarding the design of these segments the jacking and frictional resistance loads have to be considered. These loads are depending on the ground, additionally used ground improvement methods and the friction between ground and the segments. To reduce the jacking loads at the end of the tunnel segment, additional intermediate jacking stations can be installed.

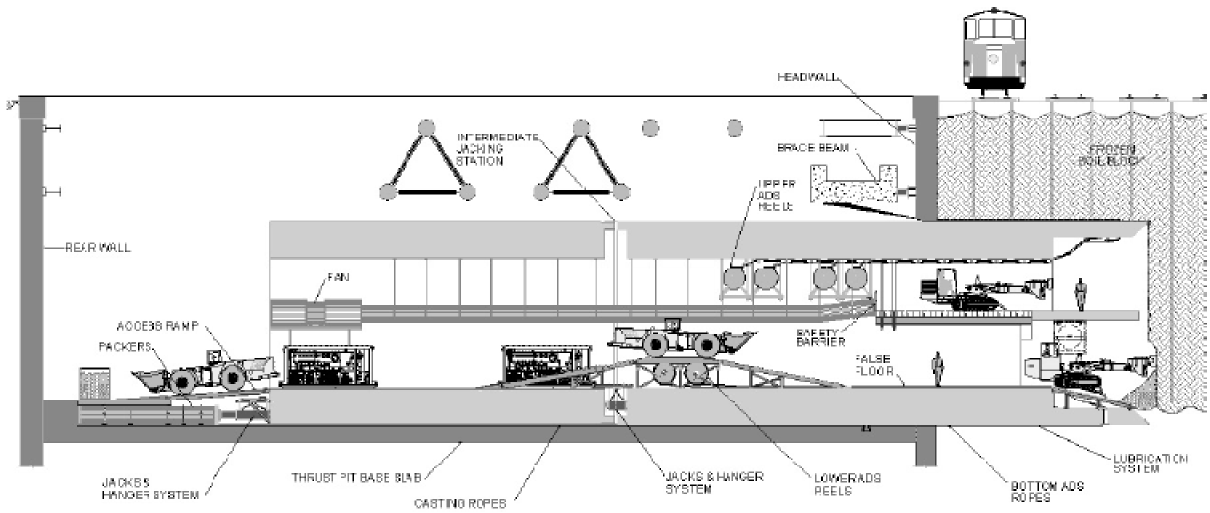

Figure 15: Layout of a tunnel jacking site[57]

[57] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

A crucial part of this method is the concrete mix. It has to undertake the part of the water tightening layer, because an additional layer on the outside of the tunnel would be damaged or destroyed during the jacking process.
The excavation at the face is executed under the protection of the tunnel box. To allow a proper ground control and safety in the tunnel, the front-shield should consist of multiple accesses to the face. That implies that during excavation just one access need to be opened, and the rest of the face is secured by the other closed accesses. The excavation itself can be done by most of the common underground excavation methods. Once a round is excavated, the tunnel is jacked forward and the excavation process starts again.

As mentioned before, the frictional resistance is a crucial factor regarding tunnel jacking. To reduce the friction additional measures have to be performed. One possibility is the use of the so called Anti Drag System, this system works with greased wire ropes which are anchored to the starting pit, running at the outside of the tunnel to the front shield, and through it back into the tunnel where they are stored. When the tunnel is now jacked forward, the ropes are pulled out of their storage letting the tunnel box gliding forward on them.

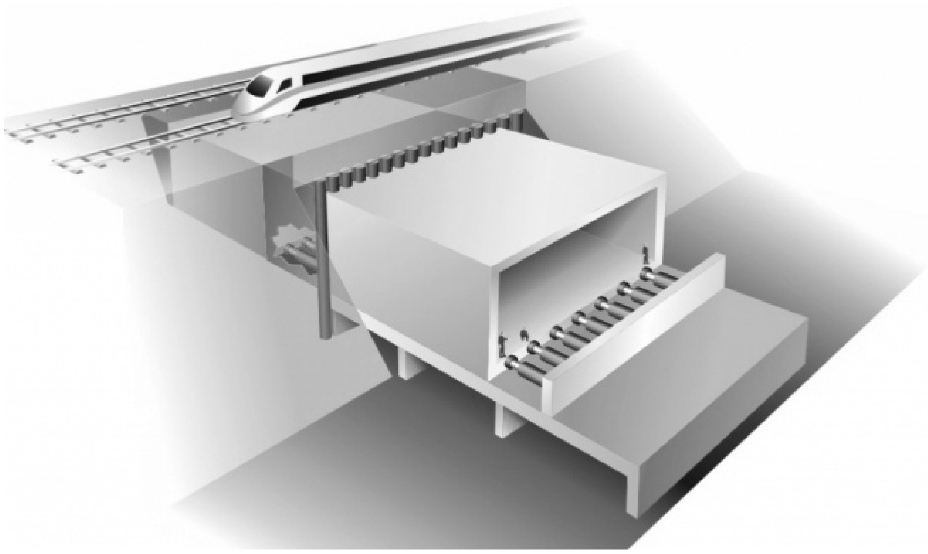

Figure 16: Principle of tunnel jacking[58]

When the jacking process starts it has to be ensured that the tunnel segments are pushed forward in the right vertical and horizontal alignment. May this is not concerning longer segments because of their conduction in the jacking pit, but for short segments this is a proper issue. For vertical alignment a steering mechanisms should be installed, while for the horizontal alignment fixed side guides should be considered.[59]

[58] Jacked Structures: http://www.jackedstructures.com/box-jacking.html (December 2010)
[59] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

3.5 Mined Tunnels

Mined tunnels, also known as conventional tunnels, are the true types of tunnels. They can be forced by the following three methods:

- Blasting
- Cutting
- Excavating

Which method is chosen is depending in first sight on the ground conditions but also on financial issues, environmental issues and site conditions.

3.5.1 Drill and Blast

Drill and Blast is a common method of loosen the ground in rock conditions. Although it is used in urban tunneling, because of the ground composition in shallow and urban conditions, often consisting of soft ground, gravel and heterogeneous conditions, other methods are more common. Other reasons for its limited use in densely populated areas are the accompanying effects. Shock waves can be a problem as well as toxic dust from the explosion, noise, vibration, air pollution and the danger of explosives in general.
Nevertheless, there are conditions where blasting is the only reasonable choice. In this case a very sensitive handling, a very experienced crew and maybe additional works for securing and reducing the above mentioned issues may be necessary.

The Drill and Blast method basically consists of the following steps:

- Drilling and Charging
- Blasting
- Ventilation
- Supporting
- Loading and Hauling

When choosing blasting for loosening the ground following considerations and parameters are important: [60]

- *Behavior of seismic noise in a particular region*
- *Maximum amplitudes and frequency spectra of vibrations*
- *Type of movement (particle motion)*

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[60] Kaláb, Z. / Knejzlík, J.: Measurements and seismic effects of vibrations caused by urban tunneling. In: Barták, Jiři: Underground Space - the 4th Dimension of Metropolises. Volume 1. London: Taylor & Francis Group 2007, pp.481-485

- *Validity of measured values for surroundings*

The keyword concerning this method is nowadays gentle blasting. Due to the use of non electrical chargers and an intelligent array of the explosives as well as good designed round lengths the negative impacts of blasting to the surroundings can be minimized and well performed blasting pictures can be ensured.

3.5.2 Cutting

When cutting a tunnel a road header or a rotary cutter is used to loosen the ground. The machines are comparable to the ones used for fully mechanized partial face excavation, with the difference that the machines are normally smaller and not stationery, but self operating on a crawler.
Cutting machines are much cheaper and more flexible than TBMs, but therefore slower and their use is also limited by the strength of the ground. Although cutting is a very indulgent way to loosen the ground.

3.5.3 Excavating

If the soil is very soft the use of special tunnel excavators can be considered. Excavating is also like cutting an indulgent way of loosening the ground.
Forcing a tunnel with excavators is a direct ascent of the early methods of digging a tunnel. During the early times of tunneling the work was carried out by men, without any mechanized help, nowadays the excavation procedure exists of high-tech excavators especially built for the tough use in underground conditions. The used shovels are also especially designed and adapted to the underground use and the ground conditions.

3.6 Excurse: NATM / SEM[61]

The New Austrian Tunneling Method or in America more often called the Sequential Excavation Method was invented in the middle of the 20th century by different Austrian engineers, lead by Rabcevicz.

The principle of the NATM is that ground is no longer just a load, but also a part of the load bearing structure. The NATM is a method of conventional tunneling, where excavation is done by blasting, cutting or excavating. Adapted to the ground conditions and the time-dependent development of ground reactions after the excavation support measures are undertaken. The applied support is evaluated and adjusted for every round and consists of shotcrete, mostly reinforced, and if necessary additional steel arches, anchors, lattice girders, face bolts, spiles etc.

The shotcrete allows a controlled deformation of the support, which is needed to activate the ground as a load bearing structure. A crucial part of the NATM is the continuous measurement of the deformations and the reevaluation of the ground behavior.

Also depending on the ground conditions an excavation cross-section is chosen. Possible cross-sections can be a full face excavation, a top heading, bench and invert excavation or a side drift galleries excavation.

When using the NATM in urban environment soft ground conditions are usual, which means a rigid shotcrete lining with short advancing rounds and maybe a rapid invert closure is necessary. Also additional works like dewatering and installation of a pre-supporting system are usually necessary. The inner lining which is concreted later on is mostly reinforced and in many cases it has to undertake water tightening tasks. Therefore the design of the concrete also has to consider the hydrostatic pressure. The thickness and reinforcement is depending on to the overburden and how many forces can be translocated into the ground. The biggest difference between soft ground and rock tunneling is, due to the ground behavior, the danger of settlements, so when using the NATM *"no attempt is made to reduce tunnel lining loads by allowing controlled ground movements"*[62].

According to the OEGG the below listed steps are needed to be considered and executed in the planning and construction phase of a NATM tunnel to ensure a successful application:[63]

Phase 1 - Design

- Step 1 – Determination of Ground Types
- Step 2 – Determination of Ground Behavior

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[61] Galler: NATM – The Austrian Practice of Conventional Tunnelling.
[62] Galler: NATM – The Austrian Practice of Conventional Tunnelling.
[63] Austrian Society for Geomechanics: Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation.

- Step 3 – Selection of a Construction Concept
- Step 4 – Assessment of System Behavior in the Excavation Areas
- Step 5 – Determination of Excavation and Support and Evaluation of the System Behavior in the Supported Areas
- Step 6 – Geotechnical Report – Excavation and Support Requirements
- Step 7 – Determination of Excavation and Support Classes

Phase 2 - Construction

- Step 1 – Identification of the Encountered Ground Type and Prediction of Ground Conditions
- Step 2 – Assessment of the System Behavior in the Excavation Area
- Step 3 – Determination of Excavation and Support
- Step 4 – Verification of System Behavior in the Supported Area

3.6.1 Adoption of the NATM in the US[64]

In the United States just a few tunneling projects have been realized using the New Austrian Tunneling Method. One important part of the NATM is the employment of good trained personnel, from the workers up to the engineer. This is crucial to ensure a fast reaction when ground is changing because in further consequence this is affecting the construction progress and the productivity. Another important part is the system of ground classification. While in the United States the ground classification from Terzaghi is mostly used, the Europeans or especially the Austrians are using a much more differentiating system.

Maybe the biggest problem in adapting the NATM in the US is the contractual system. In Austria for example the ground risk is a risk of the owner, so if unpredicted changes in the geology occur, the owner has to pay for the accumulating costs. This contradicts the usual American contractual system. Regarding the classification and pricing of the support measures, there is also a big difference. In Austria every support measure has a defined price and the contractor gives a bid consisting of this price and the ground classification of the owner. The different support measures are strictly and exactly divided, which causes a large number of them. If now an unpredicted change in ground conditions occur the contractor and the owner respectively an engineer of the owner are reevaluating the ground and the tunnel face and are deciding if and which appropriate measures are needed to be carried out. If more support is necessary the owner pays for every additionally installed item based on the unit price in the bid. Common practice in the US is the pricing of just a few basic support categories.

[64] Marcher, Thomas: NATM Strategies In The U.S. - Initial Support Design For The Caldecott 4th Bore. In: ITA–AITES World Tunnel Congress 2009: Safe Tunnelling For The City and For The Environment: Hungary: Hungarian Tunnelling Association 2009

The construction contracts in the United States are aiming to provide a clearly scoped contract which is contrary to the flexibility of the NATM. Due to these differences a direct adoption of the NATM is not very appropriate.

When adopting the NATM to the American way of tunneling, some simplifications and changes need to be done. One attempt is a more detailed in situ investigation than in Austria. This should enhance the accuracy of the ground predictions and therefore provide a more detailed geological mapping and in further consequence an in advance more precise assessment of support measures. These actions should lead to a detailed description and reduction of support categories and most important fewer changes during construction.

The support measures correlating to the ground behavior should also be adapted to the typical US ground classification system. Below you can see the ground classification including support measures given by the FHWA and in contrast to that the determination of ground types according to the OEGG, which is the basis for their determination of the support measures.

Typical determination of Ground Types in the US regarding to the FHWA Tunnel Manual: [65]

Ground Mass Quality – Soil	Excavation Sequence	Initial Shotcrete Lining	Installation Location	Pre-Support	Support Installation	Remarks
Stiff/hard cohesive soil - above groundwater table	Top heading, bench & invert; dependent on tunnel size, further sub-divisions into drifts may be required	Systematic reinforced (welded wire fabric or fibers) shell with full ring closure in invert; dependent on tunnel size 6 in (150 mm) to 16 in (400 mm) typical; for initial stabilization and to prevent desiccation, a layer of flashcrete may be required	Installation of shotcrete support immediately after excavation in each round. Early support ring closure required. Either temporary ring closure (e.g. temporary top heading invert) or final ring closure to be installed within one tunnel diameter behind excavation face.	Typically none; local spiling to limit over-break	Support installation dictates progress	Overall sufficient stand-up time to install support without pre-support or ground modification
Stiff/hard cohesive soil - below groundwater table	Top heading, bench and invert; dependent on ground strength, smaller drifts required than above	Systematic reinforced (welded wire fabric or fibers) shell with full ring closure in invert; dependent on tunnel size 6 in (150 mm) to 16 in (400 mm) typical; for initial stabilization and to prevent desiccation, a layer of flashcrete may be required; frequently more invert curvature than above	Installation of shotcrete support immediately after excavation in each round. Early support ring closure required. Either temporary ring closure (e.g. temporary top heading invert) or final ring closure to be installed within less than one tunnel diameter behind excavation face; typically earlier ring closure required than above	Typically none; locally pre-spiling to limit over-break	Support installation dictates progress	Sufficient stand-up time to install support without pre-support or ground improvement; dependent on water saturation, swelling or squeezing can occur
Well consolidated non-cohesive soil - above groundwater table	Top heading, bench & invert; dependent on tunnel size, further sub-divisions into drifts may be required	Systematic reinforced (welded wire fabric or fibers) shell with full ring closure in invert; dependent on tunnel size 6 in (150 mm) to 16 in (400 mm) typical; for initial stabilization and to prevent desiccation, a layer of flashcrete is required	Installation of shotcrete support immediately after excavation in each round. Early support ring closure required. Either temporary ring closure (e.g. temporary top heading invert) or final ring closure to be installed within less than one tunnel diameter behind excavation face	Frequently systematic pre-support required by grouted pipe spiling or grouted pipe arch canopy; alternatively ground improvement	Support installation dictates progress	Stand-up time insufficient to safely install support without pre-support or ground improvement
Well consolidated	Top heading, bench &	Systematic reinforced	Installation of shotcrete support	Frequently	Support	Stand-up time

[65] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

Ground Mass Quality – Soil	Excavation Sequence	Initial Shotcrete Lining	Installation Location	Pre-Support	Support Installation	Remarks
non-cohesive soil - below groundwater table	invert; dependent on tunnel size, further sub-divisions into drifts may be required; Pocket excavation and/or face stabilization wedge may be required	(welded wire fabric or fibers) shell with full ring closure in invert; dependent on tunnel size 6 in (150 mm) to 16 in (400 mm) typical for initial stabilization and to prevent desiccation, a layer of flashcrete is required	immediately after excavation in each round. Early support ring closure required. Either temporary ring closure (e.g. temporary top heading invert) or final ring closure to be installed within less than one tunnel diameter behind excavation face	systematic pre-support required by grouted pipe spiling or grouted pipe arch canopy; groundwater draw down or ground improvement	installation dictates progress	insufficient to safely install support without pre-support or ground improvement; Running ground conditions or boiling may occur
Loose non-cohesive soil - above groundwater table	Top heading, bench & invert; dependent on tunnel size, further sub-divisions into drifts may be required; Pocket excavation and/or face stabilization wedge may be required	Systematic reinforced (welded wire fabric or fibers) shell with full ring closure in invert; dependent on tunnel size thickness 6 in (150 mm) to 16 in (400 mm) typical for initial stabilization and to prevent desiccation, a layer of flashcrete is required	Installation of shotcrete support immediately after excavation in each round. Early support ring closure required. Either temporary ring closure (e.g. temporary top heading invert) or final ring closure to be installed within less than one tunnel diameter behind excavation face	Systematic pre-support required by grouted pipe arch canopy; alternatively ground improvement	Support installation dictates progress	Stand-up time insufficient to safely install support without pre-support and/or ground improvement
Loose non-cohesive soil - below groundwater table	Top heading, bench & invert; dependent on tunnel size, further sub-divisions into drifts may be required; Pocket excavation and/or face stabilization wedge may be required	Systematic reinforced (welded wire fabric or fibers) shell with full ring closure in invert; dependent on tunnel size thickness 6 in (150 mm) to 16 in (400 mm) typical for initial stabilization and to prevent desiccation, a layer of flashcrete is required	Installation of shotcrete support immediately after excavation in each round. Early support ring closure required. Either temporary ring closure (e.g. temporary top heading invert) or final ring closure to be installed within less than one tunnel diameter behind excavation face	Systematic pre-support required by grouted pipe arch canopy frequently in combination with ground improvement	Support installation dictates progress	Stand-up time insufficient to safely install support without pre-support or ground improvement; Running ground conditions or boiling may occur

Table 6: Elements of Commonly Used Soft Ground Excavation and Support Classes in Soft Ground

Determination of ground types in Austria according to the OEGG Guideline[66]:

Soil Classification

- Definition of grain size classes
- Grain size distribution
- Properties of plasticity
- Constituents of organic origin

Parameters of the composite

- Specific weight, unit weight, density
- Grain size distribution
- Porosity, structure - texture
- Ratio of components to matrix, kind and arrangement of the component framework
- Properties (and potential direction-dependence) of strength and deformability

Parameter of components

- Mineralogical composition of the main constituents, grain shape
- State of components (e.g. weathering, alteration)
- Mineralogical composition of the main constituents, grain shape

[66] Austrian Society for Geomechanics: Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation.

- State of components (e.g. weathering, atteration)

Parameters of matrix

- Mineralogical composition, contents of clay minerals and organic material, cementation

Permeability

4 Particular Topics of Shallow and Urban Tunneling

4.1 Importance and Chances

According to West[67] a study was saying that cities with a population of more than 1 million people are justifying the construction of underground infrastructure systems. This number is quite interesting and shows the facts of *Chapter 1 – Background information & Introduction* in a different light, because even much larger cities or metropolitan areas are still not relying on a proper underground transportation system. Population and density however is steadily increasing in those areas throughout the world, which makes proper infrastructure even more important.

When discussing the further development of a city often the question of building underground or on surface arises. The question if tunnels are worth their higher initial costs arises and too often politicians reject underground structures because they are not able to defend the much higher initial costs of them.
But when talking about costs of an urban underground project not just the initial costs have to be considered and publicized. Like already common practice for office buildings, the whole life cycle costs should be considered. Rejecting this is too often a reason for judging an underground construction as too expensive and therefore causes a bad reputation of them.

More difficult than calculating Life Cycle Costs are the assessment of social impacts and savings as a result of a structure. The OECD - Organization for Economic Co-Operation and Development stated in a report in 1995[68] that OECD Countries have to pay the following percentages of their Gross Domestic Product for:

- Road congestion: 2% GDP
- Road accidents: 1,5 - 2% GDP
- Noise pollution: 0,3% GDP
- Air pollution: 0,4% GDP
- Non local CO_2 pollution: 1 - 10% GDP

The conclusion of this data is obvious; reducing traffic problems in urban areas is saving the government, and therefore the tax payer a considerable amount of money. Road congestions can be reduced by underground structures very well. Also road accidents can be reduced by promoting an

[67] West: Innovation and the rise of the tunneling industry.
[68] Godard, J. P. / Lequeux T.: French metros: Construction costs VS. transport social costs. In: Negro, Arsenio: Tunnels and metropolises - proceedings of the World Tunnel Congress ’98. Volume 1. Rotterdam: Balkema 1998, pp.3-13

urban metro system. Same can be said for noise and air pollution. Also a road tunnel can reduce those problems. While the reduction of noise is an easy task, also polluted air from a tunnel can be cleaned by modern ventilation systems and then being transferred into the atmosphere at a proper place where it is not influencing people and their health.

When talking about underground structures in urban areas, most times we are speaking about shallow structures, nevertheless the deepest urban metro line, located in Pyongyang, North Korea has a depth of about 110 meter (361 feet). Anyway due to the rarity of such structures this chapter respectively the whole thesis is focusing on shallow structures.

An underground structure can have a great positive impact to a city. Some of these advantages are listed beneath: [69]

- *Environmental advantages: avoiding visual and acoustic pollution, slight impact on ecosystems: many environmental impact studies prove that underground interventions do not effect the biosphere which is much more effected by the works on surface;*
- *Formal advantages: the underground space has not certain references so it can be considered completely free of external restraints, planning underground means being conditioned only by internal perspectives.*
- *Functional advantages: maintenance of a constant temperature due to the natural nonconductivity, which means a significant energy saving*
- *Risk advantages: more safety towards the outdoors, more control on dangerous, inflammable and polluting products;*
- *Economic advantages:·no urbanistic restrains, possible use of volumes linked with the work construction, possibility to locate in the city centre facilities that usually are cited in the suburban quarters for lack of space elsewhere.*

Underground constructions should be an enrichment for a city and therefore only assume functionalities which are disturbing the surface. There is no sense in going beneath the surface when the prospected use of the structure has a negative impact to socio-economic issues.

[69] Gisotil, G. / Mauri, M.: The Role Of Underground Space In Sustainable City Planning And In Rational Resource Management. The Case Of Cavity System In Rome: Risk And Resources. In: Teuscher, Peter: Progress in Tunnelling after 2000 - proceedings of the AITES-ITA 2001 World Tunnel Congress. Volume 1. Bologna: Patron ed. 2001, pp.319-325

4.2 Environmental Issues

An underground structure can have a big positive environmental impact, but it can also turn into the wrong direction if work is carried out by the wrong people or with a lack of expertise.

In early stages of an underground project the following points should be considered:[70]

- *Air, water and soil pollution*
- *Noise*
- *Vibration*
- *Ground subsidence*
- *Offensive odors*
- *Obstruction of sunlight and ventilation*
- *Effects on plants and animals*
- *Topography and soil quality*
- *Historical sites and cultural objects*
- *Visual environment*

The consideration has to regard the construction stage as well as the operation stage.
During the construction stage the issues of

- Air pollution
- Noise pollution
- Vibrations

are of special importance because they are effecting the surroundings of a site in a serious way. If no consideration is taken, not just health problems can occur, but also the compliance of the inhabitants to underground projects will decrease

Important for all of these kinds of pollution is to have knowledge about limitations by local law or standards and to abide upper limits set in accordance with the public. Continuous measurements to ensure an adherence of limits and a proper action plan if limits are exceeded are essential.

4.2.1 Air Pollution

Air pollution can occur by exhausts of heavy machines, but more common or more harmful and disruptive is dust created by site traffic, blasting or other destruction methods and production facilities on site.

[70] Gisotil / Mauri: The Role Of Underground Space In Sustainable City Planning And In Rational Resource Management.

Dust pollution can be disruptive in many ways. It can limit the sight, make it harder to breath, settle down on cars and other objects and it can smell bad as well. May these effects are not harmful, but they are decreasing public compliance and can turn a technical and economical successful project into a failed one because of rejection by the people.

4.2.2 Noise Pollution

Noise pollution can be caused by the same sources mentioned above, heavy machines, site traffic, blasting or other destruction methods and production facilities on site. As noise is not that big issue during daytime because of existing road traffic and other noise pollution, generally said because of a basically higher noise level, it is a big issue during the nighttime. Most tunnel sites are operating 24/7, so special measures have to be implemented that the neighborhood is not disturbed during nighttime, weekends or holidays.

4.2.3 Vibration

Vibration in urban tunneling can occur by working machines or more common by blasting. Vibrations are a very important factor, because they can damage objects and buildings as well as annoying people. Vibrations are basically the effects created by shockwaves and have principally the same behavior like seismic waves arising from earthquakes.

4.3 Ground

Ground is always an issue in underground constructions, even more in urban areas. The most common topics regarding ground are stability issues inside the tunnel, especially before supporting, and settlements on the surface.

Mostly in urban areas and shallow conditions the ground exists of soft soil. If additionally high water tables are occurring, further problems can occur.

Beneath some common soils occurring in urban tunneling and their behavior according to the FHWA Tunnel Manual[71] are listed:

Designation	Degree of Compactness	Tunnel Behavior	
		Above Water Table	Below Water Table
Very Fine Clean Sand	Loose, N<10 Dense, N>30	Cohesive Running Fast Raveling	Flowing Flowing
Fine Sand With Clay Binder	Loose, N <10 Dense, N >30	Rapid Raveling Firm or Slowly Raveling	Flowing Slowly Raveling
Sand or Sandy Gravel with Clay Binder	Loose, N<10 Dense, N>30	Rapid Raveling Firm	Rapidly Raveling or Flowing Firm or Slow Raveling
Sandy Gravel and Medium to Coarse Sand		Running ground. Uniform (Cu <3) and loose (N<10) materials with round grains run much more freely than well graded (Cu >6) and dense (N>30) ones with angular grains.	Flowing conditions combined with extremely heavy discharge of water.

Table 7: Common soils in urban tunneling and their behavior

[71] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

4.4 Measuring & Monitoring

Measuring and monitoring is one of the most important issues in urban and shallow tunneling. The first issue is to force the tunnel in the right direction, horizontally as well as vertically. When forcing a tunnel from two sides this is even more important to ensure a correct breakthrough without considerable divergences. Anyways, even if the tunnel is forced from one side divergences can create big problems in densely populated areas.

The next issue regarding measuring and monitoring are movements of the ground around the excavated tube. It has to be ensured that the ground, even with already applied support, is not moving too much so that the designed cross-section gets affected or narrowed. When using the NATM this is a main point and monitoring gets even more important, because of the aim to allow controlled movements until a certain point and then stop it. This is achieved by the use of more or less flexible support materials and an intelligent adjustment of the support system. Not only the cross-section but also the tunnel-face has to be monitored. The reasons therefore are the issue of stability and safety and the prediction of the upcoming ground.

The third big issue are settlements and movements on the surface. This is a very common topic in shallow tunneling and can have big impacts. Especially in soft ground conditions a change of stresses beneath the surface can lead to settlements on the surface. This directly affects buildings and objects in the surrounding area. Even very small settlements can effect sensible infrastructure like railroads or machineries and disturb their proper use, while larger settlements can lead to a total collapse of buildings.

In the following paragraphs a selection of measuring and monitoring methods is given. This selection reflects some interesting and not always typical methods, like classic measuring with theodolites. This chapter is not reflecting the completeness of measuring methods.

4.4.1 GPS Monitoring[72]

GPS-real-time measurement is used to monitor single sensitive buildings or objects. A GPS station, which is automatically gathering data, is installed on every building to be surveyed. The frequency how often the position is measured can be set manually and down to one second. A frequency of 180 seconds has proofed as a common one to receive reliable data. The data from each GPS station is sent to a central processor which processes the data in real time and sends it to predefined devices. This method is used for single objects which need to be monitored over a long period of time and a high accuracy.

[72] Benecke, N. / Althaus P. / Kalz U.: Advanced online monitoring for urban Tunnelling projects. In: Barták, Jiři: Underground Space - the 4th Dimension of Metropolises. Volume 2. London: Taylor & Francis Group 2007, pp.837-840

4.4.2 Totalstation Monitoring[73]

While GPS monitoring uses one device for each measuring point, totalstation monitoring is based on the use of just one measuring station, which can additionally be monitored by GPS. The totalstation is measuring automatically and radio controlled predefined measuring points. These points are measuring prisms attached to each object which needs to be monitored. The totalstation evaluates the data and sends it to a defined device. This method is used for a large number of measuring points.

4.4.3 Metric 3D Images[74]

The method of Metric 3D Images is based on combining and evaluating pictures taken with digital cameras. It just needs two pictures taken from the tunnel face or the tunnel shape and a reference pole to create a three dimensional picture of the intended area. The pictures are evaluated and assessed with a special software using the principle of stereo-photogrammetry. As a result the processed picture allows metric measurements, due to the existence of thousands measuring points. Other data which can be gathered from these pictures are rock mass conditions, orientations and derived properties.

This method allows a measurement of the face or shape, before support measures are installed, because it is not necessary to be in the measured area. Besides that, the picture can be taken into the object-ordinate system with just a few additional works.

4.4.4 3D cable monitoring[75]

3D cable monitoring is an attempt to avoid damages on the surface by real time settlement monitoring. A borehole is horizontally drilled above and in the direction of the tunnel. After finishing drilling, the monitoring cable is put into the borehole. It is made of optical fiber and is using the Brilloun technology which ensures, due to the settlement induced change of the curvature of the cable, a detection of settlements. The cable can register very small settlements and processes the data in real time.

4.4.5 Acoustic Borehole Image[76]

This method is used to determine the ground conditions around a borehole. The principle is to measure waves sent from an acoustic signal and evaluate them. Therefore an ultrasound signal is

[73] Benecke / Althaus / Kalz: Advanced online monitoring for urban Tunnelling projects.
[74] 3G Software & Measurement: http://3gsm.at/dt/home_dt.asp?ID=2 (October 2010)
[75] Tunconstruct: Going Underground. Web: www.tunconstruct.org/tcstatic/tunconstruct_going_undergound.pdf (November 2010)
[76] Task Geoscience – The Borehole Image and Dipmeter Experts: http://www.taskgeoscience.com/ (November 2010)

sent by a rotating probe. When the probe is lowered into the borehole, it measures the returning time and amplitude of the sent signal. Out of this data images are created which are showing the ground conditions of the boreholes surrounding.

4.4.6 Radarinterferometry[77]

Radarinterferometry uses the physical effect of interference and phase difference. Waves are sent from airplanes or satellites equipped with radiointerferometry systems. The surface is reflecting these waves and they are returning with different phases. Out of the differences in the phases data about the surface can be collected. Because of the low absorption of electromagnetic waves by clouds and other atmospheric disturbances this is a very useful and practical method for the monitoring of surface movements across a large area.

Other measuring and monitoring works could be satellite image analysis, convergence meters, inclinometers, extensometers or ordinary measuring bolts.

[77] Benecke / Althaus / Kalz: Advanced online monitoring for urban Tunnelling projects.

4.5 Site logistics

Site logistic and work preparation demands much more deliberations in urban surroundings than on other sites, and it is getting even more complex if the construction takes place underground. Underground works have to be carried out beneath existing structures which means less space and more difficult access for storage and freight traffic.

Access paths and access points have to be chosen wisely, and primary as well as secondary and sometimes tertiary access routes have to be assessed. These routes have to take into consideration size, weight, height and turns of transportation vehicles as well as rush hours, congestions times, no traffic times for commercial trucks and other traffic related parameters.

Already existing underground constructions and objects, especially wires and pipes for electricity, gas, fresh water, waste water and communication lines as well as pipelines, need to be determined because they are not just influencing the planning and construction process, but also the site logistics.

A proper plan for the storage of materials is inevitable. If space is really tight on-time deliveries could be solution, although they can have major impact to the construction process when delayed. As far as possible shafts, caverns and already finished parts of an underground construction can be used as temporary storages.

Also bypasses for cars and pedestrians for particular construction stages and deliveries have to be worked out in accordance with peak times.

4.6 Financing and Costs

Financing and costs are a big deal in every construction project. Like issued in *4.1 - Importance and Chances,* underground constructions can have a big impact in reducing infrastructural and public costs.

The infrastructural costs are related to many factors which could be divided into three main points: [78]

- *Factors related to the transport system proper: line capacity, characteristics of rolling stock and equipment, spacing of stations, etc.*
- *Factors related to the physical environment: specific features of the site (topography, climate), characteristics of the urban fabric, ground and subsoil occupation, geological and hydrogeological characteristics of the soil*
- *Factors related to prevailing economic circumstances and socio-economic environment*

Like already mentioned in an earlier chapter, initial costs for underground structures are normally higher than those for on-surface or elevated ones. The keywords regarding justifying the higher initial costs are Life Cycle Costs or LCC and cost-benefits.

For a project in Downtown Seattle a study[79] is stating that initial costs for replacing a viaduct by a tunnel instead of a new one is about $1 billion more. But the tunnel produces a $450 million increase in property values, a $2 billion in additional property development and an extra of $325 million a year because of tourism for the city.
Another project with higher initial costs but considering LCC, shows that those higher costs can be easily turned into a rentable project due to noticeable savings at the maintenance costs. This particular project, the Newfoundland and Labrador Fixed-Link project[80], points out maintenance costs of $CA 16.9 million / year for the designed bridge and between $CA 6.8 and $CA 7.6 million for the proposed tunnel.
These numbers seems reasonable, because a tunnel is not exposed to weather conditions and climate can be controlled by intelligent ventilation systems which means less exposure to the structure. Maintenance works like clearing the bridge of snow are also not a source of matter in the tunnel.

[78] Godard / Lequeux: French metros: Construction costs VS. transport social costs.
[79] Reilly, John / Parker, Harvey: Benefits and life-cycle costs of underground projects. In: Barták, Jiři: Underground Space - the 4th Dimension of Metropolises. Volume 1. London: Taylor & Francis Group 2007, pp.679-684
[80] Reilly / Parker: Benefits and life-cycle costs of underground projects.

Overall a lot of issues are relating to the total cost of an infrastructure project. These can be summarized and are well addressed in the same paper than the examples above: [81]

> *"Cost-benefit analysis should include capital, operating and maintenance costs, road user time savings, public transport user time savings, travel time variability, pedestrian time savings, vehicle operating cost savings, accident reduction, etc."*
> *"The benefits accrued to underground projects should include the time value of the use of the surface over the tunnel (a value can be assigned even if it is a park), right of way advantages, increased property values and employment in the general vicinity, and overall energy savings that might result from shorter travel times, flatter grades, etc."*

Like mentioned before, the influence by natural hazards and influences like snow, storms, earthquakes etc. have to be considered.

When talking about financing and cost estimation also the chronicle cost overrun in urban underground projects has to be mentioned. Big infrastructural projects beneath the surface have a chronicle overrun of costs which is mostly connected to the expertise and policies of the owner, wrong risk mitigation, poor management and the reliability of the data used for the cost estimation. So to ensure a realistic cost estimation these problems have to be eliminated.

A deeper look into risk mitigation gives an interesting view of established project management practice[82]. Systematic risk management is not quite advanced in underground projects but it is not a new issue. First thoughts about it were made in the 1970's, but the acceptance took till nowadays. So acceptance is one problem. While technical risks were reduced by risk management, most times no overall systematic risk management was carried out and the risk plan was not adopted to different construction stages and changing parameters.
At least a cost estimation was or is a single number, which is based on one possible result. Instead a serious range of cost and time should be given.

Following projects should be mentioned because of their good and forward-looking considerations regarding initial costs, operational costs, benefits and risk mitigation:[83]

- *Groen Hart Tunnel, Netherlands (Selection based on preserving precious farmland)*
- *Dusseldorf Waterfront Highway Tunnel (Selection based on taking cars off the waterfront to improve esthetics and public access and use of the waterfront: See Reilly & Parker, 2007)*

[81] Reilly / Parker: Benefits and life-cycle costs of underground projects.
[82] Parker, Harvey W.: Life Cycle Cost Considerations Using Risk Management Techniques. In: ITA–AITES World Tunnel Congress 2009: Safe Tunnelling For The City and For The Environment: Hungary: Hungarian Tunnelling Association 2009
[83] Parker: Life Cycle Cost Considerations Using Risk Management Techniques.

- *Goteborg Waterfront Highway Tunnel (Selection based on taking cars off the waterfront to improve esthetics and public access and use of the waterfront)*
- *Oslo Waterfront Highway Tunnel (New tunnel eliminated barrier between city and fjord, allowed urban development and improved transportation)*

4.7 Safety Management

In every tunnel or rather at every construction site a proper safety management needs to be installed. Because of more critical issues in shallow and urban tunneling it is even more important, and a good quality absolutely necessary.

There should be a safety management plan for the whole project as well as for specific (ground) conditions, because uncertainties in geological conditions can occur even if the investigation was done in an excellent way.

The Safety Management should consider: [84]

- *Basic elements and structure of the Safety Management Plan*
- *Parties involved and their responsibilities*
- *Determination/Definition of the expected behavior; definition of warning and alarm levels/criteria*
- *Monitoring program; layout and frequency of monitoring in accordance with expected behavior and boundary conditions*
- *Information and communication flow*
- *Action plan; organization, and mitigation measures in case observed behavior deviates from the expected*
- *Management of a crisis*

A proper assessment of hazards is important to set the right monitoring criterions and responsibilities as well as warning levels and a target-aimed information flow.

Regarding information flow, it should be mentioned that information need to be at the right time at the right person, and in case of an emergency the information flow must be clearly defined, so that no deterioration is caused.

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[84] Schubert, W.: Geotechnical safety management on site. In: Barták, Jiři: Underground Space - the 4th Dimension of Metropolises. Volume 2. London: Taylor & Francis Group 2007, pp.1603-1608

4.8 Legal and Strategic Issues

There are many legal aspects regarding tunneling in urban areas. This paragraph is not giving an insight of actual standards, laws or restrictions but tries to point out some problems which occur or can occur in future urban tunneling.

As mentioned earlier in this chapter consideration of Life Cycle Costs can save a lot of money and it is strongly recommended to integrate this topic much more in future projects. But if we want to convince people that they have to consider LCC, a legal problem emerges. Almost all projects which are funded by public money are favoring the cheapest bid. But, as also mentioned earlier, underground constructions have higher initial costs. So laws have to be changed in a way that not just the initial costs are crucial in the bid process but also the LCC.

When pushing forward underground constructions another problem occurs: Who owns the subsurface?!
Landahl was addressing this problem in his paper "Planning and mapping of underground space - an overview"[85]. The following paragraphs are summarizing the outcomes of this paper.

There are four attempts of clarifying who owns the underground:

- *The owner owns the ground from the surface to the center of the earth*
- *The owner owns the ground as far as reasonable interest exists*
- *The owner owns the ground until a limited depth (up to 6m)*
- *Private land ownership doesn't exist*

But even if the ownership is clarified, that doesn't automatically give a right to use the underground. So there are two attempts of establishing a legal framework to use the underground. One attempt is the more or less simple establishment of easements. These easements need to be worked out by appropriate departments and rights must be obtained. The second attempt is to establish a 3D real estate with a clear definition of responsibilities for the owner of the surface and the owner of the underground.

Related to the legal issues are the strategic issues, also addressed by Landahl[86]. Proper underground development needs an intelligent strategic planning. Nowadays there are just a few tunnels, which are not interrupting each other, but if you regulate the underground use and open it to the public,

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[85] Landahl, G.: Planning And Mapping Of Underground Space - An Overview. In: Teuscher, Peter: Progress in Tunnelling after 2000 - proceedings of the AITES-ITA 2001 World Tunnel Congress. Volume 1. Bologna: Patron ed. 2001, pp.457-464
[86] Landahl: Planning And Mapping Of Underground Space.

further development could result in an overcrowded underground and therefore a loss of valuable space. The subsurface planning today is carried out in an insufficient way by most countries and there are no strategic objectives.

Governments need to work out strategic underground plans and create an underground mapping, so that underground corridors and spaces maybe turning important in the future are reserved and not destroyed by impetuous structures nowadays. The most important thing is to remember that proper usable underground space is not infinite and therefore must be managed carefully and professionally. This requires guidelines for the use of underground space and governments should consider elaborating them soon.

5 Construction Methods Particularly in Shallow Tunnels

The construction and supporting methods of a shallow tunnel can be quite different to deep ones. The reason therefore is that it is possible to do mayor works from above the surface, and not just beneath it.

The methods how to build a shallow tunnel in urban areas are defined by the ground. More specified by its the physical and geomechanic characteristics and the existing ground water. The decisive characteristics of the ground were defined by the Austrian Society for Geomechanics as followed:[87]

> *In rock: mechanical properties (intact rock - rock mass), discontinuity, characteristics and properties, rock type, rock- and rock mass conditions, hydraulic properties*
> *In soil: mechanical properties, grain size distribution, density, mineral composition, parameters of the soil components, matrix parameters, water content and hydraulic properties*

Additionally ground water is a crucial factor. The inflow of water into a tube can result in mayor damages and fatalities. Therefore it is very important to think about which amount of inflowing water is acceptable, how to deal with the rest of the water and how is this treatment effecting the surroundings and the whole ground water system. In some cases it is better to use the existing water for stabilizing purposes in other cases a nearly totally sealed tunnel is needed.

5.1 Compressed Air

If a tunnel is built beneath water, for example beneath rivers, the sea, a lake or just in ground with a water level very close to the surface, one possibility to handle the water is to force the tunnel under compressed air. The origin of this method dates back to the early 19th century.
The principle of this method is simple. The air-pressure in the tube needs to be as high as the water pressure on the bottom of the tube. This is accomplished by compressors which are compressing the air and pumping it into the tunnel. To apply this method successfully the tube needs to be sealed quite well. The entrance to the tunnel is just possible through a pressurized cabin. To reduce the loss of compressed air the cross section or the face of the tunnel need to be as small as possible and often requires a sequential excavation and a prompt sealing with shotcrete.

[87] Austrian Society for Geomechanics: Guideline for the Geotechnical Design of Underground Structures with Conventional Excavation.

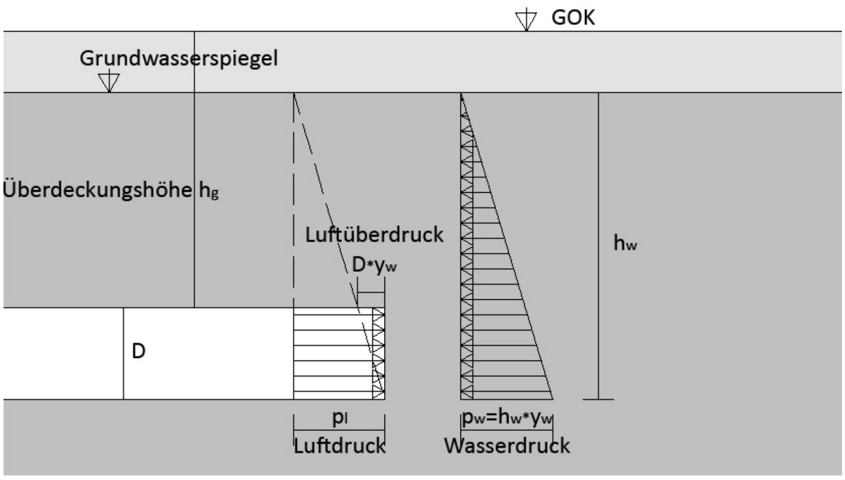

Figure 17: Correlation between air- and water-pressure

Because the workers have to excavate the bore not in atmospherical pressure but in higher pressure, the physical stress is higher than under normal conditions. Workers also have to be checked by a medic before being deployed to the tunnel.

In compressed air the danger of fires is very high. Therefore all machinery must be powered by electricity. This means an enormous effort regarding acquiring and maintaining this machines.

The pressure in the tube needs to be adjusted to the particular ground conditions of each round. This can lead to an additional loss of air which directly means higher costs due to the high expenses for compressed air.

5.2 *Artificial Ground Freezing*

Ground freezing means that a certain area of the ground, mostly around an underground construction, gets frozen by artificially lowering the temperature of the ground until the pore water is frozen.

This method can be used in almost every soil, only the amount of water in the ground and its flow is crucial. The most common areas of application are constructions beneath a river, because mostly the riverbed drains enough water into the soil, or in sites where the ground water level is higher than the depth of the construction. Most important is that the soil and its water evolve a stable continuum in frozen conditions.

There are two techniques of freezing the ground. The first one is freezing the ground with liquid nitrogen and the second one is using a brine (a salt solution). Liquid nitrogen is more expensive, but faster, while freezing with brine is cheaper but takes more time. Crucial parameters for choosing the right method are the time, how long needs the ground to be frozen and how much time do I have in advance to freeze the ground, and also the flow of the ground water. Generally it can be said, that faster freezing means less deformity of the frost body.

Both methods need an intelligent refrigerating system, containing of pipes where the coolant can circulate and a refrigerator. The grade of the icing and the affected area can be controlled by the assembling of the pipes, the kind of coolant and the refrigerator itself.

The result out of the freezing process should be a material which can be used as a temporary structure and which is totally watertight.

During the whole freezing process it is important to have sensors which are continuously monitoring the temperature and surveying the process. If possible in-situ tests should also be carried out.

To secure a consistent freezing of the ground the drilling of the pipe system is quite important. The drilling accuracy needs to be very high, which is getting more difficult with the increasing depth of the borehole. The drilling is directly related to the distance between the freezing pipes, which are decisive for the calculated frost body

As mentioned before a crucial factor is the water flow. The velocity should generally not exceed a speed of more than 2 m/d.

The two graphics below[88] shows the correlation between the velocity of the ground water and the development of the frost body. Due to the constant flow of ground water, the frost bodies are getting deformed and are not building a stable continuum.

[88] Ziegler, Martin et al.: Optimization Of Artifical Ground Freezing Applications For Tunnelling Subject To Water Seepage. In: ITA–AITES World Tunnel Congress 2009: Safe Tunnelling For The City and For The Environment: Hungary: Hungarian Tunnelling Association 2009

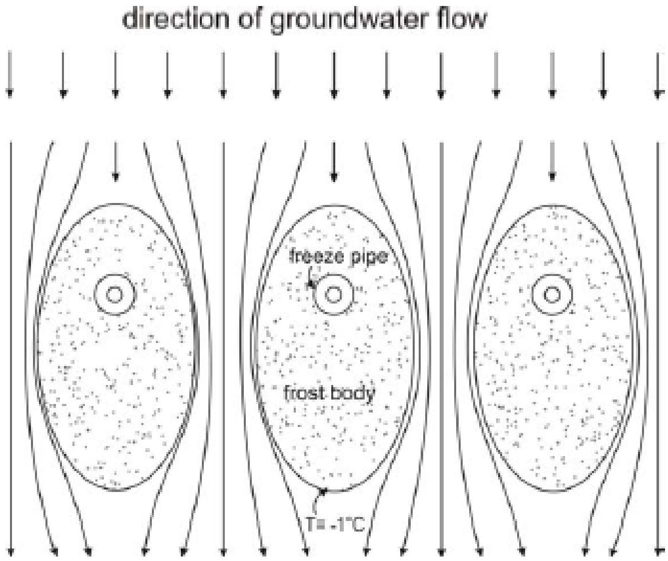

Figure 18: Effect of groundwater flow to frost bodies

A fictional sample crosscut investigated by Ziegler[89] outlines the correlation of groundwater flow velocity to freezing time. The assumed example is a crosscut with an inner diameter of 5,5 m, a necessary frost body of 1,5 m thickness and 18 pipes arranged continuously around the profile. While a proper frost body is achieved after 20 days in non flowing groundwater, the time rises up to 50 days in water with a flow velocity of 0,75 m/d. If the flow velocity is doubled to 1,5 m/d the frost body needs a time of 234 days to reach its assumed thickness.

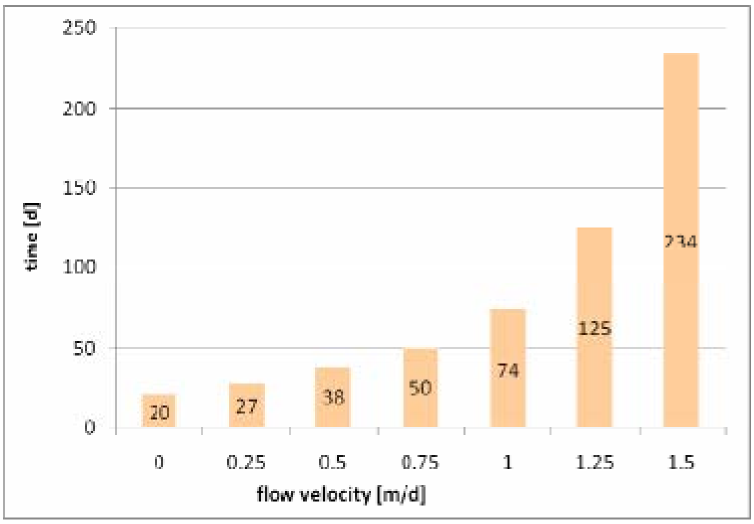

Figure 5 - Rise in freezing time with an increasing flow velocity

Figure 19: Dependency of freezing time to flow velocity

[89] Ziegler: Optimization Of Artifical Ground Freezing Applications For Tunnelling Subject To Water Seepage.

When using ground-freezing the following considerations have to be made.

The characteristics of the ground water and in further consequence the time-temperature behavior is, like already mentioned, a crucial point.

It also needs to be considered that when using a brine, it already takes a few months for just reaching its ready-for-use temperature of -35° C.

Another point is the length of the boreholes, which are affecting the preciseness. Generally could be said that as longer the borehole is as more deviation occurs.

While the method itself has no impact to the environment because it is completely reversible, some problems can occur in the thawing phase due to heaves and settlements caused by the change of the volume of the soil.

5.3 Grouting

When talking about grouting in underground construction, it is meant to improve the ground by injecting cement or similar materials, called grout, into it. There are different methods of how to inject the grout.

- Compaction Grouting: This method increases the density of the soil by controlled ground displacement with grout.
- Permeation Grouting: This injection method uses a very low viscosity grout and fills the spaces between the ground particles.
- Jet Grouting or High Pressure Grouting: Jet Grouting means to inject a suspension and mix it with the ground. The most common use is to create grouted columns or bodies in the soil.
- Claquage or Fracture Grouting: At this method the soil is intentionally fractured by a high pressure injection, which leads to a reinforcement of the ground.

Grouting was at first designed for ground improvements. As the technique was getting more developed it was also used for underpinning foundations, buildings and other objects and for sealing construction pits in dense areas. Over the last few years engineers established this method also in tunnel constructions, for sealing the tunnel or to reduce settlements. Nowadays the whole tunnel cross section can be prebuilt with jet grouted columns.

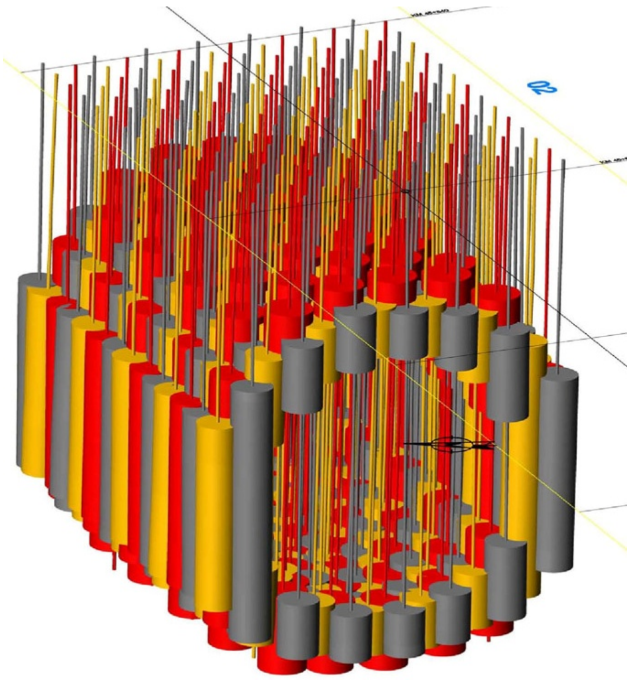

Figure 20: Model of a tunnel lining consisting of jet grouted columns

The picture above, taken by the ARGE BEG H4-3 Stans, shows the computed model of jet grouted columns erected for the Brenner railroad tunnel Contract H4 in Tyrol / Austria.

The tunnel lining was erected according to the model and divided into compartments for a better construction process. After the compartments were finished, the soil between the columns was removed. In addition compressed air was used to prevent an inflow of water.

This is another good example for the interaction of the different construction methods in a complex underground structure. The Grouting method was chosen because of a very high ground water table and the necessity of underpinning very sensitive constructions like a highway and a high-speed railroad track. The total settlements with a maximum of one to two millimeters showed the big success of this method and proofed it for further applications.

The crucial part when using grouting methods is the right choice of the suspension, depending on grain size distribution and environmental constraints.
If the method is applicable at all, depends on the permeability parameters of the ground: [90]

- *$k=10^{-6}$ or less: ungroutable*
- *$k=10^{-5}$ to $k=10^{-6}$: groutable with difficulty by grouts under 5cP viscosity and ungroutable for higher viscosities*
- *$k=10^{-3}$ to $k=10^{-5}$: groutable by low-viscosity grouts but with difficulty when k is more than 10 cP*
- *$k=10^{-1}$ to $k=10^{-3}$: groutable with all commonly used chemical grouts*
- *$k=10^{-1}$ or more: use suspended solids grout or chemical grout with a solids filler.*

Remarks: k is given in cm/s and cP (centipoise) stands for the dynamic viscosity and equals 1/1000 Ns/m².

[90] Koronakis, N. / Kontothanassis, P. / Katsaris, D.: Design of water isolation grouting for reducing high water inflows in urban shallow tunnels. In: Erdem / Solak: Underground Space Use: Analysis of the Past and Lessons for the Future. Volume 1. London: Taylor & Francis Group 2005, pp.271-276

5.4 Pipe Umbrella (Pipe Roofing)[91]

A pipe umbrella is a construction method to pre-support an underground structure in soil. When the soil itself does not have the consistence to be stable, additional works to secure a safe drift have to be carried out.

The basic idea of a pipe umbrella or also called Pipe Roofing, Umbrella Arch Method or Steel Pipe Canopy, is to install steel pipes from the top of the actual tunnel face to the front. The steel pipes, sometimes also pipes consisting of fiber glass, usually range from a diameter of 60 to 200 mm (2,4 to 15,8 in) and a thickness of 4 to 8 mm (0,16 to 0,32 in). The length of the pipes is varying from about 6 to 15 m (20 to 50 ft). The overlap of the pipes is depending on the objectives which wanted to be achieved. Is the umbrella just for increasing the stability, the excavation can proceed as long as the face is stable. Is this no longer the case another pipe umbrella needs to be installed.

If the pipe roof is used for reducing settlements, the overlap needs to be longer and a crucial parameter is the effectiveness of the pipe roof foundation which emerges with every constructed compartment of the pipe roof. As soon as the effectiveness of this foundation decreases a new compartment needs to be installed.

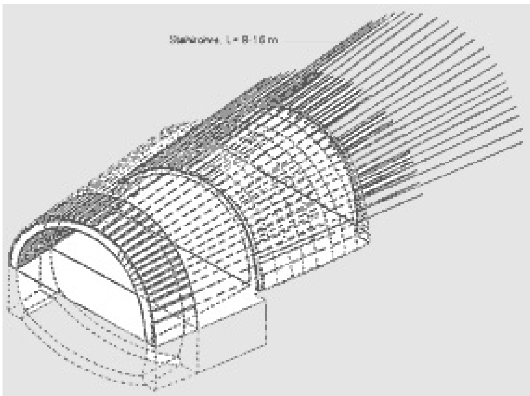

Figure 21: Model and principle of a pipe umbrella[92]

The standard inclination of the bores is 4 to 6° and there are two methods of installing the pipes. The first is called the pre-drilling system where in a first step the bore is drilled. After that, the driller is pulled out of the bore and the pipe is pushed into it.

The second method is called cased-drilling system. Thereby the bore is drilled using the pipe behind the drilling pit as a kind of shield. This provides an immediate support und prevents the hole from being backfilled.

In both methods the last step is to press concrete into the pipes.

[91] Ge, J.K.: New tunnel construction technique of pipe-roof method in saturated soft soil. In: Erdem / Solak: Underground Space Use: Analysis of the Past and Lessons for the Future. Volume 1. London: Taylor & Francis Group 2005, pp.365-369

[92] Rodio Geotechnik AG: http://www.rodio.ch/site/index.php?site=20&submenu=4 (February 2010)

Figure 22: Installation of a pipe umbrella[93]

Figure 23: Excavation beneath a pipe umbrella[94]

[93] Purrer: http://www.purrer.cc/web/detail.php?ID=33 (February 2010)
[94] Marti Holding AG: http://www.martiag.ch/go/Newsarchiv%3B1%3B211 (February 2010)

5.5 Premill Method

The Premill technology[95] is an alternative method to grouting, nailing, soil freezing etc. to pre-support the ground ahead of the tunnel face. The Premill method was first used in France in the 1970s and further developed in Italy in the 1980s. In nowadays need for proper underground construction methods, this method is once more rediscovered.
The main element of the Premill method is a milling saw, mounted on a steel trolley. The saw can be equipped with different kinds of teeth, so it can be adjusted to different types of ground.
The idea of this method is to create a concrete shell around the tube, before excavating it. Therefore the laser guided saw starts at the side walls and continues to the head of the tunnel. This process is divided in different stages and after each cutting stage, the produced cavity is refilled with special, fast hardening, concrete.
Nowadays Premill shells are able to cut three to five meter (16,5 ft) deep, and each cut is overlapping the prior one. This leads to a barrel vault created by the concrete shell and therefore more support for the tunnel.
A big advantage of the Premill method is the space saving equipment, which makes it possible to perform further works at and near the face.

Figure 24: Premill machine with milling saw[96]

[95] Manasser, V. / Mongilardi, E.: The Premill Method For Tunnel Excavation. In: Teuscher, Peter: Progress in tunnelling after 2000 - proceedings of the AITES-ITA 2001 World Tunnel Congress. Volume 2. Bologna: Patron ed. 2001, pp.329-336
[96] Lunardi, Pietro: Design and construction of tunnels: analysis of controlled deformation in rocks and soils. Springer 2008

5.6 Slurry Wall

Basically a slurry wall can have two purposes. The first is to seal a construction pit in an area with a high water table. The second purpose is to erect load bearing walls in advance for oncoming underground constructions.

The principle is in both cases the same, just the procedure is varying a bit.

A slurry wall with sealing purposes is not intended to carry loads, it consists of bentonite. Bentonite is a material consisting of impure clay and most parts of montmorillonite.

At first a trench is excavated by a special slurry wall excavator. Therefore a guide wall is erected in the ground. It serves as a guidance for the excavator so that it keeps the right direction. While excavating the wall trench a slurry, bentonite, is pumped into the trench to stabilize the surrounding ground and prevent it from collapsing. Once the actual segment of the wall is completed the cutter is removed from the trench. When not activated bentonite has the characteristics of a gel, which is reacting with water to a watertight wall.

If the wall is intended to carry loads and a part of the future structure, additionally steps are necessary.

After the cutter is removed, a reinforced steel cage is put into the trench. Afterwards concrete is pumped into the bottom of the trench. At the same time the bentonite, which is floating on the much heavier concrete is removed from the trench. This process continues till the whole bentonite is replaced by concrete.

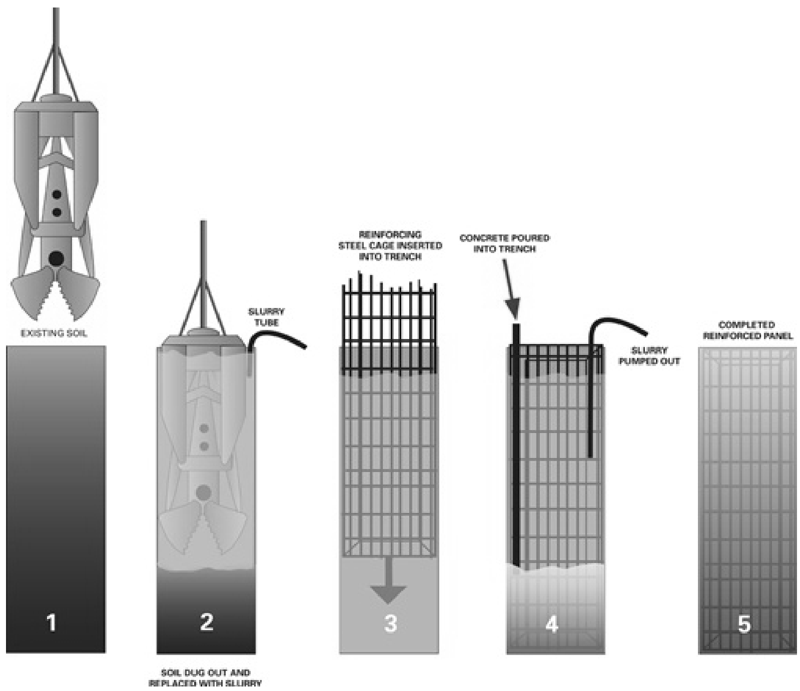

Figure 25: Principle of the erection of a Slurry Wall[97]

[97] Massachusetts General Hospital: http://www2.massgeneral.org/pubaffairs/Issues2008/071108slurry.htm (November 2010)

5.7 URUP

The following paragraphs and images are based and referring to a paper written in 2009 by Keizo[98]. URUP stands for Ultra Rapid Under Pass and is a new method for constructing a tunnel beneath sensitive or crucial objects in urban areas. Compared to conventional methods it is faster and causes less noise and air pollution as well as reduces vibrations and decreases the used space.
It is a kind of shield tunneling, and basically a TBM starts from ground level, digs beneath the obstacle and returns back to the surface.

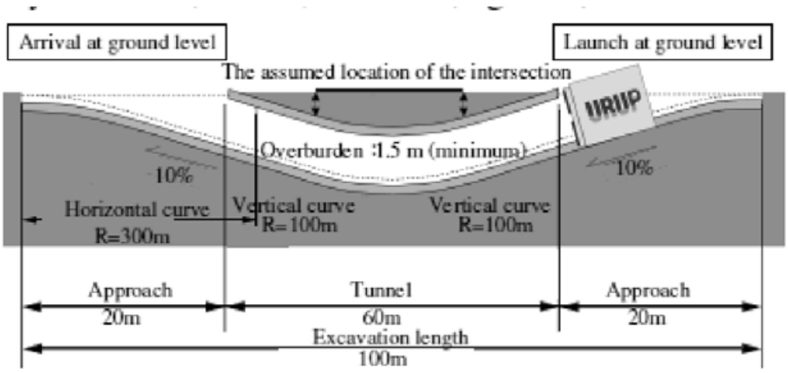

Figure 26: Principle of the URUP

This is achieved by a special and further developed Tunnel Boring Machine. This machine is using special side cutters and a matrix shield assembled in a rectangular shape. The side cutters act like preinstalled walls and have the purpose to prevent the ground from loosening. The matrix shield itself consists of two levels, an upper level and a lower level. The upper level is overhanging the lower level. As a result of this the upper half of the face gets excavated first, which reduces the stresses in the ground and therefore produces fewer settlements.

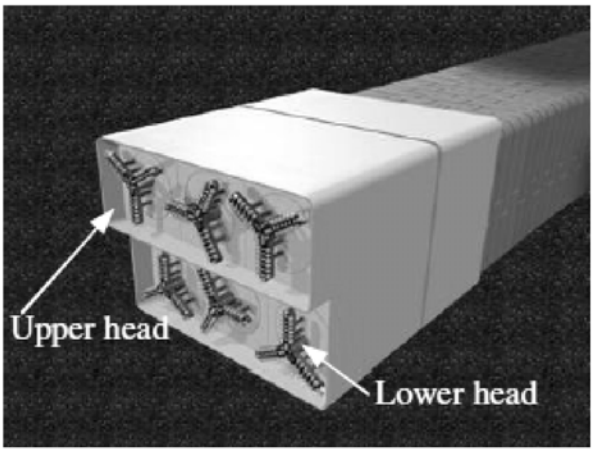

Figure 27: Model of the URUP

98 Miki, Keizo et al.: Development Of Construction Method For A Road Underpass At Intersection. In: ITA–AITES World Tunnel Congress 2009: Safe Tunnelling For The City and For The Environment: Hungary: Hungarian Tunnelling Association 2009

Because the machine is starting from the surface no works, for example the erection of a starting shaft, are needed in advance. When finished, the machine stops also on the surface, which makes it easier to reassemble it.
Furthermore there is no interruption of the ground water, due to the design of the machine and the needed overburden is estimated with just one half of the excavation height.
As a result of not just these listed points, the estimated construction period of a 500 m (1640 ft) long two lane underpass takes, according to the URUP-Team, about one-third compared to conventional methods.

5.8 Footing Reinforcement Pile

The following paragraphs and image are referring to a paper written in 2009 by Cui [99].
A very common problem when constructing surface near tunnels with shallow overburdens are settlements on the surface as well as the accompanied settlements on the crown and the foot of the tunnel.
This is where the approach of the footing reinforcement pile assesses. The idea is to stop the settlements on the surface by preventing settlements of the tunnel, by using reinforced piles. The piles can be installed horizontally or vertically and are located in the lower part of the cross-section.
Although the attempt is quite new, analyses show, that especially in the bottom section, foot reinforcement piles can be a useful method to prevent settlements. Interesting is the fact that at a certain point, the length of the pile is just influencing the settlements in the foot area, but not at the crown and surface.

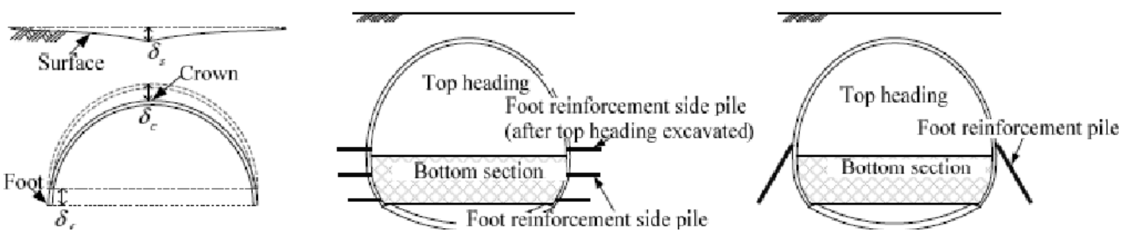

Figure 28: Principle of the Footing Reinforcemnet Piles

[99] Cui, Ying et al: Control Of Surface Settlement Arising From The Phenomenon Of Accompanied Settlement Using Footing Reinforcement Pile. In: ITA–AITES World Tunnel Congress 2009: Safe Tunnelling For The City and For The Environment: Hungary: Hungarian Tunnelling Association 2009

5.9 Ground Improvement

Improving the ground means to improve its physical properties. The crucial properties are compression, consolidation, shear strength and the permeability of the ground. To achieve an improvement of the ground, there are different techniques.
The most common ones are:

- Soil Mixing
- Soil Replacement
- Vertical Drains
- (Dynamic) Compaction & Consolidation

Soil mixing can be either used for improving the ground surface or deeper layers. In both cases the ground-improving materials, mostly chalk or cement, are mixed in-situ into the existing ground without removing any part of it. Even if the principle is always the same there are some different methods, adapted to the different requirements, of how to mix the soil.

Soil replacement is a quite simple method and already explained by the name itself. At first the unusable soil is removed and further deposited. Afterwards new material, with the needed properties, is brought in place. This method is just useful in shallow depths and relatively small areas.

Vertical drains have the aim to relieve the ground from pore water and its pressure. This is achieved by installing different kinds of vertical pathways in the ground, which are providing the water a shorter way to flow out of the soil. Examples are the use of gravel columns or prefabricated geosynthetics. To speed this process up, extra loads can be put on the soil to provide extra pressure. Vertical Drains are also very successful preventing soil liquefaction caused by earthquakes.

Compaction and consolidation of soil are also possibilities to improve the ground’s properties. When talking about compaction, the dynamic compression of the ground is meant. This can be achieved with a (street) roller, compacting plates or something similar. Consolidation therefore means a static compression of the ground, mostly with extra loads, provided by soil, raised on the ground. Also possible, but not very common, is the so called vacuum consolidation, where an airtight membrane is used to cover the ground and filled with vacuum to provide extra loads.
Both methods, compaction and consolidation, are performed till the ground reaches an acceptable strength and are removed afterwards.

6 Caverns in Urban Areas

6.1 General

Caverns are underground structures which are relatively wide and high but not quite long. They are naturally originated by water washing out stone, glaciers and lava tubes eroding the ground beneath the surface or other underground erosions. For this chapter caverns which are artificially built are examined. These, by men built caverns, are gaining more and more importance in nowadays underground development.

For different reasons, which have been already mentioned detailed in earlier chapters, underground constructions are becoming more important. The associated advance of construction technology led to a reduction of limitations in underground constructions.

Due to this advancement it is not just possible building tunnels for road- and public traffic under more challenging conditions, but also big caverns for multipurpose use even in shallow depths without interrupting the surface. This point is crucial because big underground constructions in the past have been realized by shafts or cut-and-cover methods, which were always dependent on the existing grid of a city. Nowadays it is possible to build these structures without interrupting the surface and therefore independent from grids in dense areas.

The difficulties and challenges in constructing a cavern are quite the same than in tunneling. These issues are stated in a paper of Pistone, who is saying that: [100]

> *Urban underground caverns of significant volume are an engineering challenge as they have to be dug avoiding excessive surface settlements likely to cause damage to buried services and existing structures. These are works that carry a high level of risk and have to be designed and constructed under a very tight control. The designer's main concerns are several and complex:*
>
> - *Difficulty to carry out extensive site investigation*
> - *Consequent uncertainties of the geological and geotechnical model*
> - *Serviceability limit of surface structures; settlements and deformations that can be supported by the structures without major damages*
> - *Lowering of the phreatic level and consequences on the environment and on nearby building foundations*
> - *Levels of noise and vibrations that the neighbourhood can tolerate during the construction*

[100] Pistone, Raúl Sarra: Underground Caverns In Urban Environments. In: ITA–AITES World Tunnel Congress 2009: Safe Tunnelling For The City and For The Environment: Hungary: Hungarian Tunnelling Association 2009

- *Constructive phasing that could ensure an appropriate performance of the primary support*
- *Real time intense monitoring*

Because problems and challenges are quite familiar in tunneling, the same applies to the construction methods. Mayor differences are appearing during the design process and regarding the construction process and sequence.

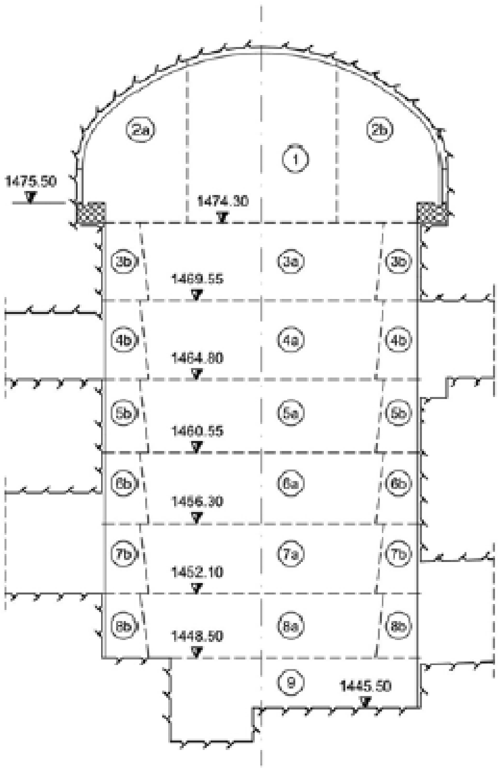

Figure 29: Zoning of the excavation of a cavern

Figure 29[101] shows an example of an excavation process for a cavern in hard rock conditions, excavated from the top to the bottom.

[101] ETH Zürich: http://www.tunnel.ethz.ch/events/hs07_amberg (October 2010)

6.2 Building a Cavern

There are different practices of building a cavern, depending on the ground, the size and the form. An ordinary excavation is divided into several horizontal and vertical sequences to minimize the disturbance of the ground.

The excavation process of a cavern can start from different access paths. An already existing tunnel can be one of those. If a tunnel is in existence the cavern can be erected by widening and enlarging the proposed area of the tunnel. Another possibility is to dig a pilot tunnel and start the excavation from the end of it. Common in urban areas is the use of pilot tunnels combined with shafts. The shafts can be sunken at a site where they are not disturbing the surface too much. Then pilot tunnels are forced till the site of the cavern and excavation starts from the tunnel's end. The shafts are needed to reach a proper depth, if working in undulating conditions, pilot tunnels can also be started from a hillside and forced horizontally till the proposed site of the cavern is reached.

When forcing caverns from a pilot tunnel one possibility is to excavate them from the top down to the bottom. That means that first the heading is excavated and then the cavern is forced in vertical steps, which are further divided in horizontal steps, to the bottom. If the cavern is of smaller size it can also be dug from the bottom to the top.
Important is that the excavation is done without disturbing the ground too much. This has to be ensured because most times the ground is not able to absorb all additional loads emerging by artificial erected holes.

Considering the construction of a cavern, the common method is to force it with the conventional method. The main reason therefore is the observational approach, but the adoption of this method in urban areas and soft ground has to consider that there are different problems occurring than in those caverns commonly built in hard rock conditions. A very stiff lining or primary structure, consisting of reinforced shotcrete and other support elements, has to be used to control the ground and reduce settlements as well as increase face stability.

TBMs can be also adapted and used to excavate a cavern.

6.3 *Chances of Caverns in Urban Areas*

Caverns can be very useful structures in urban areas, although the construction is quite challenging. While some years ago caverns were just erected in uninhabited areas and used as storage facilities for liquid gas, oil, nuclear waste, waste disposal, for accommodating powerhouses, generators and turbines in alpine regions or as protected and secured spaces for sensible (military) infrastructure, nowadays they are more and more used for public facilities in populated areas. They accommodate infrastructure, public facilities and are used as stations. The reasons why they are becoming more interesting in urban areas are the development of construction methods and monitoring instruments, which makes it easier and safer to build them.

Caverns have the advantage that they do not have to adhere on grids, buildings and objects on the surface. Access shafts can be built away from the main cavern and be a gateway to it.
If an underground metro is constructed caverns can be used as stations beneath almost any existing structure. This brings also chances for caverns in the construction phase with it. During construction caverns can be adapted as utility facilities, material storages, temporary muck storages and much more. So they can be a crucial part of the site logistics and reduce the costs of a project because of a decrease in occupied space.

In the future caverns can be even more important when implementing them into an intelligent city planning and development process. As they are already used for infrastructure like metro stations, caverns could for example also be used for nightclubs reducing the noise impact in urban areas significantly, for parking lots combined with access tunnels to reduce traffic on surface and for industrial facilities, which are disturbing the surface and on the other side are disturbed by the conditions at the surface like weather.

6.4 *Caverns in actual projects*

6.4.1 Oporto Metro Station, Portugal[102]

At the Oporto Light Rail System in Portugal two stations, the Bolhao station and the Combatentes station were built as caverns.

The Bolhao station exists of a main cavern which is about 70 m (230 ft) long and another transversal crossing cavern. They are located under the Bolhao Market and a cultural heritage chapel which demanded a special control of settlements. The Combatentes station consists of two perpendicular caverns.

The design was based on a well performed ground investigation, while using the observational method during construction. The construction sequences were calculated by numeric iterations, to choose the most appropriate one.

Construction started in the already existing, by TBM forced, main tunnels. The main caverns were constructed by widening and enlarging the tunnel in the needed area. The other caverns were forced from transversal pilot tunnels. All caverns have been divided into several horizontal and vertical sequences.

The graph below shows the design methodology flow chart of the stations:

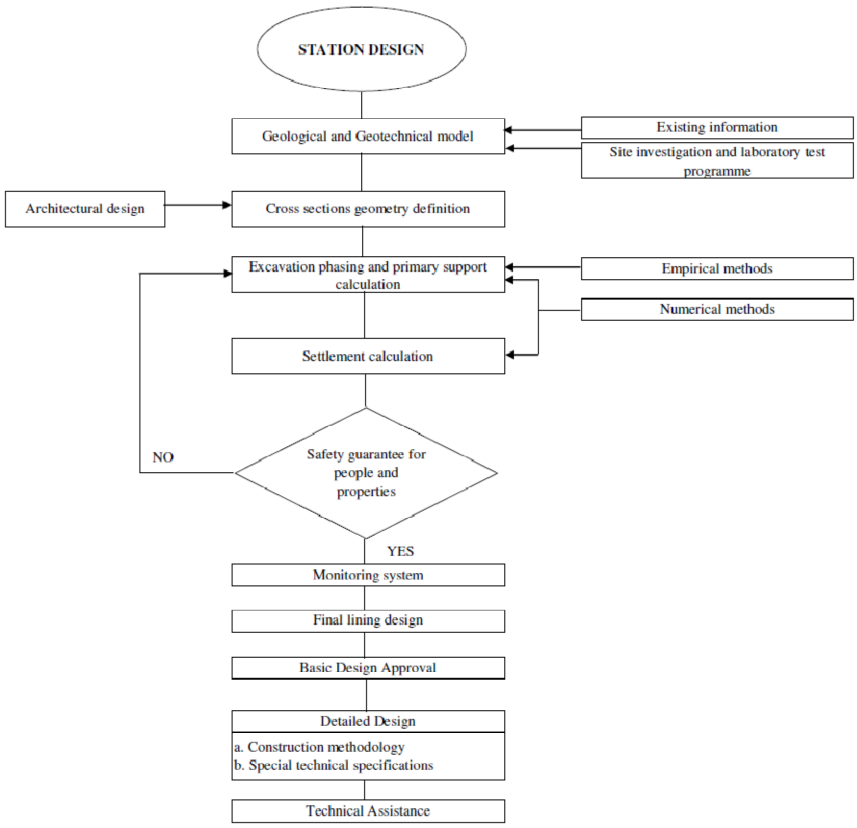

Figure 30: Design methodology flow chart for a station

102 Pistone: Underground Caverns In Urban Environments.

6.4.2 Trans Hudson Express[103]

The Trans Hudson Express is expected to be completed in 2015 and links New Jersey and New York with an additional rail system. One part of this project is a six track station cavern situated in one of the most dense and populated areas in the world, under the 34th street in Manhattan, New York. The additional tracks will transport about 86.000 people each way during the morning peak times and shall satisfy the ridership increase of about 70 percent till 2025.

The station will exist of two caverns with a width of about 20 m (65 ft), a height of about 23 m (75 ft) and a mezzanine level, installed in both caverns, about 35 m (115 ft) below surface. The ground in this area exists of granitic sill, serpentinite and schist. The ground near the surface consists of different sediments, which are not infecting the project because the crown of the cavern is situated 17 m (55 ft) below rock surface.

The graphic below shows the location of the 34th street caverns:

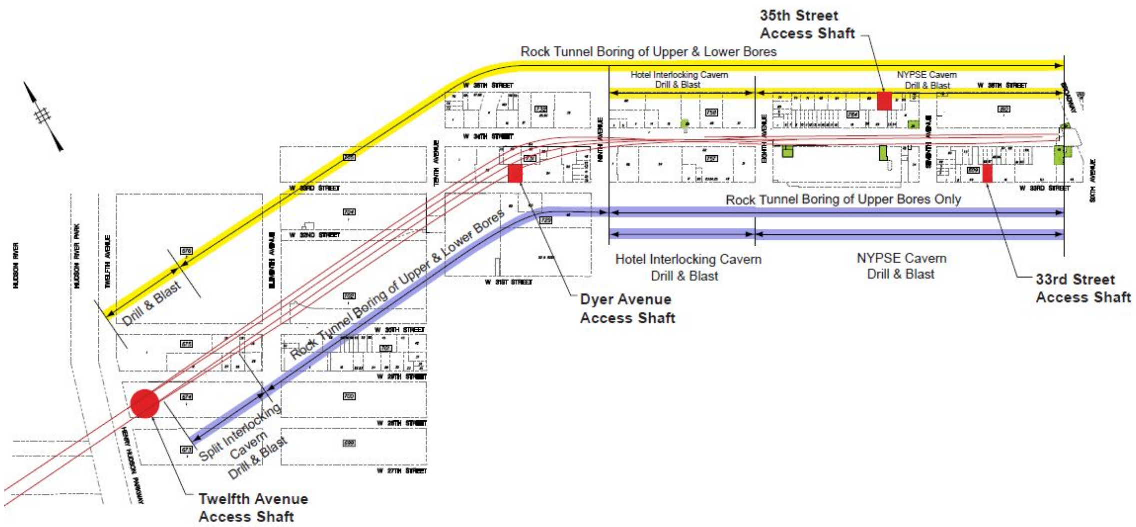

Figure 31: Layout of the 34th street station

6.4.3 New York Second Avenue Subway[104]

Another proposed project in New York is the construction of the Second Avenue Subway Line. It is located in the eastern part of Manhattan and will have a length of 14 km (8,7 mi) and serving 16 stations. Six stations and five crossovers will be built as caverns, all in shallow depth and some with

[103] Munfah, Nasri / Silber, Arthur D.: The Trans Hudson Express (THE) Tunnel. In: Barták, Jiři: Underground Space - the 4th Dimension of Metropolises. Volume 1. London: Taylor & Francis Group 2007, pp.131-136

[104] Rossler, K. / Stone, C.: New York Second Avenue Subway – Initial support design of shallow rock caverns. In: Barták, Jiři: Underground Space - the 4th Dimension of Metropolises. Volume 1. London: Taylor & Francis Group 2007, pp.685-691

large spans. The soil overburden will be around six to maximum 12 m (20 - 39 ft). The clear span of the caverns will be up to 30 m (98 ft). This project is actually in its preliminary engineering phase.

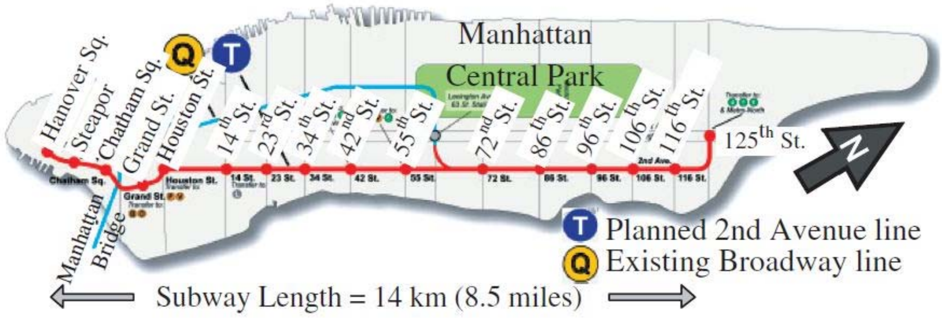

Figure 32: Location of the Second Avenue Line

6.4.4 Trondheim Railroad Shunting Area[105]

Although this project is not directly situated in a dense populated area and carried out in hard rock conditions it is very interesting and shows the possible future development of cities and their industrial facilities and underground constructions.

The city of Trondheim was in need of a new railroad shunting area. While searching for a proper location the following issues played a crucial role:

- *It is noisy*
- *It is aesthetically adverse*
- *It is an around the clock operation*
- *It is space demanding*

During that search, the idea of building the shunting area underground arose. The question why to go underground is summarized in the following points:

- *It allows valuable surface space to be utilized and developed for other purposes, or to be reinstated to its original use*
- *It improves the physical environment and limits awareness of and disturbance to the public.*
- *It eases flexibility for future expansion.*
- *It reduces the need of construction activity at the surface and provides a surplus on the mass balance*

[105] Grov, E.: Rail Road Shunting Area In Rocks Caverns. An Alternative Utilising The Underground. In: Teuscher, Peter: Progress in tunnelling after 2000 - proceedings of the AITES-ITA 2001 World Tunnel Congress. Volume 3. Bologna: Patron ed. 2001, pp.167-175

- *It has a constant climate around the year that ensures reliable and regular operation*
- *It preserves the environment*

So an already existing tunnel of the railroad ring connection was selected to be an adequate site. It was decided to built the shunting area in a 42 m (138 ft) wide and 700 m (2300 ft) long cavern with a cross section of about 400 m² (4300 sf). The maximum height was about 13 m (43 ft) and the proposed construction time was about 120 weeks.

Some advantages of being underground, like no exposition to weather, have a big impact to the work itself. For example slipping hazards for the workers caused by rain or ice are practically not existent. Another point is the public safety. If hazardous materials are treated and an accident happens, the fallouts to the public are minimized. The enclosed area allows a better control of these materials and when the structure is properly designed the environment should not be affected.
For the workers safety, several measures are undertaken. Examples are various types of fire-fighting equipment, optical detectors for smoke and fire, an emergency alarm control system, safety containers which are resistant to fire, redundant power supply to allow an uninterruptible operation and a ventilation system which has a maximum air flow of 100.000 m³ (3.531.000 cf) per hour which shall allow workers to escape in fresh air during a fire.

This project shows the intelligent development of the underground and its positive impact to the people, the environment and therefore the economy. The problem in such a project is to sell these advantages and that a safe operation is ensured to the public. Safety issues regarding erecting underground constructions are well controlled nowadays, and this is also appreciated by the public - operational safety therefore still has to proof itself.

7 Seismic Design

7.1 Introduction

Whenever talking about structures and buildings, seismic hazards have to be considered, even though the seismic potential and hazards are varying a lot, depending on the determined location. While for structures in Austria seismic loads are not decisive, and for underground constructions almost negligible they are a big deal in California and other parts of the United States. The reasons therefore are simply the tectonic plates and their movements.

This chapter will not go further into details of plate tectonics and the incurrence of earthquakes, but will point out some hazards to structures, especially underground structures, their consequences, how design could affect seismic effects to structures and how to calculate a basic seismic design. Also an idea about codes in the United States and their appliance is given.

The map below[106] shows the hazard of seismic events all over the world, based on the probability of earthquakes and their expectable peak ground velocity. Red and brown areas are the most endangered ones, while green and white areas are having a low hazard.

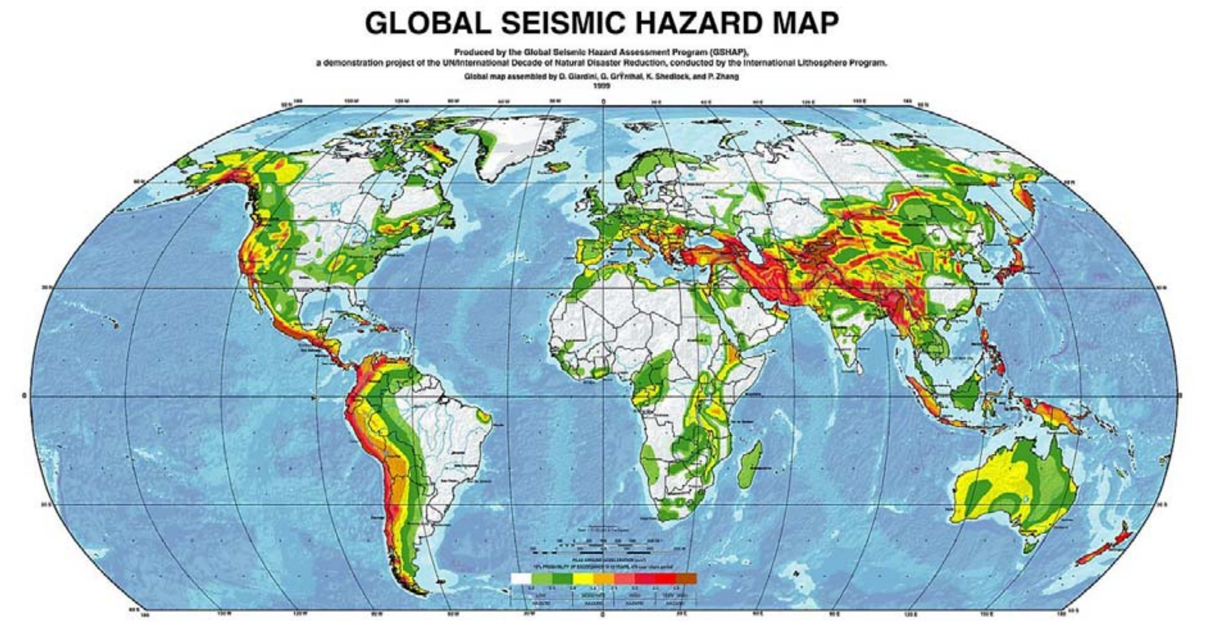

Figure 33: Global seismic hazard map

To understand the hazard of an earthquake some parameters need to be mentioned. These parameters are:

[106] Geologic Maps: http://geology.about.com/library/bl/maps/n_map_GSHAP1500.htm (December 2010)

- M … Earthquake Magnitude … Measure of the energy released by an earthquake
- PGA … Peak Ground Acceleration … Maximum acceleration which is experienced by a ground particle during an earthquake and index for intensity of strong ground motion at a site
- PGV … Peak Ground Velocity … Maximum velocity and important for tunnels to characterize the damage potential of ground motions
- PGD … Peak Ground Displacement … Maximum displacements

The map[107] beneath shows the earthquake hazards in California.

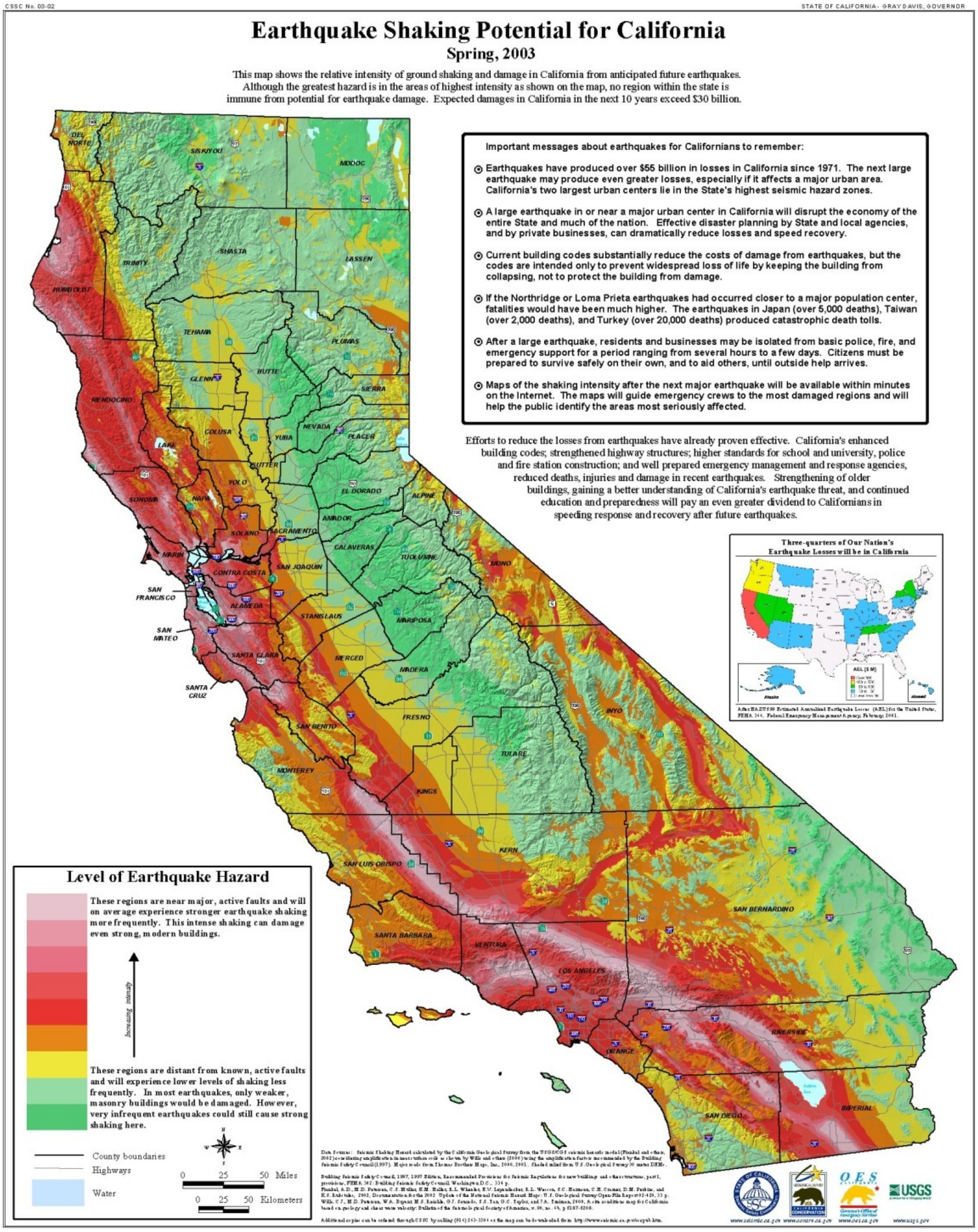

Figure 34: Earthquake shaking potential for California

107 California Seismic Safety Comission: http://www.seismic.ca.gov/pub/shaking_18x23.pdf (November 2010)

7.2 Effects of Earthquakes

If an earthquake occurs, there are different impacts on the environment and structures. The two mayor affects concerning underground constructions are ground failure and ground shaking. Both are responsible for mayor damages, but ground failure has, according to performance records, even more damaging effects on underground structures.

Is an underground structure erected in stable ground, the structure is not moving independently, which means that the behavior of the structure is basically depending on the ground deformations and not on the ground acceleration.

7.2.1 Ground Failure

Ground failure means that the ground becomes unstable which can result in:[108]

- Ground displacement
- Fault ruptures through a tunnel: Active faults crossing a tunnel can result in shearing displacements through it and cause serious damage.
- Land sliding: The problem of land-sliding is more common at tunnel portals and shallow parts of a tunnel. It can also cause large shearing displacements.
- Ground liquefaction: Ground liquefaction is a big issue of ground failure. This affects underground structures situated below the groundwater table when additionally soil is loose to medium-dense and cohesionless. In a seismic event the ground liquefies because of the pore water pressure and the structure can start floating or sinking. Ground liquefaction also leads to an increase of the lateral earth pressure.

Most of these failures can be controlled by an appropriate tunnel design.

7.2.2 Ground Shaking

Ground shaking means movement of the ground initiated by shock waves, normally as a result of an earthquake. There are two mayor types of waves caused by a seismic event, those travelling beneath the surface and those travelling on the surface.
When travelling beneath the surface, more precise at the inner layers of the earth, the waves are called body waves. These waves can be further divided into Primary Waves (P-Waves) and Secondary Waves (S-Waves). P-Waves are moving in longitudinal direction and are having a higher speed than

[108] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

S-Waves, so they are perceived first. S-Waves therefore are moving perpendicular to the propagation direction.
If waves are travelling on surface they are called surface waves and can be further divided into Rayleigh Waves and Love Waves.
All of them are deforming the ground but having different effects on underground structures.

Ground shaking is affecting underground structures in three different ways:

- Ovaling / Racking
- Axial deformation
- Curvature deformation

7.2.2.1 Ovaling / Racking

Ovaling / Racking is the deformation of a tunnel caused by seismic waves moving perpendicular to the longitudinal tunnel axis. The deformations are caused in the plane of the cross-section of the tunnel. Vertically propagating shear waves are considered to be most critical.
While at a circular tunnel the effects are called ovaling, at rectangular tunnels they are called racking.

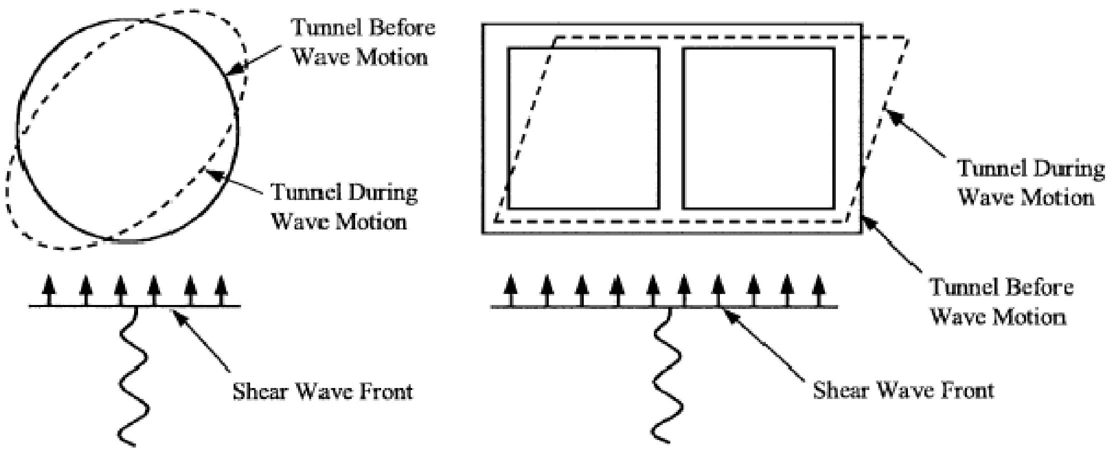

Figure 35: Ovaling and Racking of a tunnel

7.2.2.2 Axial Deformation

When seismic waves are propagating parallel to the tunnel axis, they are causing axial deformations. These deformations are consequences of tensions and compressions in the tunnel lining in direction of the tunnel axis, caused by frictional forces between the ground and the structure. Generally S-Waves are the predominant ones.

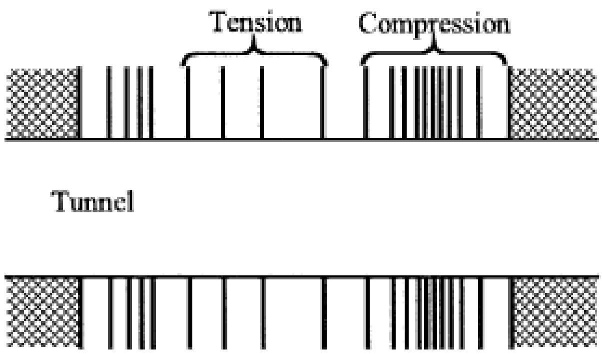

Figure 36: Tension and Compression due to seismic waves

7.2.2.3 Curvature Deformation

Curvature or bending deformations are caused by seismic waves propagating perpendicular to the longitudinal tunnel axis and are caused by the ground resistance normal to the tunnel lining.

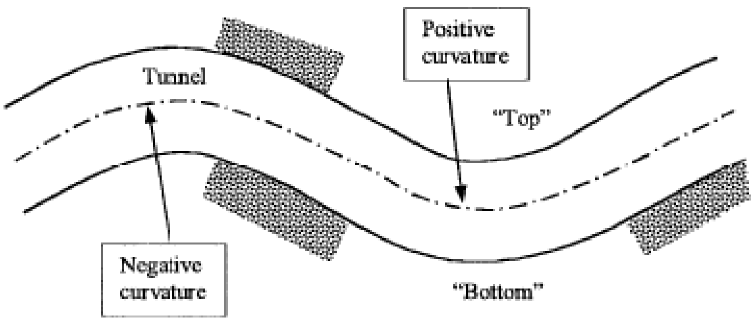

Figure 37: Curvature deformations due to seismic waves

7.3 Behavior of Underground Constructions

Underground constructions must withstand different influences from earthquakes, although history proofed that underground structures are less likely subjects to damages. One explanation therefore is the interaction with the surrounding ground, but this has only a significant effect in rock conditions. Another explanation is the depth of the structure. With an increasing depth, the amplitude of the seismic ground motion is decreasing. The table below shows the ratio of the decreasing ground motion depending on the depth of the structure. [109]

Tunnel Depth (m)	Ratio Of Ground Motion At Tunnel Depth To Motion At Ground Surface
≤ 6	1,0
6 - 15	0,9
15 - 30	0,8
≥ 30	0,7

Table 8: Ratio of the ground motion depending on the tunnel depth

Important for the performance of an underground structure are the soil conditions, the construction itself and most important the interaction between both of them.

The seismic performance of underground structures was investigated by Hashash and summarized as followed: [110]

- *Underground structures suffer appreciably less damage than surface structures.*
- *Reported damage decreases with increasing overburden depth. Deep tunnels seem to be safer and less vulnerable to earthquake shaking than are shallow tunnels.*
- *Underground facilities constructed in soils can be expected to suffer more damage compared to openings constructed in competent rock.*
- *Lined and grouted tunnels are safer than unlined tunnels in rock. Shaking damage can be reduced by stabilizing the ground around the tunnel and by improving the contact between the lining and the surrounding ground through grouting.*
- *Tunnels are more stable under a symmetric load, which improves ground-lining interaction. Improving the tunnel lining by placing thicker and stiffer sections without stabilizing surrounding poor ground may result in excess seismic forces in the lining. Backfilling with non-cyclically mobile material and rock-stabilizing measures may improve the safety and stability of shallow tunnels.*

[109] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

[110] Hashash, Youssef M.A. et al.: Seismic design and analysis of underground structures. In: Tunnelling and Underground Space Technology 16 (2001), pp. 247-293

- *Damage may be related to peak ground acceleration and velocity based on the magnitude and epicentral distance of the affected earthquake.*
- *Duration of strong-motion shaking during earthquakes is of utmost importance because it may cause fatigue failure and therefore, large deformations.*
- *High frequency motions may explain the local spalling of rock or concrete along planes of weakness. These frequencies, which rapidly attenuate with distance, may be expected mainly at small distances from the causative fault.*
- *Ground motion may be amplified upon incidence with a tunnel if wavelengths are between one and four times the tunnel diameter.*
- *Damage at and near tunnel portals may be significant due to slope instability.*

7.4 Codes

Building codes in the United States are quite different to those in Austria and the European Union. For buildings there are three different codes regulating the construction. These are the National building Code, the Standard Building Code and the Uniform Building Code.
The crucial thing about these codes is that the local governments can decide if they are adopting these codes or not, therefore some states do not require codes and other states do require them. But even if a state is applying a code, local governments can adopt their own ones and therefore overrule state regulations. This leads to an absence of proper codes in many seismic vulnerable areas.
Regarding the compliance of seismic codes it was figured out that just one percent of the total purchase of a home or one to two percent of the total costs of a new commercial or industrial building are needed to build it in accordance with seismic codes.[111]

For buildings the *NEHRP Recommended Seismic Provisions*[112] are a good source, but they are not dealing with underground constructions.
For underground constructions Chapter 13 of the *FHWA Technical Manual for Design and Construction of Road Tunnels*[113] published by the Federal Highway Administration is giving good practice, although it is no standard or regulation.

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[111] Alesch, Daniel et al.: Promoting Seismic Safety: Guidance for Advocates - The ABCs of Seismic Building Codes Web: http://mceer.buffalo.edu/publications/Tricenter/04-sp02/1-03abcs.pdf (November 2010)
[112] Building Seismic Safety Council: NEHRP Recommended Seismic Provisions for New Buildings and Other Structures. Washington D.C.: Building Seismic Safety Council 2009

7.5 Seismic Design Procedure

Seismic design means to design an underground structure in a way that it resists earthquakes in a safe way. That does not always mean that it has to withstand an earthquake with minor or without damages. The most important thing is that it is not collapsing or hurting any people by falling parts or the like.

The seismic design process is described as followed: [114]

- *Definition of the seismic environment and development of the seismic parameters for analysis*
- *Evaluation of ground response to shaking, which includes ground failure and ground deformations*
- *Assessment of structure behavior due to seismic shaking including a) development of seismic design loading criteria, b) underground structure response to ground deformations, and c) special seismic design issues*

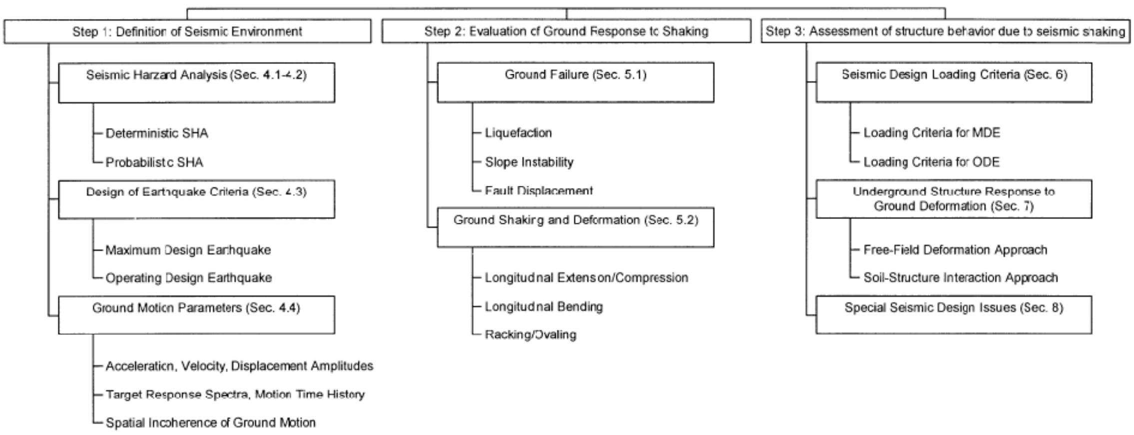

Table 9: Underground structure seismic analysis and design procedure

7.5.1 Seismic Hazard Analysis[115]

7.5.1.1 Deterministic Seismic Hazard Analysis (DSHA)

Deterministic seismic hazard analysis is the development of a particular seismic scenario, which means a particular size of an earthquake at a particular site, to determine and summarize all hazards resulting by ground motion.

The identification of these hazards is divided into four steps.

[113] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034
[114] Hashash: Seismic design and analysis of underground structures.
[115] Hashash: Seismic design and analysis of underground structures.

- *Identification and characterization of all earthquake sources capable of producing significant ground motion at the site, including definition of the geometry and earthquake potential of each*
- *Selection of a source-to-site distance parameter for each source, typically the shortest epicentral / hypocentral distance or the distance to the closest ruptured portion of the fault*
- *Selection of a controlling earthquake (i.e. that which produces the strongest shaking level at the site), generally expressed in terms of a ground motion parameter at the site.*
- *Formal definition of the seismic hazard at the site in terms of the peak acceleration, velocity and displacement, response spectrum ordinates, and ground motion time history of the maximum credible earthquake. Design fault displacements should also be defined, if applicable*

The DSHA provides a worst-case scenario at one particular site but gives no information about likelihood or frequency of occurrence of an earthquake. These information can be gathered by a probabilistic analysis.

7.5.1.2 Probabilistic Seismic Hazard Analysis (PSHA)

A probabilistic seismic hazard analysis identifies and quantifies uncertainties in the size, location and recurrence rate of an earthquake. The goal is to provide a more complete description of seismic hazards at a certain site.

The identification process is like the DSHA also divided into four steps:

- *Identification and characterization of earthquake sources, including the probability distribution of potential rupture locations within the source zone. These distributions are then combined with the source geometry to obtain the probability distribution of source-to-site distances*
- *Characterization of the seismicity or temporal distribution of earthquake recurrence*
- *Determination of the ground motion produced at the site by any size earthquake occurring at any source zone using attenuation relationships*
- *Combination of these uncertainties to obtain the probability that a given ground motion parameter will be exceeded during a given time period*

The PSHA reveals uncertainties in source-to-site distance, magnitude, rate of recurrence and variation of ground motion characteristics.

7.5.1.3 *Ground Motion parameters*

The differences between PGA, PGV and PGD were already explained in *7.1 - Introduction*. Regarding their application can be said that the PGA is more useful to design structures on surface and the PGV and PGD are better for describing damages on underground structures. While values for PGA are available at several hazard maps, there are little information about values for PGV and PGD. So ratios of PGV and PGD related to the PGA were established.

The following two tables are showing the ratios of peak ground velocity to peak ground acceleration at surface in rock and soil and ratios of peak ground displacement to peak ground acceleration at surface in rock and soil: [116]

Moment magnitude (M_w)	Ratio of peak ground velocity (cm/s) to peak ground acceleration (g)		
	Source-to-site distance (km)		
	0–20	20–50	50–100
Rock[a]			
6.5	66	76	86
7.5	97	109	97
8.5	127	140	152
Stiff soil[a]			
6.5	94	102	109
7.5	140	127	155
8.5	180	188	193
Soft soil[a]			
6.5	140	132	142
7.5	208	165	201
8.5	269	244	251

[a] In this table, the sediment types represent the following shear wave velocity ranges: rock ≥ 750 m/s; stiff soil is 200–750 m/s; and soft soil < 200 m/s. The relationship between peak ground velocity and peak ground acceleration is less certain in soft soils.

Table 10: Ratios of peak ground velocity to peak ground acceleration

Moment magnitude (M_w)	Ratio of peak ground displacement (cm) to peak ground acceleration (g)		
	Source-to-site distance (km)		
	0–20	20–50	50–100
Rock[a]			
6.5	18	23	30
7.5	43	56	69
8.5	81	99	119
Stiff soil[a]			
6.5	35	41	48
7.5	89	99	112
8.5	165	178	191
Soft soil[a]			
6.5	71	74	76
7.5	178	178	178
8.5	330	320	305

[a] In this table, the sediment types represent the following shear wave velocity ranges: rock ≥ 750 m/s; stiff soil is 200–750 m/s; and soft soil < 200 m/s. The relationship between peak ground velocity and peak ground acceleration is less certain in soft soils.

Table 11: Ratios of peak ground displacement to peak ground acceleration

[116] Hashash: Seismic design and analysis of underground structures.

When a structure is longish, like tunnels, the spatial incoherence of ground motion should also be considered, which means that different parts of the structure are encountering different ground motions. Also the effects of the travelling wave should be taken into account. The four mayor factors causing spatial incoherence are. [117]

- *Wave-passage effects*
- *Extended source effects*
- *Ray-path effects caused by inhomogeneities along the travel path*
- *Local soil effects*

7.5.2 Two-level design[118]

Whenever designing and calculating earthquake loads for a structure there is a high degree of uncertainty, which is in the nature of earthquakes and its shock waves. While structures on surface are designed to inertial load forces and resonant effects, underground structures are designed considering ground interactions and the displacement and deformation aspects of the ground. Nowadays it is usual to apply a two-level design. That means that the structure is calculated to so called Operating Design Earthquakes (ODE) and a Maximum Design Earthquakes (MDE).
The ODE is designed to withstand earthquakes with lower magnitudes, but a more likely appearance during the structure's lifetime. The structure must withstand those seismic loads in a manner that the operation can continue.
The MDE is focusing on an earthquake with a high magnitude, but therefore with an unlikely appearance. The focus of this design is to maintain public safety, which means that the structure shall not collapse, but operation does not have to continue. Anyways the MDE should consider the importance of a structure, and if it is likely that a particular structure is the best or only choice for maintaining operation after an earthquake, it should be designed for operation as well.

7.5.3 Seismic Design Issues[119]

When considering the seismic design of underground constructions there are some topics which need special attention. This chapter gives an overview about these topics and gives ideas how to deal with them.

Underground constructions can have abrupt changes in structural stiffness. Reasons therefore can be connections between tunnel tubes and stations, conjunctions of tunnels, local restraints from hard-

[117] Hashash: Seismic design and analysis of underground structures.
[118] Wang, Jaw-Nan: Seismic Design Philosophy for Tunnel Structures. Web: www.pbworld.com/library/fellowship/wang/chp2.pdf (October 2010)
[119] Hashash: Seismic design and analysis of underground structures.

spots and varying geological conditions. The differing stiffness can lead to different movements of the structure and subsequently to stress concentrations in it. These problems can be eliminated by the installation and use of flexible joints. Such joints need to be designed according to the projected differential movements in longitudinal and transversal direction, relative rotation and also the dynamic earth and water loads. Also portals and ventilation structures should be isolated from the main structure by the use of flexible joints.
In soil-to-rock zones it is advisable to make an over-excavation and backfill it with soil. This should prevent hard-points at the transition. Is the tunnel constructed with a TBM and an over-excavation not possible, a flexible lining should be installed.

When calculating ovaling or racking of a tunnel, see *7.6.2.2 - Ovaling deformations (circular tunnel)*, it is assumed that the tunnel is consisting of a continuous cross-section. If the tunnel cross-section is made of segments connected with joint connections, as likely when using TBMs, these joints must accommodate the expected ground deformations. Depending on the elastic or inelastic behavior of the joint, ground-lining interactions must be considered.

Regarding the lining can be said that an increase of the thickness or more reinforcement is not always leading to a better seismic performance. The reason for that is because a stiffer lining is attracting more forces, so more effective may be the use of ductile materials and circumferential joints.
More important than the stiffness is the soil-structure interaction which allows the lining to transfer the forces into the ground and leads to a reduction of loads in the tunnel lining. Despite that the frame of the structure needs a proper moment resistance. Cut and Cover tunnels have a higher risk of collapsing because of the absence of moment resistance and the dynamic loads of the soil backfill. If designing a tunnel with a relatively thin lining, the effect of buckling has to be taken into consideration as well.

Curvature caused by ground shaking can be controlled by reducing the distortion and the strains with the installation of transverse joints.

The elastic distortion or racking distortion can be calculated with the rotation capacity of the most rigid exterior corner joint. This elastic rotation capacity must be larger than the predicted shearing distortion. If this is not the case, plastic distortion on the less rigid joint member has to be calculated. If the end rotation exceeds the expected rotation further plastic yielding design needs to be carried out.

Exterior walls need a reinforcement on the inside face which is extended into the bottom and top slabs to prevent seismic racking.

If structural components are having no contact with the ground but are in continuous connection with other outer structural elements they may suffer plastic rotation. To prevent this, ductile sections or hinges should be installed in between. The dynamic forces of interior columns, walls, beams and slabs have to be calculated normal to their longitudinal axis.

When installing compression struts, attention should be paid to the end connections and if they are in interaction with continuous parts of the structure, their presence shall not interfere with the overall design assumptions.

Most underground structures are having appurtenant structures. If ground shearing distortion does not exceed the elastic capacity of the frame all attachments can be treated as rigidly attached. When shearing distortion is exceeding the elastic capacity of the frame, the main attachments should be loosely linked with a deformable or easy repairable joint.

Generally the placing of joints should consider in first sight that the structure is not collapsing due to plastic deformations of the frame. If deformable joints are used, they have to maintain their water tightness, which can be achieved by included rubber gaskets or bentonite reservoirs.

When considering ground failures one point is ground deformation. Because it is not quite possible to build underground structures which are resisting large and permanent ground deformations, the only effective methods are ground improvements, draining, soil reinforcements, grouting and other soil foundation works. If, for certain reasons, these measures cannot be undertaken, a relocation of the tunnel alignment should be considered.

Another ground failure issue is flotation, which is caused by ground liquefaction. If the ground liquefies the structure can either sink or float. When the structure floats the danger of further uplifting because of liquefied soil continuously moving beneath the tunnel is imminent. This effect can be prevented by constructing cut-off-walls, which can exist among others of pile walls, grouted columns or drained stone columns. Their existence leads to a reduced rise of abundant pore water pressure at the bottom of the structure as well as the ground beneath.

When dealing with an instable slope the only way to handle it is to stabilize the ground. Even if the movements are small, the underground structure will most likely not withstand these loads.

Underground constructions crossing faults is another big design issue. The generally established philosophy is to allow displacements and adapt the design of the structure in a way that occurring damages in the lining can be repaired or lining parts replaced easily.
The estimation of these deformations can be carried out by different methods. One of them is gathering data from a database which is collecting worldwide source parameters of earthquakes and developing empirical relationships. Another method is based on the PSHA, elucidated in *7.5.1.2 - Probabilistic seismic hazard analysis (PSHA)*, adjusted with a displacement attenuation function as third step.
When crossing fault zones, another possibility is to enlarge the tunnel cross-section in this area. The widening of the cross-section is directly related to a decrease in post-earthquake curvatures.
The enlarged cross-section can also be implying an inner tunnel, combined with a backfill in between. This leads to a minimization of the lateral loads. When the structure is just crossing small faults, joints can be installed to allow tunnel deformations. This will result in a future S-Shape of the tunnel, with the performance depending on the present soil.

7.6 Calculations

When calculating an earthquake, there are two possible approaches. The first is the free-field deformation method and the second is the soil-structure interaction method.

The free-field deformation method considers the ground strains caused by earthquakes, ignoring the structure. So the interaction between ground and structure is not considered. The results can be over- or underestimated, but are good enough for a first estimation.

The soil-structure interaction method therefore considers that an underground structure is present and interacting with the ground.

7.6.1 Important Parameters

As mentioned earlier in this chapter, the seismic performance of a tunnel is very closely related to the ground conditions at site and the interaction between ground and tunnel lining. There are two important factors which are part of the ground-lining interaction and are describing the relative stiffness between them. These factors are the compressibility and flexibility ratios. [120]

Compressibility Ratio

$$C = \frac{E_m(1-\nu_l^2)R_l}{E_l t_l (1+\nu_m)(1-2\nu_m)} \qquad [1]$$

Flexibility Ratio

$$F = \frac{E_m(1-\nu_l^2)R_l^3}{6E_l I_{l,1}(1+\nu_m)} \qquad [2]$$

Where:

E_l … Elastic modulus of the lining

E_m … Elastic modulus of the surrounding ground

ν_m … Poissons ratio of the surrounding ground

R_l … Nominal radius of the tunnel lining

ν_l … Poissons ratio of the tunnel lining

$I_{l,1}$ … Moment of inertia of the lining along the tunnel axis

t_l … Thickness of the lining

The flexibility ratio F is suggested to be the more important factor regarding resisting distortion. If F is greater than about 20, which means the ground is 20 times stiffer than the tunnel lining, the

[120] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

ground-lining interactions can be ignored. Then the fee-field deformation method is used to calculate an earthquake.

If a tunnel is built in very soft soil, and F is smaller than 20, the ground-tunnel interactions have to be considered, which means regarding the calculation that the soil-structure interaction method is required.

7.6.2 Free-Field Deformation

As mentioned above, if the interaction between ground and tunnel is ignored, the calculations are called free-field deformations.

When calculating the impacts of an earthquake, two effects need to be considered, the longitudinal and curvature strains as well as the ovaling deformations.

7.6.2.1 Longitudinal and Curvature Strains[121]

When a tunnel is suffering axial and curvature deformations imposed by the surrounding ground, the tunnel lining will absorb these loads by axial and bending strains. The axial and curvature strains can be combined and differ depending on the kind of wave hitting the tunnel. The following equations are based on the closed-form elastic solution, which connotes that the tunnel is assumed as an elastic beam and the seismic waves are assumed as plane waves with the same amplitude at the whole length of the tunnel, just with another time of arrival.

P-Waves

$$\varepsilon^{ab} = \left[\frac{V_P}{C_P}\cos^2\phi + r\frac{a_P}{C_P^2}\sin\phi\cos^2\phi\right] \qquad [3]$$

S-Waves

$$\varepsilon^{ab} = \left[\frac{V_S}{C_S}\sin\phi\cos\phi + r\frac{a_S}{C_S^2}\cos^3\phi\right] \qquad [4]$$

Rayleigh-Waves (compressional component)

$$\varepsilon^{ab} = \left[\frac{V_R}{C_R}\cos^2\phi + r\frac{a_R}{C_R^2}\sin\phi\cos^2\phi]\right] \qquad [5]$$

Where:

r … Radius of circular tunnel or half height of a rectangular tunnel

[121] Hashash: Seismic design and analysis of underground structures.

a_P … Peak particle acceleration associated with P-wave

a_S … Peak particle acceleration associated with S-wave

a_R … Peak particle acceleration associated with Rayleigh-wave

ϕ … Angle of incidence of wave with respect to tunnel axis

V_{P} … Peak particle velocity associated with P-wave

C_{P} … Apparent velocity of P-wave propagation

V_{S} … Peak particle velocity associated with S-wave

C_{S} … Apparent velocity of S-wave propagation

V_{R} … Peak particle velocity associated with Rayleigh-wave

C_{R} … Apparent velocity of Rayleigh-wave propagation

In rock conditions S-Waves are generally the ones which are causing the most strains, while in shallow tunnels and soil deposits Rayleigh-Waves are tending to be the decisive ones. An increase of the tunnel radius is causing higher bending strains and curvature deformations, but anyway these loads are still *"relatively small compared to the axial strains"*.

7.6.2.2 Ovaling Deformations (Circular Tunnel)

The predominant strains, when calculating ovaling deformation effects on a circular tunnel, are the ones caused by vertically propagating shear waves. According to Hashash the maximum shear strains, depending on the type of waves, are: [122]

Maximum shear strain for P-Waves ($\Phi = 45°$)

$$\gamma_{max} = \frac{V_P}{2C_P} \qquad [6]$$

Maximum shear strain for S-Waves ($\Phi = 0°$)

$$\gamma_{max} = \frac{V_S}{2C_P} \qquad [7]$$

Maximum shear strain for Rayleigh-Waves (compressional component) ($\Phi = 45°$)

$$\gamma_{max} = \frac{V_P}{2C_R} \qquad [8]$$

Maximum shear strain for Rayleigh-Waves (shear component) ($\Phi = 0°$)

$$\gamma_{max} = \frac{V_{RS}}{C_R} \qquad [9]$$

[122] Hashash: Seismic design and analysis of underground structures.

Additionally the FHWA is stating another equation which was especially developed for shallow tunnels. The maximum shear strain is there given by: [123]

$$\gamma_{max} = \frac{\tau_{max}}{G_m} \quad [10]$$

Where:

G_m … Effective strain-compatible shear modulus of ground surrounding tunnel

τ_{max} … Maximum earthquake induced shear stress, and

$$\tau_{max} = \left(\frac{PGA}{g}\right)\sigma_v R_d \quad [10.1]$$

Where:

R_d … Depth dependent stress reduction factor

R_d	$z = (H + D)$
1.0 - 0.00233z	< 10 m (30 ft)
1.174 - 0.00814z	10 m (30 ft) < z < 23 m (75 ft)
0.744 - 0.00244z	23 m (75 ft) < z < 30 m (100
0.5	z > 30 m (100 ft)

Table 12: Stress reduction factor in relation to the depth of the tunnel

σ_v … Total vertical soil overburden pressure at invert elevation of tunnel, and

$$\sigma_v = \gamma_t(H + D) \quad [10.1.2]$$

Where:

γ_t … Total soil unit weight

H … Soil cover thickness measured from ground surface to tunnel crown

D … Diameter of circular tunnel or height of rectangular structure

Once the maximum shear strains are calculated, with either method, the type of ground distortion needs to be determined. The ground can be assumed as either non-perforated or perforated.

In non-perforated ground the diametric distortion is calculated assuming that the ground is consisting of continuous soil. This is plausible if the stiffness of the lining is equal to those of the ground.

[123] U.S. Department of Transportation Federal Highway Administration: FHWA-NHI-10-034

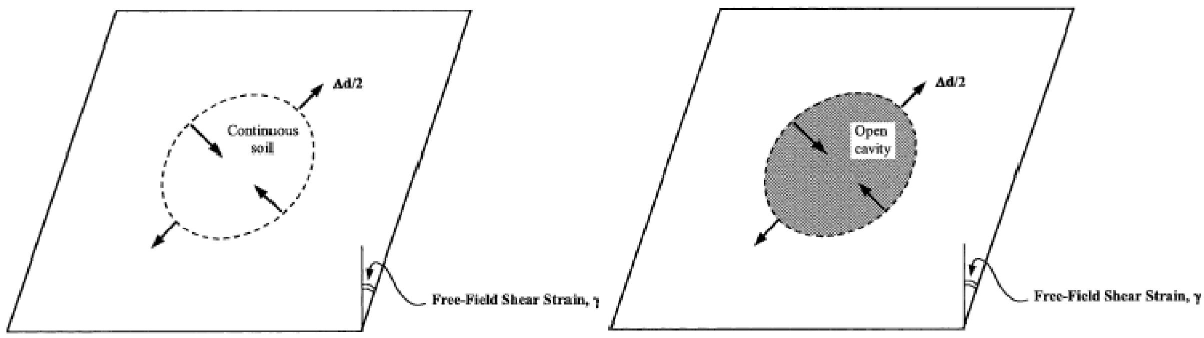

Figure 38: Schematic representation of non-perforated and perforated ground

In perforated ground therefore the diametric distortion is calculated assuming that there is an open cavity in the ground. The existence of a cavity is leading to a much higher distortion than in non-perforated ground, but is plausible if the lining has a smaller stiffness compared to the ground.

Maximum diametric strain in non-perforated ground

$$\Delta d = \pm \frac{\gamma_{max}}{2} d \qquad [11]$$

Where:

d … Diameter of the Tunnel

Maximum diametric strain in perforated ground

$$\Delta d = \pm 2\gamma_{max}(1-\nu_m)d \qquad [12]$$

Remark: Figure 34, 35,36 and 37 as well as Table 9, 10 and 11 are adopted from Hashash and his paper *Seismic design and analysis of underground structures*. [124]

7.6.3 Soil-Structure Interaction

The soil-structure interaction considers the interaction between the tunnel lining and the surrounding ground. This method is used if a very stiff tunnel is built in soft soil.

7.6.3.1 Longitudinal and Curvature Strains

The soil-structure interaction calculation of the longitudinal and curvature strains is based on the beam-on-elastic foundation approach. It assumes a quasi-static model which ignores dynamic interaction effects.

[124] Hashash: Seismic design and analysis of underground structures.

The maximum structural strains (axial and bending strain, shear force) are according to Hashash: [125]

Maximum axial strain (caused by a 45° incident shear wave)

$$\varepsilon_{max}^{a} = \frac{\left(\frac{2\pi}{L}\right)A}{2+\frac{E_l A_c}{K_a}\left(\frac{2\pi}{L}\right)^2} \leq Q_{max} \qquad [13]$$

Where:

A_c … Cross-sectional area of the tunnel lining

E_l … Elastic modulus of the tunnel lining

L … Wavelength of an estimated ideal sinusoidal shear wave, and

$$L = TC_s \qquad [13.1]$$

Where:

T … Predominant natural period of a shear wave in the soil deposit, the natural period of the site itself or the period at which maximum displacements occur, and

$$T = \frac{4h}{C_s} \qquad [13.1.1]$$

Where:

h … Thickness of soil deposit

The ground displacement response amplitude A, is based on site specific conditions. It considers "*the spatial variations of ground motions along a horizontal alignment"* and generally *"increases with increasing wavelength".*[126]

A For free-field axial strains

$$\frac{2\pi A}{L} = \frac{V_s}{C_S} \qquad [13.2]$$

A For free field bending strains

$$\frac{4\pi^2 A}{L^2} = \frac{a_s}{C_S}\cos^3\Phi \qquad [13.3]$$

The longitudinal spring coefficient of the medium, K_a, is a function of the incident wavelength and includes *"the ratio of pressure between the tunnel and the medium and the reduced displacement of the medium when the tunnel is present"*[127]. Because of the assumed sinusoidal wave, this spring has

[125] Hashash: Seismic design and analysis of underground structures.
[126] Hashash: Seismic design and analysis of underground structures.
[127] Hashash: Seismic design and analysis of underground structures.

to consider the negative and positive alternation. When applying to shallow tunnels the *"soil spring resistance values are limited by the depth of cover and lateral passive soil resistance".* [128]

$$K_a = \frac{16\pi G_m(1-\nu_m)}{(3-4\nu_m)}\frac{d}{L} \quad [13.4]$$

Where:

G_m … Shear modulus of the medium

The maximum frictional force between the tunnel lining and the ground Q_{max} limits the axial strain in the lining.

$$Q_{max} = \frac{fL}{4E_l A_c} \quad [13.5]$$

Where:

f … Ultimate friction force between tunnel and surrounding soil

Maximum bending strain (caused by a 0° incident shear wave)

$$\varepsilon^b_{max} = \frac{\left(\frac{2\pi}{L}\right)^2 A}{1+\frac{E_l I_c}{K_t}\left(\frac{2\pi}{L}\right)^4} r \quad [14]$$

Where:

I_c … Moment of inertia of the tunnel section

$K_t = K_a$ … transverse spring coefficient of the medium

Total strain as a combination of axial strains and bending strains for a conservative estimation

$$\varepsilon^{ab} = \varepsilon^a_{max} + \varepsilon^b_{max} \quad [15]$$

The maximum shear force on the tunnel cross section can be expressed as a function of the maximum bending strain

$$V_{max} = \frac{\left(\frac{2\pi}{L}\right)^3 E_l I_c A}{1+\frac{E_l I_c}{K_t}\left(\frac{2\pi}{L}\right)^4} = \left(\frac{2\pi}{L}\right) M_{max} = \left(\frac{2\pi}{L}\right)\left(\frac{E_l I_c \varepsilon^b_{max}}{r}\right) \quad [16]$$

Because of the cyclic loadings of earthquakes, positive and negative extremes have to be considered. The soil-ground interaction is only needed for structures in soft ground, while for tunnels in stiffer ground the free-field deformation approach is sufficient.

[128] Hashash: Seismic design and analysis of underground structures.

7.6.3.2 Ovaling Deformations (Circular Tunnel)

The following equations for diametric strain, maximum bending moment and maximum thrust are functions of the compressibility and flexibility ratios given in [1] and [2].

When calculating ovaling deformations of a circular tunnel, it needs to be differentiated between full-slip and no-slip conditions. Furthermore there are two attempts, basically from Wang and Penzien, adapted by Hashash, of how to calculate them.

Calculation of the maximum thrust caused by ovaling of a circular tunnel in full-slip conditions and without tangential shear force according to Wang adapted from Hashash: [129]

$$T_{max} = \pm\frac{1}{6}K_1\frac{E_m}{(1+\nu_m)}r\gamma_{max} \qquad [17]$$

Where:

K_1 … Full-slip lining response coefficient, and

$$K_1 = \frac{12(1-\nu_m)}{2F+5-6\nu_m} \qquad [17.1]$$

Maximum bending moment in full-slip conditions

$$M_{max} = \pm\frac{1}{6}K_1\frac{E_m}{(1+\nu_m)}r^2\gamma_{max} \qquad [18]$$

Diametric strain

$$\frac{\Delta d}{\mathrm{d}} = \pm\frac{1}{3}K_1F\gamma_{max} \qquad [19]$$

When calculating the maximum lining thrust of a circular tunnel in no-slip conditions the maximum thrust caused by simple shear needs an adjusted lining response coefficient. This is because full-slip calculations can result in significant underestimations of the maximum thrust: [130]

Maximum thrust in no-slip conditions

$$T_{max} = \pm\frac{1}{6}K_2\frac{E_m}{2(1+\nu_m)}r\gamma_{max} \qquad [20]$$

Where:

K_2 … No-slip lining response coefficient, and

$$K_2 = 1 + \frac{F[(1-2\nu_m)-(1-2\nu_m)C]-\frac{1}{2}(1-2\nu_m)^2C+2}{F[(3-2\nu_m)+(1-2\nu_m)C]+C\left[\frac{2}{5}-8\nu_m+6\nu_m^2\right]+6-8\nu_m} \qquad [20.1]$$

[129] Hashash: Seismic design and analysis of underground structures.
[130] Hashash: Seismic design and analysis of underground structures.

While *"slip at the interface is only possible for tunnels in soft soils or cases of severe seismic loading intensity"*[131], at most tunnels the slip at the interface is between full-slip and no-slip, therefore both cases need to be examined.

As K_1 and K_2 are functions of the flexibility ratio and the Poisson's ratio, following conclusions can be made: [132]

- When Poisson's ratio <0,5 seismically-induced thrusts increase with decreasing compressibility and flexibility
- When Poisson's ratio ≥0,5 seismically-induced thrusts are independent of compressibility because the soil is considered as incompressible
- When F <1 the tunnel lining will deform less than the free-field
- When F ≥1 the tunnel lining will deform more than the free-field

Like mentioned before, there is a second attempt by Penzien, also adapted from Hashash. For full-slip conditions the following equations are available: [133 / 134]

At first a lining-soil racking ratio R is given to estimate the diametric deformation of the tunnel

$$R = \frac{\Delta_{structure}}{\Delta_{free-field}} \qquad [21]$$

Diametric strain

$$\pm\Delta d^n_{lining} = \pm R^n \Delta d_{free-field} = R^n \frac{\gamma_{max} d}{2} \qquad [22]$$

Where:

R^n … Lining-soil racking ratio under normal loading, and

$$R^n = \pm\frac{4(1-\nu_m)}{(\alpha^n+1)} \qquad [22.1]$$

Where:

$$\alpha^n = \frac{12E_l I(5-6\nu_m)}{d^3 G_m(1-\nu_l^2)} \qquad [22.1.1]$$

[131] Hashash: Seismic design and analysis of underground structures.
[132] Hashash: Seismic design and analysis of underground structures.
[133] Hashash: Seismic design and analysis of underground structures.
[134] Hashash, Youssef M.A. / Park, Duhee / I.-Chiang Yao, John: Ovaling deformations of circular tunnels under seismic loading, an update on seismic design and analysis of underground structures. In: Tunnelling and Underground Space Technology 20 (2005), pp.435–441

Where:

G_m … Shear modulus of the ground

ν_l … Poisson's ratio of the lining

Maximum thrust

$$T_{max} = \pm \frac{12 E_l I \Delta d_{lining}^n}{d^3(1-\nu_l^2)} = \pm \frac{6 E_l I R^n \gamma_{max}}{d^2(1-\upsilon_l^2)} \quad [23]$$

Maximum moment

$$M_{max} = \pm \frac{6 E_l I \Delta d_{lining}^n}{d^2(1-\nu_l^2)} = \pm \frac{3 E_l I R^n \gamma_{max}}{d(1-\upsilon_l^2)} \quad [24]$$

Maximum shear

$$V_{max} = \pm \frac{24 E_l I \Delta d_{lining}^n}{d^3(1-\nu_l^2)} = \pm \frac{12 E_l I R^n \gamma_{max}}{d^2(1-\upsilon_l^2)} \quad [25]$$

Regarding no-slip conditions equation [21] and the following ones are valid:

$$\pm \Delta d_{lining} = \pm R \Delta d_{free-field} = R \frac{d}{2} \gamma_{max} \quad [26]$$

Where:

R … Lining-soil racking ratio, and

$$R = \pm \frac{4(1-\nu_m)}{(\alpha+1)} \quad [26.1]$$

Where:

$$\alpha = \frac{24 E_l I (3-4\nu_m)}{d^3 G_m (1-\nu_l^2)} \quad [26.1.1]$$

Moment

$$M_{max} = \pm \frac{6 E_l I \Delta d_{lining}}{d^2(1-\nu_l^2)} = \pm \frac{3 E_l I R \gamma_{max}}{d(1-\upsilon_l^2)} \quad [27]$$

Shear

$$V_{max} = -\frac{24 E_l I \Delta d_{lining}}{d^3(1-\nu_l^2)} = \pm \frac{12 E_l I R \gamma_{max}}{d^2(1-\upsilon_l^2)} \quad [28]$$

Hashash[135] compared the results of the calculation methods by Wang and Penzien, with the conclusion, that the results in full-slip conditions are almost the same, but that in no-slip conditions the thrust computed by the method of Penzien is several times lower.

In a further paper, Hashash investigated[136] this disparity, using three cases with different ground characteristics. He calculated each case based on Wang and also on Penzien and additionally carried out a numerical analysis.

The outcome was that the approach by Wang is much closer to the data gathered from the numerical analysis. Whereas the approach by Penzien provided far too low results regarding thrust in no-slip conditions.

For this reason the calculation of thrust in no-slip conditions according to Penzien are not included in this chapter.

[135] Hashash: Seismic design and analysis of underground structures.

[136] Hashash / Park / I.-Chiang Yao: Ovaling deformations of circular tunnels under seismic loading, an update on seismic design and analysis of underground structures.

8 Conclusion

The following paragraphs are briefly summarizing the outcomes of this thesis. More detailed outcomes can be found in the individual chapters.

It is obvious when having a statistical or real view on the infrastructure of the United States that tunnels do not have that significance like here in Austria or Europe. Sometimes they even seem like an attraction.
In the United States they mostly prefer bridges or accept high grades instead of going underground. A reason therefore is that the country has much more space and wideness, so an alignment around a hill is no problem and also people are used to and do not care about driving longer distances. This is in further consequence leading to an uneconomic and pollutive increase of gas usage in these areas. Just in densely populated urban areas with a good public transportation system, tunnels are more common. So the situation nowadays stands in contrast to the potential of tunnels which American engineers recognized in the 70s.

In Austria maybe the narrow valleys and lack of space are responsible for the big amount of tunnels, but anyways, it seems the overall attempt is to go the fastest and direct way, and there is a long history of tunneling. Also the different contractual systems in the United States and Austria are playing a big role. The ones in the US are anything else but ideal for constructing a tunnel, because the contractor carries all the risks and they are written more like disclaimers.[137]

But it has to be mentioned that, despite the points above, the US are beginning to make progress in tunneling. The Boston Big Dig[138] for example was a project according to the American way with many superlatives. It included the erection of two new bridges and three tunnels accommodating an eight to ten lane Highway replacing the main infrastructure in the heart of Boston. The three tunnels are altogether 10,6 km (6,6 mi) long and are existing of immersed, cut and cover and tunnel jacking segments.

Tunnels can be divided in different ways, like their construction, their site etcetera. Regarding construction many methods have been developed. They may be quite different, but have in common to make tunneling easier, safer and are providing a steady increase in knowledge and technology. An

[137] Parker: Life Cycle Cost Considerations Using Risk Management Techniques.
[138] The Massachusetts Department of Transportation - Highway Division: http://www.massdot.state.ma.us/Highway/ (December 2010)

interesting fact regarding construction methods is, that in the US about half of the tunnels "*needed to be stabilized, but not because of the low strength of the rock, but because of poor blasting*"[139].

Shallow tunnels are bringing some more problems with them than deep ones. A reason therefore is that they are mostly built in highly populated areas. In contrast to this there are also a lot of chances. Topics like pollution and collapsing can nowadays be eliminated to a high degree. So if the construction companies take their job serious, negative impacts can be reduced to a minimum. This is important so that positive impacts, like safety and reduction of costs are the dominant ones.

Regarding the elimination of risks and incidents during the construction and operation, adapted accompanying construction methods are playing a big role. There are special accompanying methods for shallow tunnels, for example ground freezing or grouting. It is essential for a tunnel engineer not just being confident with the classical tunneling techniques, but also being inventive and comfortable in adapting the right accompanying techniques.

Similar to tunnels are the construction processes and methods of caverns. They can have a very positive impact in the development of an urban infrastructure by their diverse use. Projects, like in New York the Trans Hudson Project and in Europe the Trondheim Railroad Shunting Area, are proofing this.

The seismic design of underground structures is very important in areas like California, but even there, there are no clearly defined codes which are needed to be satisfied. Instead researches or papers are giving a good practice, and are pointing out what is important to consider.
An earthquake can have several effects to an underground structure, like ovaling or racking, axial deformation and curvature deformation. The effects are influenced by the depth of the tunnel as well as the used materials and the method of construction. Besides the influences which can be controlled by humans, there are some which are dominated by nature. One of these are the propagating seismic waves. They are differentiating in the kind of the wave itself, the layers they are travelling in, their velocities and their way of propagating.
Most effects of earthquakes can be quite easily and cheap handled by proper seismic design, if only the crucial points are known.
For calculating seismic loads, the papers written by Hashash are a very good source. For this reason they are used as a basis for the seismic calculations in this thesis.

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9 References

9.1 List of Figures

9.2 List of Tables

9.3 List of Literature

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